

Composition Effects on Thermo-Physical Properties and Evaporation of Suspended Droplets of Biodiesel Fuels

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ABSTRACT

From the energy security and environment standpoint, the biodiesel fuels derived from vegetable oils or animal fats appear to be promising alternative to fossil diesel. Although the engine experiments prove their viability, the scientific data base for characterizing biodiesel combustion is limited. Detailed studies on the characterization of biodiesel fuels and their effects on fundamental engine processes like droplet evaporation and combustion are essential. The present study evaluates the useful thermo-physical properties and droplet evaporation characteristics of biodiesel fuels. The droplet evaporation measurements are carried out using suspended droplet experiments on five biodiesel fuels of Indian origin viz. jatropha, pongamia (karanja), neem, mahua and palm.

The droplet evaporation rates of these fuels are related to properties such as binary diffusivity and molecular weight, which in turn depend on their fatty acid composition. It is observed that palm methyl ester has the highest evaporation constant value of 0.1634 mm²/s and thus the lowest life time among the biodiesel fuels investigated. This value is attributed to its lowest molecular weight and highest molecular mass diffusivity. On the other hand, a reverse trend is observed for karanja biodiesel resulting in the highest lifetime among the fuel tested.

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INTRODUCTION

Fatty acid methyl esters (FAME) obtained from plant and animal resources commonly known as biodiesels are becoming a viable alternative to fossil diesel. Replacing or blending petroleum diesel with biodiesel is advantageous in mitigating environmental [1] and energy security concerns arising due to ever depleting fossil fuel reserves and the rising energy demands, particularly, in developing countries like India. About 70% of the fossil fuel demands of India are met by importing these fuels from other oil producing nations. The announcement of biodiesel policy and setting up of a biodiesel mission are the two major initiatives by the Government of India to encourage substitution of petroleum diesel with biodiesel of Indian origin [2, 3]. There are several vegetable oil resources available for producing biodiesel fuel in India which include non-edible oil sources like castor, jatropha, mahua, sal, linseed, neem, pongamia (karanja) [4] and edible oil sources like rice bran, rapeseed, sunflower, coconut, palm [4,5]. A techno-economic feasibility study [6] suggests that the biodiesel fuels from non-edible oils are cheaper than those developed from edible oils and also avert food-fuel conflict. Azam et al. [7] identified 26 plant species of Indian origin for producing biodiesel fuels which are found to meet international fuel quality standards.

There are innumerable studies on the engine performance evaluation with different biodiesel fuels available in various countries. These investigations invariably reported advantages of using biodiesel in compression ignition engines without any engine modifications [8] and changes in engine performance [9, 10, 11, 12, 13, 14]. However, understanding the biodiesel combustion behavior requires characterization of fuel properties as well as the fundamental processes like droplet evaporation [15,16], ignition [17,18], burning [19] etc. There are interesting review articles detailing the state-of-the-art on these aspects [20,21]. Though there are several fundamental investigations concerning droplet behavior of diesel and its surrogate fuels exist in literature, the corresponding investigations concerning biodiesel fuels and more specifically of Indian origin are quite scanty. Matlosz et al. [22] experimentally and analytically studied the evaporation phenomenon of n-hexane droplets under inert and stagnant ambience at higher temperature (548 K) and varying pressures (6.8-102 atm). Kracke and Puckett [23] conducted experiments on less than 150 microns hexadecane droplets at low Reynolds numbers (~7) and ambient temperature. They observed that the droplet evaporation, though follows d²-t law, it occurs in two different regimes depending on their size and velocity of the air-stream. The first regime has a constant evaporation rate while in the second regime the evaporation rate tends to be

lower at later stages. The deviation was explained by the reduced concentration of boundary layers existing at the surface of droplets at high air velocities.

From the biodiesel experiments, Wang et al. [24] compared the measured mass evaporation rates of diesel and neat rapeseed methyl ester (RME) for a temperature range of 323–423 K and observed that diesel droplets are more sensitive to ambient temperatures than biodiesel droplets. The fibre-suspended droplet experiments reported in reference [15] for droplets of rapeseed and sunflower methyl esters at atmospheric pressure and varying temperatures from 473 to 1020 K shows that the biodiesel evaporation is more like a single component fuel. Based on these experimental data, Dirbude et al. [25] developed an infinite thermal conductivity model for the single droplet evaporation process of biodiesel fuels and suggested suitability of Ranz-Marshall and Clift correlations for droplet regression calculations and confirmed the single component based evaporation behavior. In similar experiments, Daho et al. [26] carried out model analysis for evaporation characteristics of cottonseed vegetable oil and showed that the Ranz-Marshall correlation remains applicable with a simple change in the evaporation constant. There are some studies comparing single component [25], multi-component [27, 28, 29, 30] and hybrid [31] droplet evaporation models for diesel-biodiesel blends. These models require accurate values of thermo-physical properties of fuels. An et al. [32] discussed about different methods to estimate properties of biodiesel fuels. Anand et al. [33] presented different correlations to estimate the thermo-physical properties of biodiesel based on their chemical structure and composition. From these limited available experimental and modeling studies on biodiesel, it is amply evident that the biodiesel evaporation rate determination requires experiments on biodiesel fuels of varied composition and also the accurate values of thermo-physical properties. The present work is a fundamental study which concerns evaluation of thermo-physical properties and the measurement of evaporation rates for five biodiesels of Indian origin derived from non-edible sources namely *Jatropha*, *Karanja*, *Mahua*, *Neem* and *Palm* (edible) methyl esters.

Composition and Property Measurements

The fatty acid methyl ester (FAME) compositions of biodiesel are measured using gas chromatography with flame ionization detector (GC-FID) technique. GC-FID can detect methyl esters ranging from C10:0 to C24:0. For composition measurements, the biodiesel samples are prepared conforming to EN 14214 standards. A fuel sample of mass 0.25 g is mixed thoroughly with laboratory quality n-hexane using an ultrasonic vibrator in the containers which are cleaned using acetone. The sample is pre-warmed for 1 hour and then introduced into the respective channel of the gas chromatograph. The output of the gas chromatograph is obtained in a personal computer having proper interface to the device. Each experiment was repeated three times to ensure the accuracy and repeatability of the measured data.

Density of biodiesel sample was measured at room temperature (298 K - 303 K) using a hydrometer before conducting the droplet evaporation experiments for that particular sample. An Ubbelohde type glass capillary viscometer was used to determine the viscosity of the fuel sample. Liquid phase thermal conductivity and specific heat capacity was measured using C-therm thermal effusivity sensor.

Suspended Droplet Evaporation Setup

A schematic of the experimental setup is shown in Fig. 1. The experiments have been conducted using suspended droplet technique. Fuel droplets with initial diameters in the range of 2.1 mm to 2.3 mm, have been suspended on a quartz fibre of 1 mm diameter with a bead (~1.5 mm dia.). The suspended droplet is held over a vertical wind tunnel which supplies laminar hot air flow. The wind tunnel is a stainless steel pipe, 640 mm long, 57 mm internal diameter and insulated at its outer surface using ceramic wool. A 1000 W heating tape, which is capable of heating the inlet air to a temperature of 650 K, is sandwiched around the wind tunnel between the stainless steel body and the thermal insulation.

Flow straighteners and three meshes placed at equal intervals are attached in the inside and towards the bottom of the stainless steel pipe to condition the flow to the expected requirements at the exit. The pressure and discharge rate of the flow is regulated using a series arrangement of pressure regulator, a control valve and an air rotameter. The rotameter has been calibrated using a digital flow-meter at the required range of pressures to ensure the accuracy of operation.

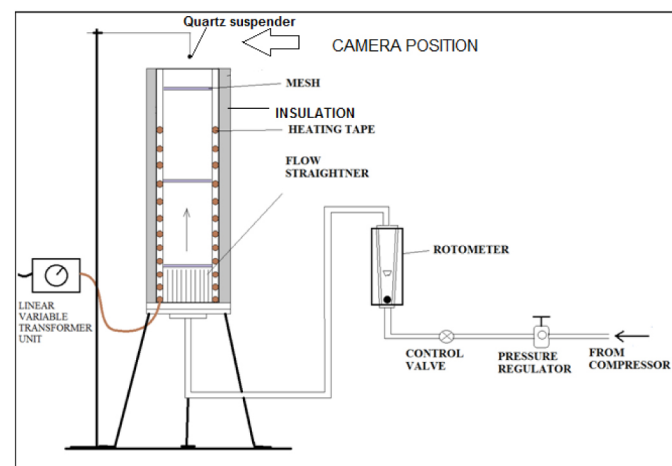


Figure 1. Setup for droplet evaporation experiment

The experiments have been conducted at a constant flow rate of $0.00035 \text{ m}^3/\text{s}$ (0.000819 kg/s) ensured by the rotameter operating at an absolute pressure of 2 bar. This imparts a superficial air flow velocity of 0.15 m/s at the exit of wind tunnel. A high quality digital video (30 frames per second) of the evaporating droplet is captured using a Casio Exilim-EXF1 digital camera. The video has been recorded continuously until the biodiesel drop vanishes from the quartz bead. Images have been extracted from this video using image-processing

software called ImageJ. The images have been post processed using a MATLAB code to extract the surface area of the droplet. Since the evaporation time is long, around 30 to 40 seconds, 2 frames in 1 second time have been used in post processing without loss of accuracy. The details of the methodology to post process an image using the MATLAB code and surface regression estimation are reported in the next section.

Surface Regression Calculation - Methodology

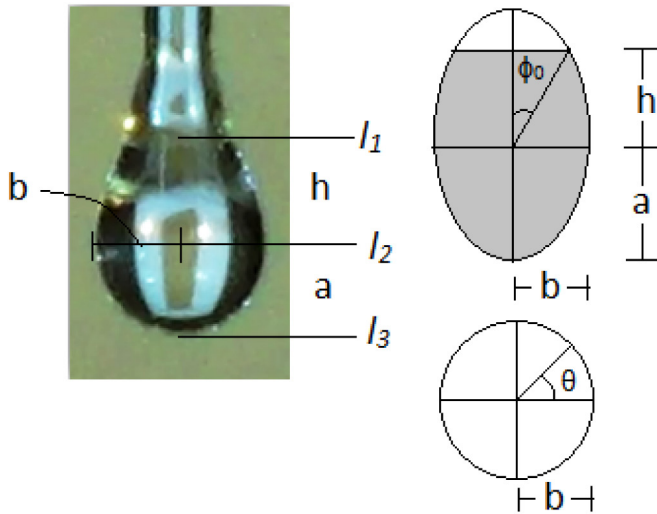


Figure 2. Image of bead type suspended droplet

The surface regression of the evaporating suspended biodiesel droplet is quantified from the visual data by post-processing the frames captured by the camera using a MATLAB code. The surface area of the suspended droplet is evaluated by assuming it to be a section of a prolate spheroid as shown in Fig. 2. The required surface area of the section is shown as a gray-shaded region in Fig. 2. The profile of the suspender (distance between the left and right points as a function of height) has been first stored. The profile of the suspender with the droplet is compared with that of the suspender alone, to identify the starting point of suspension of the droplet (denoted by the line l_1 in Fig. 2). Next the minor axis of the sectional spheroid is identified (denoted by line l_2 in Fig. 2) by searching for the location where the diameter of the droplet is the maximum. The radius at this location is the minor radius, denoted by b . The distance between lines l_1 and l_2 gives the height (from the minor axis) at which the spheroid is cut, denoted by h . The bottom point of the droplet, denoted by line l_3 in Fig. 2 - is identified. The distance between lines l_2 and l_3 gives the major radius of the spheroid, denoted by a .

$$A = \int_0^{\pi} \int_0^{2\pi} \sin \phi \sqrt{(b \sin \phi)^2 \{ (b \cos \theta)^2 + (a \sin \theta)^2 \} + (ab \cos \phi)^2} d\theta d\phi \quad (1)$$

where, $\phi_0 = \cos^{-1}(z_d/a)$, $d\phi = (\pi - \phi_0)/n$, $d\theta = 2\pi/n$.

The surface area of the droplet is evaluated by numerically integrating equation (1), where z_0 equals h and the step size of integration is n . From the surface area, the equivalent diameter of the droplet, $d = (A/\pi)^{0.5}$. The same procedure is adopted to find the diameter of the bead.

THEORETICAL CALCULATIONS

Estimation of Gas Phase Properties

The gas phase properties of biodiesel fuels like specific heat and binary diffusion coefficient have been calculated from the correlations available in literature [34, 35]. The vapor phase thermal conductivity has been determined by assuming Lewis number as unity and equating mass and thermal diffusivities. These properties are required for theoretical estimation of mass evaporation rate. The vapor phase specific heat capacity of biodiesel fuels has been calculated using a fifth-order polynomial in temperature using the method described in [34].

The binary diffusion coefficient is determined using Fuller correlations taken from reference [35].

Theoretical Evaporation Rate for Single Droplet Evaporation

The steady state mass evaporation rate of a single isolated droplet in a convective environment is theoretically estimated following reference [36] as:

$$\dot{m}_{evp,s} = \frac{\pi d \lambda_v Nu}{C_{pv}} \ln(1+B) \quad (2)$$

where, d is the droplet diameter, λ_v is the thermal conductivity of the gas surrounding the droplet, C_{pv} is the specific heat capacity of the vapor, Nu is the Nusselt number and B is the transfer number. As evaporation is an interfacial phenomenon, the assumption of Lewis number equal to unity is valid. In this case, equation (2) is written as,

$$\dot{m}_{evp,s} = \pi d \rho_l D_{bi} Nu \ln(1+B) \quad (3)$$

where, ρ_l liquid density, D_{bi} is binary diffusion coefficients.

The steady state evaporation constant during the process is given by

$$K_{evp,s} = \frac{2\dot{m}_{evp,s}}{\pi \rho_l d} \quad (4)$$

The square of diameter of the droplet at anytime during the steady phase evaporation can be defined as,

$$d^2 = d_c^2 - K_{evp} t \quad (5)$$