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Application of D^2 -law to Determine Time Evolution Drop-size Distribution Function of Bio-diesel drops and Their Burn-out Time

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Abstract: *This paper applies the D^2 -law to a group of heterogeneous size of bio-diesel drops in order to determine the time evolution of the drop-size distribution and its burn-out time. The drop-size distribution has been first transformed into a dimensionless form before its time evolution distributions and the evaporation time are analyzed. Experiment to verify the measurement procedures proposed have been performed on a bio-diesel spray issuing from a small scale industrial burner. It can be found that the D^2 -law for evaporation of a droplet can be adapted well to calculate the time evolution of distribution of the group of drops and their burn-out time. The dimensionless evaporation time is shortest for a single size drop distribution. For a broader drop-size distribution the dimensionless evaporation time takes longer time. The results of this paper are confined to the analyses of evaporation time obtained from line-of-sight measurement data.*

Keywords: Bio-diesel spray, Burn-out time, D^2 -law, Dimensionless mass frequency, Time evolution mass-based drop-size distribution

1. INTRODUCTION

Bio-diesel is a pertinent bio-fuel for Thailand. It has already been used in the form of diesel-biodiesel blend (2%) for automobiles and trucks. In the industrial section, it has also been used as diesel substitution for burner and furnaces. Most of the existing technologies to convert fuel to power, particularly the spray combustion technologies, have been designed for the conventional diesel fuel combustion conditions. The replacement of bio-diesel in the system originally designed for the diesel usage results in an off-design operating conditions. Thermal performance also is prone to be lower or sometimes the system cannot keep its combustion stability.

This paper tries to find the mean to predict the burn out time of the hetero size drops with in the biodiesel spray generated from a small scale industrial burner. The burn out time or life time of the drops together with the drops' velocity can give out the characteristic length of the combustion chamber. We adapt a simple combustion model originally used for a single droplet, the D^2 -law, to the hetero size drops within the spray in order to calculate the time evolution of the drop-size distribution and then to predict its burn out time.

Although the measurements of the time dependent mass-based and volume-based PDFs are beyond the scope of this paper, the measurement techniques and reports can be found in [1] and [2].

2. METHODOLOGY

2.1 Experimental setup

Malvern Spraytec instrument is used in this research to measure drop-size distribution of the bio-diesel spray. The measurement is based on laser diffraction technique. Schematic diagram demonstrating the experimental setup is shown in Fig.1. The measurement volume for this technique is the entire laser beam containing drops of hetero size. Laser from light source scatters from drops; the forward diffracted light are focused by the Fourier lens onto the ring detectors. Unscattered light are focused onto the central detector. These measured intensities are then converted into drop-size distribution using the embedded software within the Malvern instrument. The technique takes into account the forward diffraction and refraction scattering effects.

The nozzle used in this research is a pressure swirl nozzle giving a solid cone spray. The injection pressure used is 12 bar giving the flow bio-diesel flow rate 3.8 liter per hour. Site of the measurement is on the plane at 7 cm below the nozzle's exit. There are seven line-of-sight measurements, scanning from the center of the spray($y = 0$) to outer edge of the spray($y = 6$ cm); each measurement is 1 cm apart.

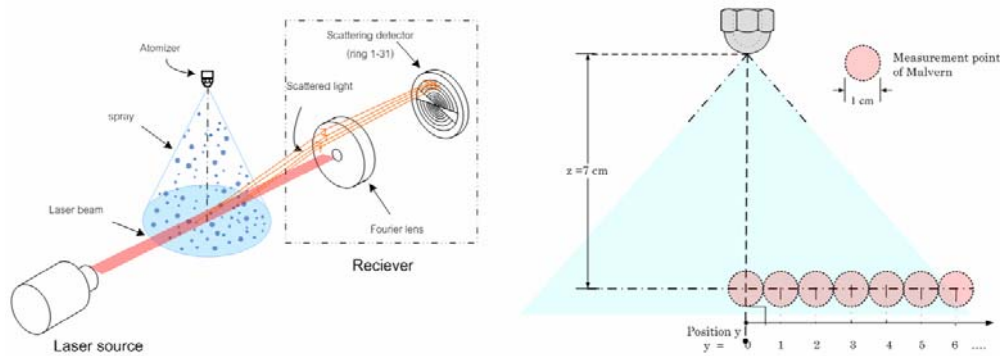


Fig.1 Schematic diagram of drop-size distribution measurement

2.2 The measurement of mean diameter

The Malvern Instrument reports volume fraction of drops along the line-of-sight of the laser beam. The volume fraction is the ratio of the volume of drops, ΔQ_i , within the class width, ΔD_i , to the total volume of drops, Q_{Total} , from all diameter classes ($i = 1$ to M) within the measure volume. The volume fraction distribution can be used to obtain different type of mean diameters. We are interested in the De Brouckere mean or D_{43} which is used commonly in combustion application [3]. This is defined in term of the measured volume fraction by

$$D_{43} = \sum_{i=1}^M D_i \Delta Q_i / Q_{Total}, \quad (1)$$

where D_i is the middle point of drop diameter of class i .

2.3 Dimensionless drop-size distribution

To reduce number of variables and to be independent of system of unit, the dimensionless diameter is used in this work. The diameter D_i of each class of the volume fraction distribution is nondimensionalized by the mean diameter, D_{43} , of the distribution to obtain the dimensionless diameter, ξ_i [4]. The width of the dimensionless diameter of class i can also be calculated as

$$\Delta \xi_i = \frac{\Delta D_i}{D_{43}}. \quad (2)$$

The volume fraction, on the other hand, is expressed in the form of mass fraction. This is of more meaningful when the evaporation or combustion of the group of drops is concerned. As far as the density of the liquid fuel is constant, the mass and the volume fraction distributions are equal. Therefore, the dimensionless mass frequency can be determined directly from the measured volume fraction by

$$\frac{\Delta w_i}{w_{Total}} / \Delta \xi_i = \frac{\Delta Q_i}{Q_{Total}} / \left(\frac{\Delta D_i}{D_{43exp}} \right). \quad (3)$$

The dimensionless mass frequency shown in the above equation is in turn used as the initial distribution for analysis of evaporation process.

2.4 Evaporation of hetero-size droplets

When a single fuel droplet evaporates under a quasi environment, either with or without combustion, its size against the evolution time is commonly expressed by the D^2 -law [5]

$$D^2 = D_0^2 - \lambda t, \quad (4)$$

where D_0 is initial diameter, λ is the evaporation constant and t is the evolution time.

The burn out time, t_b , is arrived when the diameter of the droplet becomes zero. The D^2 -law can be written in dimensionless form [4], using the mean diameter, D_{43} , and hence

$$(\xi_{i,\tau})^2 = (\xi_{i,0})^2 - \tau, \quad (5)$$

where $\tau (= \lambda t / D_{43})$ is the dimensionless time.

When a group of drops evaporates under combustion process, the number of drops having the same diameter does not change with time although their sizes are reducing, this idea is shown in Fig. 2.

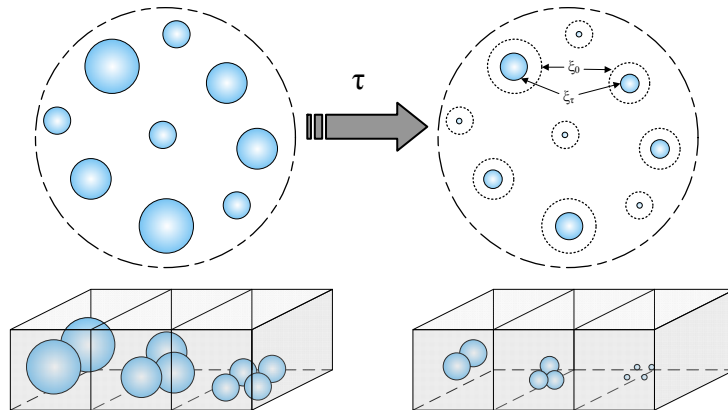


Fig. 2 The evaporation concept of hetero size drops

The concept shown schematically in Fig. 2 can be written in the form of equation as $\Delta N_{\tau > 0} = \Delta N_{\tau = 0}$. This can be transformed into the relation between the dimensionless mass frequency at any evolution time τ and at the initial time, with the help of Eq. (5). The time dependent dimensionless mass frequency can then be written by

$$\left(\frac{\Delta w_{i,\tau}}{w_{T_0}} / \Delta \xi_{i,0} \right) = \frac{(\xi_{i,0}^2 - \tau)^{3/2}}{\xi_{i,0}^3} \left(\frac{\Delta w_{i,0}}{w_{T_0}} / \Delta \xi_{i,0} \right). \quad (6)$$

Note that the time evolution of the dimensionless mass frequency is the relative change of mass fraction to the change of dimensionless diameter at the initial time, $\Delta \xi_{i,0}$ [4]. The dimensionless burn out time, τ_b , is arrived when the evaporated mass ratio ($= 1 - (\Delta w_{i,\tau} / w_{T_0})$) is more than 99%.

3. RESULTS AND DISCUSSION

3.1 Volume fraction distribution

The measurement results of volume fraction distribution are shown in Fig. 3. It can be seen from the Fig.3 that the distributions obtained are broader and the average diameters are smaller as the line of measurements get closer to the center of the spray. The mean diameters obtained from the different line-of-sight measurement are 46.8, 47.8, 52.6, 57.9, 63.9, 70.9 and 77.6 μm .

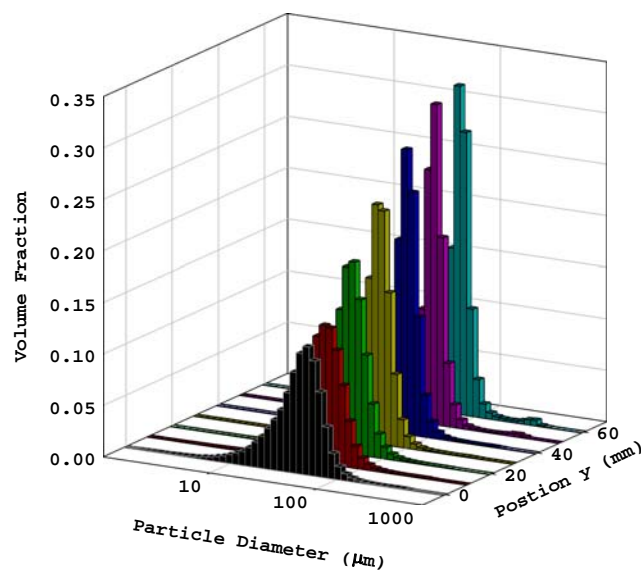


Fig. 3 Volume fraction distributions at different line-of-sight measurements

3.2 Time evolution dimensionless mass frequency

Volume fraction distribution data at position $y = 0$ is changed into dimensionless mass frequency, using the relationship given by Eq. (3). The dimensionless mass frequency is plotted in Fig. 4 (the solid line). Since the diameter space is nondimensionalized by the mean diameter, D_{43} , then the dimensionless mass frequency locates on the dimensionless diameter space of order one.

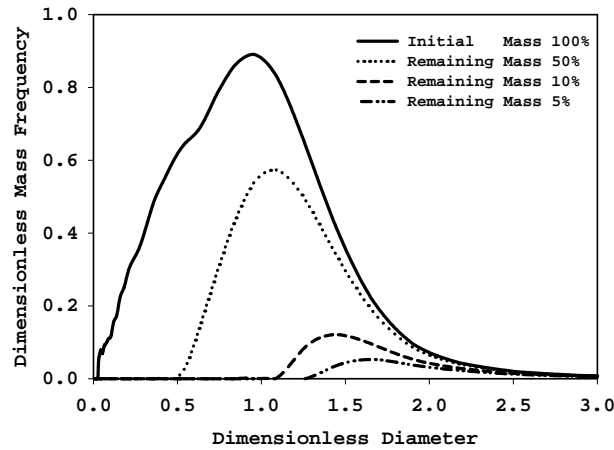


Fig. 4 Time evolution dimensionless mass frequency

Integration of the mass frequency results in the ratio of mass at the evolution dimensionless time to the mass at the initial time. Since the solid line represents initial dimensionless drop-size distribution, then the area under the curve of solid line (the mass ratio) is one. When combustion (or evaporation) occurs, the D^2 -law is applied to the dimensionless mass frequency and the curve becomes evolving with time. The dot, dash and center lines shown in Fig.4 are the dimensionless mass frequency when the remaining mass ratio is at 50, 10 and 5% respectively. It can be seen from Fig. 4 that the small drops disappear first and large drops remain. It should be reminded here that the dimensionless mass frequency is plotted against the dimensionless diameter at the initial time.

3.3 Evaporated mass ratio

The evaporated mass ratio against the evolution time of the above distribution (at the position $y = 0$) is calculated and plotted in Fig. 5. There are two time scales within the plot: the scale on the bottom x-axis is the dimensionless time scale and the scale on the top x-axis is the real time scale. Since at current state of the research, we do not know the value of the evaporation constant (λ) of the bio-diesel then the magnitude of the real time (t) is scaled by λ .

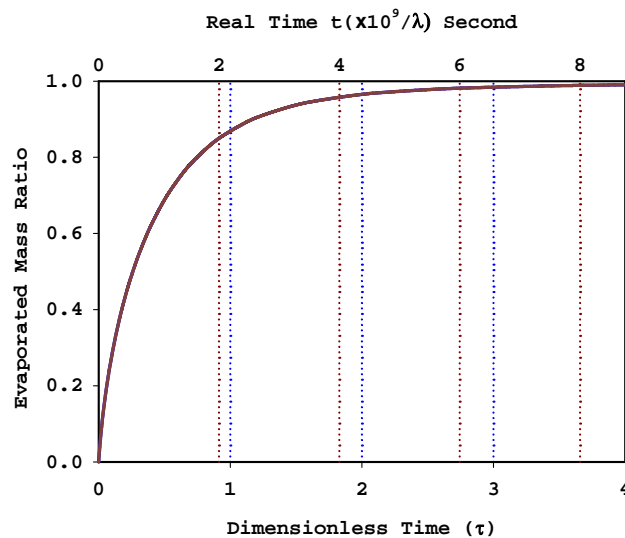


Fig. 5 Evaporated mass versus real and dimensionless time scales

Fig.6 shows the comparison of the dimensionless mass frequency from different line-of-sight measurements at initial time. The distributions are broader as the line of measurements get closer to the centre of spray than those at the outer edge.

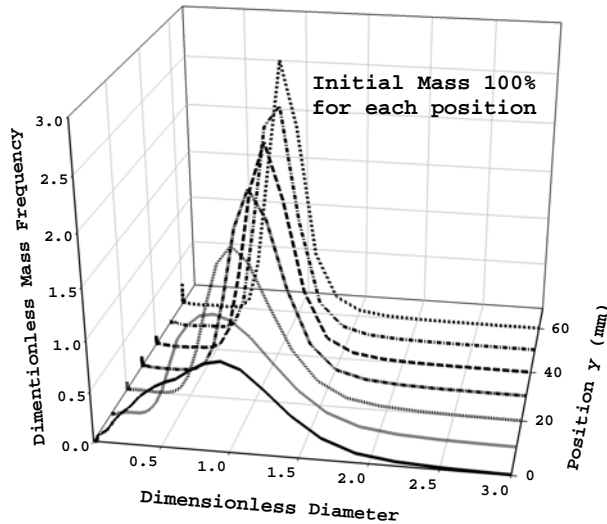


Fig. 6 Mass frequency of different line-of-sight measurements at initial time.

It has been found that the broader the dimensionless mass frequency, the longer the dimensionless time takes to evaporate the drops within the distribution. The dimensionless evaporated time is shortest (with the value of 1) when the distribution is of a single size drop distribution.

Fig.7 shows the remaining mass ratio of different line-of-sight measurements at the same evolution time. The mass ratio at the centre (= 10%) remains less than that at the outer edge (= 36%)

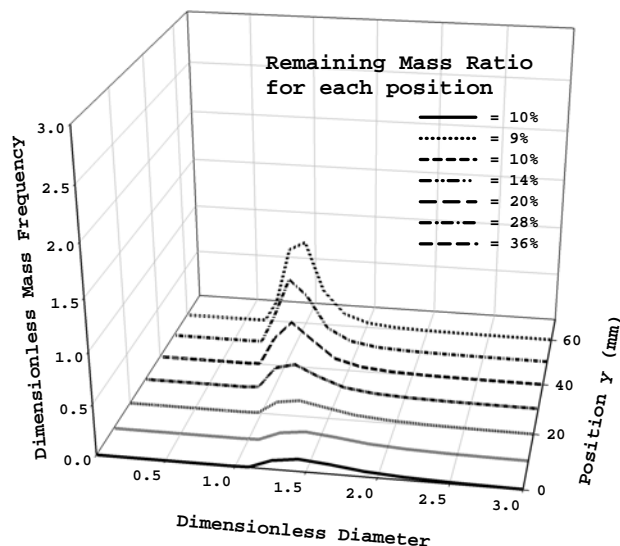


Fig. 7 Mass frequency of different line-of-sight measurements at a particular evolution time.

It can be seen that when the initial dimensionless mass distribution contains high proportion of small drops, it is prone to evaporate faster. In the case where the fuel and the combustion conditions are similar (λ is a constant and independent of drop-size), the real burn-out time depends only on the mean diameter: the smaller the mean diameter the faster the real evaporation time of the distribution.

The real evaporation time for the line-of-sight measurement past the center core is shortest which means that the hetero size drops within the measurement volume contains ratio of smaller drops more than those distribution measured at the edge of the spray

4. CONCLUSION

The classical D^2 -law for evaporation of a droplet can naturally be adapted to calculate the time evolution of distribution of the group of drops and their burn-out time. It can be seen that the dimensionless burn-out time delays for the case of heterogeneous sizes drop comparing with that of the single drop distribution. To calculate the real evaporation time from its dimensionless value, evaporation constant and mean diameter of the distribution are needed. The results of this paper are confined to the evaporation time obtained from line-of-sight measurement data; analysis of the local drop-size distribution within the spray is the subject for the future research.

5. ACKNOWLEDGMENTS

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