
Experimental analysis of biodiesel atomization characteristics

C.A.W. ALLEN and K.C. WATTS

Department of Biological Engineering, DalTech-Dalhousie University, P.O. Box 1000, Halifax, NS, Canada B3J 2X4. Received 30 July 1998; accepted 30 November 1998.

Allen, C.A.W. and Watts, K.C. 1998. **Experimental analysis of biodiesel atomization characteristics**. *Can. Agric. Eng.* **40**:281-285. Atomization is the first process encountered during the combustion of fuels in a compression ignition engine. This paper outlines an experimental analysis of the atomization characteristics of five types of methyl ester biodiesel fuels. The biodiesel fuels were produced by transesterifying canola, coconut, palm, peanut, and soya oils. A Malvern 2600 Laser Diffraction Particle Sizer was used to analyze the fuel sprays. Using the Duncan Mean Range Test, the Sauter Mean Diameters (SMD) and Rosin-Rammler distribution parameters of the five biodiesel fuels were compared with each other and with diesel #2 fuel. No statistical difference was found between the atomization characteristics of coconut and diesel #2 fuels. All of the other biodiesel fuels had atomization characteristics that were significantly different from diesel #2 fuel. **Keywords:** atomization, biodiesel, SMD.

La première étape du processus de combustion des carburants dans un moteur à compression diesel consiste à atomiser le carburant liquide. Cette étude décrit une méthode expérimentale qui servira à déterminer les caractéristiques de cinq différents carburants atomisés. Il s'agit de cinq types de carburants bio-diesels à base de méthyle ester réalisés à partir d'huiles de colza, de noix de coco, de palmier, d'arachide ou de soja en utilisant le procédé de transestérification. L'analyse du diamètre des particules dans un jet de carburant a été faite à l'aide de la méthode de diffraction de rayon laser (Malvern 2600 Laser Diffraction Particle Sizer). Des analyses statistiques (Duncan Mean Range Test) ont été effectuées sur les diamètres moyens (Sauter) et les paramètres de distribution de ces diamètres (Rosin-Rammler). Les résultats de ces analyses ont indiqué qu'il existe une différence significative entre les caractéristiques de quatre des cinq carburants bio-diesels et celles d'un carburant standard (diesel #2). Seul le biodiesel à base d'huile de noix de coco a donné des caractéristiques semblables à celles du diesel #2.

INTRODUCTION

Biodiesel fuels are emerging as a potentially viable alternative to conventional fossil-based diesel fuel. These biofuels generally take the form of methyl esters of plant and animal oils produced by means of the transesterification process. Many authors have investigated this fuel type, the results of which are reviewed by Graboski and McCormick (1998) and Bhattacharyya and Reddy (1994). The parameters that have been measured include density, viscosity, efficiency, power changes, emissions, injector coking, oil dilution, pour point, flash point, and cetane number, but seldom atomization because of the difficulty in measuring atomization. The exception is Ryan et al. (1982) who did measure 'atomization' using high speed photography in terms of spray angle and penetration into a cell. However, good atomization is very important. If droplets

are too large, they will not burn well, giving rise to sluggish behavior, oil dilution, higher emissions, injector coking, and poor efficiency. Atomization in turn is thought to be determined by viscosity and surface tension, as well as temperature, since temperature affects the first two parameters. The general conclusion from the literature is that, in terms of power, wear, efficiency and emissions, biodiesel fuels are a viable alternative. However, the results of studies on the various performance parameters have varied depending on the type of fuel used. The authors believe that these parameters are affected by the atomization of the fuel since the atomization process is the initial stage of combustion of a fuel in a diesel engine. This paper presents an experimental analysis of the atomization characteristics of five types of biodiesel fuels and diesel #2 fuel with the aim of identifying differences, if any, between fuels types that may lead to differences in their performance characteristics.

MATERIALS and METHODS

Sample preparation

Methyl ester biodiesel fuels from canola, coconut, palm, peanut, and soya oils were produced in a batch transesterification unit described by Allen and Watts (1996). Transesterification is the process by which the three fatty acids attached to the glycerol backbone of the triglycerides in neat vegetable oils are stripped off and each one is attached to a methyl alcohol group to form methyl esters. Although other alcohols could be used, methyl alcohol is usually the alcohol of choice for biodiesel fuels. By this means, the more viscous triglycerides are changed into lower viscosity methyl esters. The purity of the biodiesel fuels produced by the transesterification process was verified using thin-layer chromatography on Chromarods-SIII (silica gel) with flame ionization of the components (TLC-FID) by scanning in an Iatroscan Mark III (Ackman et al. 1990). The fatty acid compositions of the five biodiesel fuel types (Fig. 1) were determined using gas chromatography (GC) on a Perkin-Elmer Model 8420 Capillary Gas Chromatograph (Perkin-Elmer Corp., Norwalk, CT).

Droplet analysis

A Malvern 2600 droplet analyzer (Malvern Instruments, Malvern, Worc., UK) was used for all droplet analyses. The operational principles of this analyzer have been discussed in several papers (Gulder 1990; Hirtleman and Dellenback 1989; Dodge et al. 1987; Meyer and Chiger 1986; Dodge 1984). Its

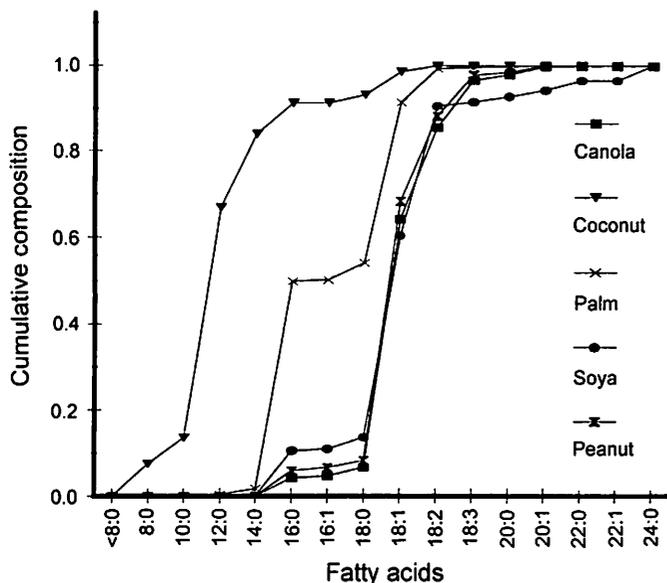


Fig. 1. Fatty acid composition of the five methyl ester biodiesel fuel types tested.

accuracy and repeatability were verified using a calibration reticle (RR-50-3.0-0.08-102-CF - #201) before tests were carried out.

The droplet analyzer was installed on a test bench that accommodated suitable fixtures for a diesel injection system. The diesel injection system was comprised of an electric motor with a cam shaft attached that drove a high pressure diesel fuel pump taken from a "Kubota" single cylinder direct injection engine. The injector had four orifices and a cracking pressure of approximately 23 MPa. The spray from only one orifice was analyzed while the sprays from the other orifices were captured in a special 'cup' attachment placed on the nozzle tip. The

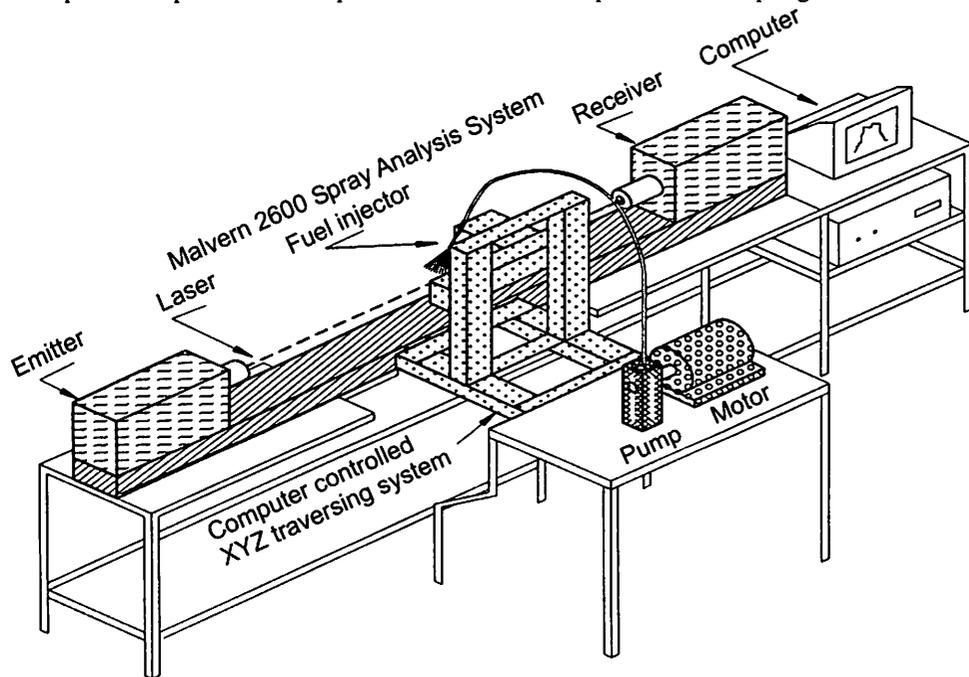


Fig. 2. Schematic of the Malvern analyzer and the spray system.

injector was mounted on a computer controlled precision X-Y-Z traversing table that facilitated the exact, repeatable positioning of the nozzle tip with respect to the laser beam (Fig. 2). The fuel temperature was maintained constant at 40°C by a water bath. The viscosity of the oils was measured at 40°C using a Parr rolling ball viscometer Model AVM 200 micro-viscometer (Parr Instruments, Moline, IL). The surface tension was also measured at the same temperature using a Kruss model K8600E Interfacial Tensiometer (Kruss, Hamburg, Germany) employing a Du Nouy ring. The results are given in Table I.

Table I. Viscosities and surface tensions for all biofuels tested (from Allen 1998).

Fuel	Viscosity (mPa s)	Surface tension (mN/m)
canola	3.70	23.6
coconut	2.32	26.5
palm	3.87	24.4
peanut	3.77	23.0
soya	3.67	23.4

The injection mode from the diesel pump is pulsatile, thus a special electronic system was designed to ensure that the droplet analyzer sampled at a specified angle during the spray period. This electronic control system was comprised of an optical shaft encoder and a specially designed counter circuit that provided an electrical pulse signal to trigger the droplet analyzer at any given angle. Thus the system was capable of sampling at different stages during the spray period, e.g. at the beginning of the spray, at the end, or any point between those extremes. The signal used to trigger the analyzer was also used to trigger a stroboscope that enabled visual examination of the spray prior to testing.

To maintain comparability between runs, the pump and injector settings were not changed after the initial setup. The pump rack and injector tip were both locked in place after the fuel line was initially bled to remove any air in the system. Once bled, the lines were not cracked since this may have led to either a change in the nozzle position or a change in the flow condition due to air traps. To reduce cross contamination, the fuel pump and lines were flushed with the test sample before proceeding with the analysis. The number of fuel line

changes corresponding to this duration and rack setting was computed from the displaced volume of the plunger to be approximately 20.

Each fuel test was comprised of ten replications and before each replication the droplet analyzer's laser beam alignment and the background light intensity were checked. For each replication, the pump was allowed to run for 10 seconds before 400 samples of the spray were taken by the Malvern analyzer, one for every second revolution of the pump shaft (shaft speed = 1725 rpm). The position of the spray, the point in time during the spray period, and the pump rack position were chosen to give the optimal condition for analysis by the Malvern. The spray timing was set at mid spray, maximum flow period. The rack position was set to give a steady spray that was dilute enough to give an obscuration of less than 45% (Gulder 1990). The spray was directed so that the laser beam passed through its midpoint in the lateral direction and the distance between the injector tip and the beam was set at a point where the spray was completely dispersed, but not too far downstream where the spray was unstable (tip-to-beam distance = 70 mm). This tip-to-beam distance is much greater than the typical distance available in a diesel engine combustion chamber. However, to facilitate physical measurements and comparisons of the droplet sizes and distributions of different fuel types, a relatively large tip-to-beam distance is required, as is common with all droplet analyzers. These tests show the relative differences in droplet sizes and distributions that are conventionally assumed to exist in an actual engine, although at much shorter distances. Confirmation of this will be shown experimentally in subsequent research at higher pressures and temperatures.

All of the above spray parameters were fixed for all fuel tests. A 300 mm range lens was used for all tests and the spray-to-lens distance was 130 mm, within the cut-off distance for that lens. A skylight filter was used to protect the optics and was cleaned regularly. The laser beam alignment checks carried out before each test indicated when there was a need to clean this cover lens.

Table II. Typical log-differences of four distributions for all fuels tested.

Model	Log-difference					
	Diesel	Coconut	Canola	Soya	Peanut	Palm
Model Independent (15 parameter)	3.83	4.17	3.73	3.73	3.72	3.89
Rosin-Rammler	3.68	3.80	3.97	3.72	3.74	3.91
Log-Normal	4.37	4.43	4.46	4.43	4.39	4.43
Normal	5.73	5.83	5.91	5.93	5.91	5.90

RESULTS and DISCUSSION

The optimal distribution function to represent the droplet distribution of the fuels was selected by comparing the Rosin-Rammler (Eq. 1), Normal (Eq. 2), and Log-Normal (Eq. 3) models available from the Malvern data analysis system with the 15 parameter 'model independent' distribution [Anon 1986]. The model independent distribution is normally used as

a reference since it is a 15 parameter polynomial equation which is capable of following complex data patterns given in the 16 droplet size classes from the Malvern 2600. The Malvern software system fits these models to the energy distribution obtained from the receiver diodes and a least square analysis is carried out to establish the goodness of fit. The log-difference, or log of the sum of squared errors (Eq. 4), is obtained by comparing the actual light energy measured on a given diode with the light energy calculated assuming a least squares fit for a fitting model. This is used as a guide to the selection of a model. The lower the log-difference, the better the model fits the data. Ideally the log-difference of a model should be below 5.5, but, as a 'rule-of-thumb', a log-difference with a similar or lower value than the log-difference of the model independent distribution is desired [Anon 1986].

$$1 - Q = R = \exp \left[- \left(\frac{d}{X_1} \right)^{N_1} \right] \quad (1)$$

$$f_d = \frac{1}{N_2 \sqrt{2\pi}} \exp \left[- \frac{d - X_2}{2N_2^2} \right] \quad (2)$$

$$f_d = \frac{1}{\ln(N_3) \sqrt{2\pi}} \exp \left[- \frac{\ln(d) - \ln(X_3)}{2[\ln(N_3)]^2} \right] \quad (3)$$

$$\log \text{ difference} = \log \sum_{j=1}^n (\text{light calculated} - \text{light measured})^2 \quad (4)$$

where:

Q = fraction of total volume contained in droplets of diameter less than 'd',

R = normalized fraction of droplets over diameter 'd',

f_d = relative frequency of size 'd',

X_1 = a measure of the peak diameter of the Rosin-Rammler distribution,

X_2 = a measure of the mean diameter of the normal distribution,

X_3 = a measure of the geometric mean diameter of the log-normal distribution,

N_1 = a measure of the 'spread' of the Rosin-Rammler distribution,

N_2 = standard deviation of particle sizes using the normal distribution, and

N_3 = geometric standard deviation of particle sizes using the log-normal distribution.

Having established the pattern of the energy distribution using the 'model-independent' model, the selection of one of the two parameter models is usually desired since these models can be readily incorporated into complex combustion models.

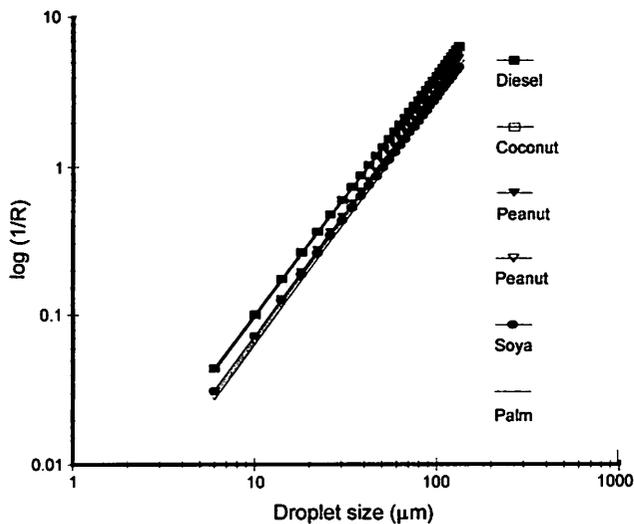


Fig. 3. Verification of the Rosin-Rammler distribution for all fuels tested.

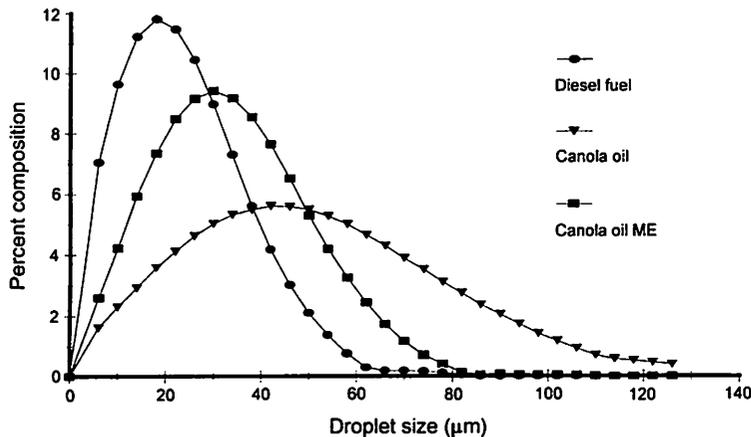


Fig. 4. Droplet distribution of diesel fuel, neat canola oil, and canola oil methyl ester.

Table III. Summary of atomization parameters for all fuels tested.

Fuel type	SMD (μm)		X_1 (μm)		N_1	
	Mean	SD	Mean	SD	Mean	SD
Diesel	10.88	0.31	24.55 ^a	0.59	1.62 ^a	0.03
Coconut	11.16	0.50	25.09 ^b	0.96	1.63 ^a	0.05
Soya	13.37	1.12	30.04 ^c	0.76	1.63 ^a	0.07
Canola	13.58	0.97	29.16 ^d	1.15	1.68 ^b	0.08
Peanut	13.99	0.78	30.30 ^e	0.63	1.67 ^{bc}	0.04
Palm	14.51	0.85	31.55 ^f	1.65	1.67 ^{bc}	0.05

^aSimilar letters in any one column indicate no significant difference.

Table II shows typical log-differences for each model using the fuels tested. The log-difference for each fuel was practically constant for all replicates. Of the three two parameter models, the Rosin-Rammler had the lowest log-difference that was comparable with the log-difference for the model independent distribution; thus this model was selected to represent the droplet distribution of all the tests carried out in this study. To verify the suitability of the Rosin-Rammler model, the log of the inverse of the computed Rosin-Rammler distribution was plotted against the droplet diameter on a log-log scale for each fuel type (Fig. 3). The linear line achieved for all fuels verifies the suitability of the Rosin-Rammler distribution for modeling the distribution of biodiesel and diesel fuels. The Rosin-Rammler model is conventionally used for droplets (Meyer and Chigier 1986).

Droplet analyses were carried out to establish if there were any distinct differences between typical diesel, vegetable oil methyl ester, and neat vegetable oil fuels. The droplet distribution of these three sample types, using canola oil as a reference, are shown in Fig. 4 where the distinct differences between the three can be seen. The droplet distribution for the neat vegetable oil was flat and wide indicating the existence of several large-size droplets. These would contribute to poor combustion in a diesel engine, as is known to be the case in practice.

The Rosin-Rammler distribution parameters and the calculated SMDs for coconut, canola, peanut, soya, and palm oil methyl ester biodiesel fuels were compared with each other and with diesel fuel using the Duncan Mean Range Test (DMRT) at a 95% confidence level. The droplet distributions for these fuels are compared in Fig. 5. An analysis of these SMDs using the DMRT showed that all were significantly different at the 95% level except for canola compared with soya, canola compared with peanut, and coconut compared with diesel. Compared to diesel fuel, the SMDs for coconut, canola, soya, peanut, and palm biodiesel fuels were respectively 2.6, 24.8, 22.9, 28.55, and 33.36% higher than that for diesel fuel. The values of the SMDs are summarized in Table III.

The Rosin-Rammler distribution function parameters ' X_1 ' and ' N_1 ' are also summarized in Table III. The ' X_1 ' parameter is a measure of the mean diameter of the distribution while the ' N_1 ' parameter is a measure of the spread of the distribution. As ' N_1 ' tends to infinity, the distribution tends to a mono-size distribution. The DMRT found that all the ' X_1 ' parameters were significantly different at the 95% level except for soya compared with peanut. The ' N_1 ' parameters showed a high degree of variation and several of them were found to be similar. At the 95% level, the ' N_1 ' parameters for soya and diesel; soya and coconut; canola and peanut; peanut and palm; canola and palm; and coconut and diesel were not significantly different.

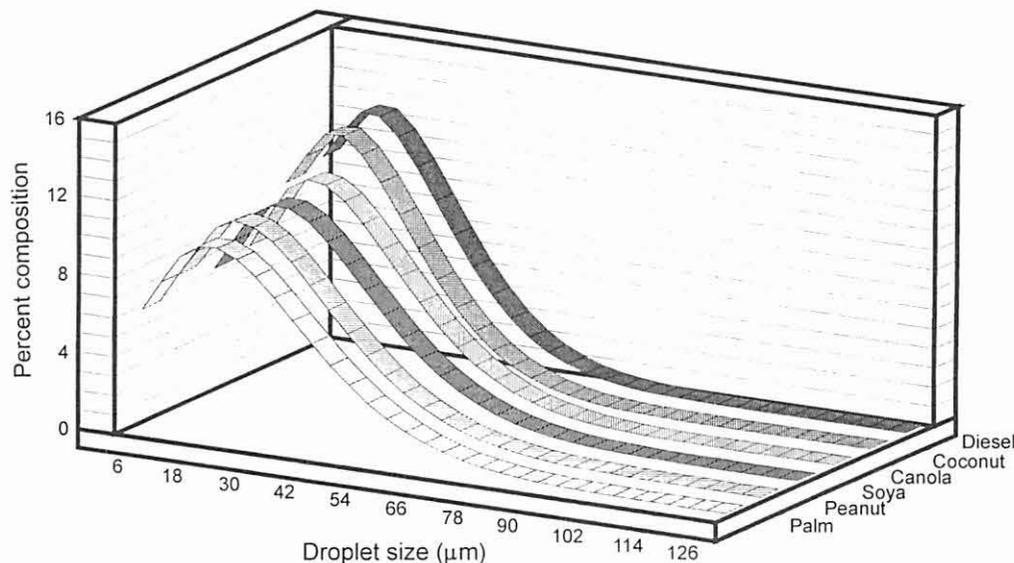


Fig. 5. Droplet distributions of all fuels tested.

CONCLUSIONS

The experimental analysis of the atomization characteristics of canola, coconut, palm, peanut, and soya methyl ester biodiesel fuels has led to the following conclusions.

1. The Rosin-Rammler distribution function adequately modeled the droplet distribution of biodiesel fuels tested.
2. Of the fuels tested, only coconut oil methyl ester biodiesel fuel had statistically similar atomization characteristics to those of diesel fuel.
3. The SMDs of the biodiesel fuels tested were 2.6 - 33.4% higher than the SMD of diesel fuel.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support by the Natural Science and Engineering Research Council by way of an operating grant to K.C. Watts.

REFERENCES

Ackman, R.G., C.A. McLeod and A.K. Banerjee. 1990. An overview of analysis by Chromarod-Iatroscan TLC-FID. *Journal of Planar Chromatography* 3: 450-490.

Allen, C.A.W. 1998. Prediction of biodiesel atomization characteristics based on measured fuel properties. Thesis as partial requirement for the degree of Doctor of Philosophy, Agricultural Engineering, Technical University of Nova Scotia, Halifax, NS.

Allen, C.A.W. and K.C. Watts. 1996. A batch type transesterification unit for biodiesel fuels. CSAE Paper 96-404. Saskatoon, SK: CSAE.

Anon. 1986. Malvern Instruments Particle Sizer Reference Manual. Malvern Instruments, Malvern, Worc, UK.

Bhattacharyya, S. and C.S. Reddy. 1994. Vegetable oils as fuels for internal combustion engines: A review. *Journal of Agricultural Engineering Research* 57(3): 157-166.

Dodge, L.G. 1984. Calibration of the Malvern particle sizer. *Applied Optics* 23(14): 2415-2419.

Dodge, L.G., D.J. Rhodes and R.D. Reitz. 1987. Drop-size measurement techniques for sprays: Comparison of Malvern laser-diffraction and aerometrics phase/doppler. *Applied Optics* 26(11): 2144-2154.

Graboski, M.S. and R.L. McCormick. 1998. Combustion of fat and vegetable oil derived fuels in diesel engines. *Progress in Energy and Combustion Science* 24(1): 125-164.

Gulder, O.L. 1990. Multiple scattering effects in dense spray sizing by laser diffraction. *Aerosol Science and Technology* 12: 570-577.

Hirleman, E.D. and P.A. Dellenback. 1989. Adaptive Fraunhofer diffraction particle sizing instrument using a spatial light modulator. *Applied Optics* 28(22): 4870-4878.

Meyer, P. and N. Chigier. 1986. Dropsize measurement using a Malvern 2200 particle sizer. *Atomization and Spray Technology* 2: 261-298.

Ryan, T.W., T.J. Callahan and L.G. Dodge. 1982. Characterization of vegetable oils for use as fuels in diesel engines. In *Vegetable Oil Fuels - Proceedings of International Conference on Plant and Vegetable Oils as Fuels*, 70-81. St. Joseph, MI: ASAE.