

Measurements of the Dimensionless Extinction Constants for Diesel and Biodiesel Soot

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Abstract: The values of the dimensionless extinction constant, K_e , for soot produced from various practical fuels reported are important in quantifying the optical measurements of soot concentration, temperature measurements and soot radiation analysis. The measurements of K_e for soot produced from F-76 and B-100 *methyl soyate* (soy methyl ester) biodiesel fuels were performed using a unique transmission cell reciprocal nephelometer (TCRN). Light transmission measurements were performed using a 632.8 nm He-Ne laser. In this technique, K_e was determined from simultaneous measurements of soot concentration using a gravimetric technique, which were compared with the light extinction measurements. The measured value of K_e for both F-76 and B-50 soot at 632.8 nm is 10.2. These experiments represent the first measurements of dimensionless extinction constant of soot produced from diesel and biodiesel diffusion flames.

Keywords: Biodiesel, Soot, Transmission Cell Reciprocal Nephelometer (TCRN), Dimensionless extinction constant

NOMENCLATURE

f_v	Soot volume fraction [ppm]
f_{vg}	Soot volume fraction measured using gravimetric technique [ppm]
I	Transmitted laser intensity
I_o	Incident laser intensity
K_e	Dimensionless extinction constant
L	Path length of light extinction [m]
m_s	Mass of filter collected soot [g]
v_{air}	Volume of air flow [m^3/min]
t	Soot sampling time [min]

Greek Symbols

λ	Wavelength of light [nm]
ρ_s	Density of soot [g/cc]
δ	Overall uncertainty
w_n	Uncertainty associated with the n^{th} parameter

1. INTRODUCTION

Diesel fuel is still very widely used in many areas of commercial and military applications. Of the variety of diesel fuels, F-76 type of diesel is more widely used especially in ground-based and water-based gas turbines. It is estimated that more than 282 million gallons of F-76 diesel are used each year by the United States military alone. In its usage, F-76 diesel produces very serious particulate emission characteristics [1,2]. Recently, according to guidelines established by the environmental protection agency (EPA), reduction of diesel emissions has become a major focus for experimental and numerical analysis in the field of diesel combustion research [1,3,4].

For these reasons, alternative fuels, such as biodiesel B-100 (methyl soyate biodiesel), have received a great deal of attention and scrutiny [4]. Biodiesel is produced from renewable resources such as vegetable oils and animal fats [5]. Numerous studies have demonstrated that biodiesel displays low emission characteristics such as unburned hydrocarbons, carbon monoxide and particulate matter as compared to petroleum-based diesel. Another attractive feature of biodiesel is that it can be used in a conventional diesel engine with little or no modifications [6-11]. B-100 is 99.9% miscible in F-76 diesel [12].

From a fire safety standpoint, there are many instances of hazards associated with refuelling of mobile and stationary powerplants using diesel and biodiesel fuels. Accidental spillage during the

refuelling process can lead to unwanted fires from which the dominant mode of radiative heat transfer will result from the particulate mass by-products. Therefore, it is very important to study the optical properties of the particulate mass produced from F-76 diesel and B-100 biodiesel fuels. Through these measurements, it will be possible to determine the impact of the burning of these fuels on the environment, health, thermal hazards^[13,14].

In the combustion and fire research community, soot concentration is measured by light extinction technique. In these measurements, the dimensionless soot extinction constant, K_e , is required to determine soot concentrations through Bouguer's Law:

$$\frac{I}{I_o} = \exp(-K_e \frac{f_v}{\lambda} L) \quad (1)$$

Bouguer's Law relates the ratio of the transmitted (I) and incident (I_o) light intensities to the concentration of soot (f_v , volume fraction), and the light pathlength through the soot, L .

In this study, the dimensionless extinction constants, K_e , for soot produced from F-76 diesel and B-50 (50% B-100 methyl soyate mixed with 50% F-76) were measured using a transmission cell reciprocal nephelometer at 632.8 nm.

2. EXPERIMENTAL DESCRIPTION

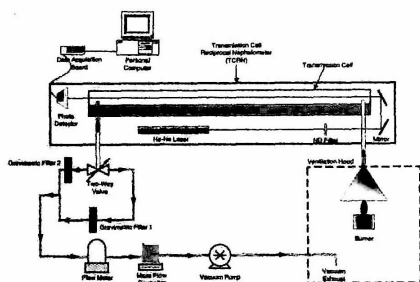


Figure 1: Schematic diagram of experimental set-up

Experiments were performed using a portable transmission cell reciprocal nephelometer which provides a pathlength for light extinction of nearly 1 m (see Figure 1). Detailed description of this apparatus can be found in Mulholland and Bryner^[15]. This apparatus and system was used in previous experiments for soot optical property measurements^[16-18].

Soot generated from a wick burner is directed into the transmission cell through a cone shaped funnel

located under a ventilation hood. The exhaust flow containing soot created by a vacuum pump is directed through a glass fiber filter assembly to collect the soot. For light extinction measurements, a 10 mW helium-neon laser of wavelength 632.8 nm was used as the light source. A variable neutral density filter was also attached to prevent saturation of the detector. The voltage signals from the detector were monitored and recorded using a computer-based data acquisition system.

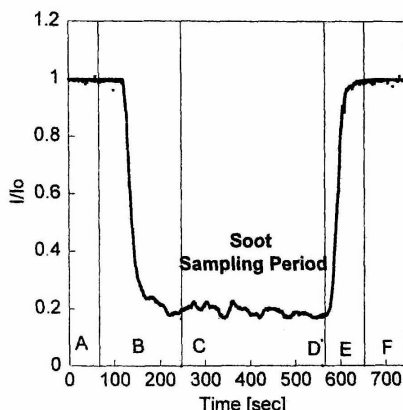


Figure 2: Laser transmittance through the TCRN for B-50 at 632.8 nm

Before soot was introduced into the transmission cell, the incident intensity, I_o , was monitored for approximately 60 s beginning at time denoted by A in Figure 2. Soot produced from the burner was then introduced into the transmission cell through suction from the vacuum pump at time denoted by B. The filling of the transmission cell with soot decreased the transmitted laser intensity (beginning at time denoted by B) until steady state conditions were obtained (denoted by time C). After attaining steady transmitted laser intensity measurements, the exhaust flow containing soot was directed through the glass fiber filter assembly to collect the soot for a period of approximately 5 minutes. This period of soot collection (denoted by C to D) was required to ensure sufficient mass of soot for accurate measurements. Clean air was then introduced to purge the transmission cell of soot (denoted by E). The incident intensity measurement was again performed after all of the soot in the transmission cell was purged (denoted by F). For all of the experiments, the incident intensity measurements (measurements through the transmission cell without the presence of soot) before and after the sampling was identical, indicating that soot was not deposited on any of the optical components during the collection period.

The mass of soot collected on the glass fiber filter was then weighed using a microbalance (with 2 to 3 microgram sensitivity). Typical mass of the collected

soot ranged from 1.2 *mg* to 6.67 *mg*. The gravimetrically-determined soot volume fraction, f_{vg} , was then calculated using the following equation:

$$f_{vg} = \frac{m_{soot}}{v_{air} t \rho_{soot}} \quad (2)$$

where m_{soot} is the mass of soot collected on the filter, v_{air} is the volumetric flow rate of the soot-containing gas, t is the soot sampling time, and ρ_{soot} is the density of soot. For the density of soot, a value of 1.74 *g/cc* was used^[20]. By noting that the soot volume fractions using gravimetric formulation and the light extinction formulation are the same, since measurements are performed simultaneously within the TCRN and at the same time, eqn. (2) and eqn. (1) can be combined to determine K_e :

$$K_e = -\frac{v_{air} t \rho_{soot} \lambda \ln\left(\frac{I}{I_0}\right)}{L m_{soot}} \quad (3)$$

3. UNCERTAINTY ANALYSIS

The uncertainty in calculating the value of K_e using eqn. (4) can be determined with knowledge of the uncertainty of each individual parameter. There are several parameters that may affect the uncertainty in measuring the value of K_e , but the primary parameters of interest in this analysis are the ratio of the transmitted to incident light intensities, and the measurement of the mass of soot collected. If we assume that these parameters are not correlated, then we can find the cumulative uncertainty as follows^[21],

$$\frac{\delta K_e}{K_e} = \sqrt{\sum_{i=1}^n \left[\frac{\partial K_e}{\partial X_n} w_n \right]^2} \quad (4)$$

where δK_e is the overall uncertainty in K_e , X_n is the variable associated with the n th parameter and w_n is the uncertainty associated with the n th parameter. The cumulative uncertainty in the value of K_e is summarized in the Table 1.

Table 1: Total uncertainty in the measured values of K_e for F-76 Diesel and B-50 at 632.8 *nm*

Fuel	F-76	B50
w_m ($\times 10^{-9}$ g)	3.33	3.09
w_{I/I_0} ($\times 10^{-3}$)	0.525	0.545
v ($\times 10^{-3}$ m ³ /min)	6.91	6.92
Mean K_e	10.2	10.2
δK_e	0.34	0.36

The uncertainty in the value of K_e at 632.8 *nm* using a 95% confidence interval represents in Table 1. The uncertainties for the fifteen experiments carried out over three days are 3.4% of the mean for F-76 and B-50, respectively^[21-22].

4. RESULT AND DISCUSSION

In Figure 3, the optical thickness of the soot containing region (as defined as I/I_0) for each fuel is plotted versus the mass of soot measured using gravimetric technique. The data illustrates that the magnitude of attenuation was proportional to the amount of soot contained in the TCRN.

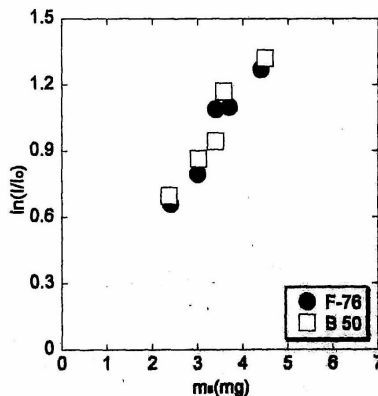


Figure 3: Light attenuation, $-\ln(I/I_0)$ as a function of soot collected, m_s

The measured values of K_e are plotted as a function of light attenuation in Figure 4. The averaged K_e values of 5 tests illustrated in Figure 4 are listed in Table 3. The average K_e values for F-76 and B-50 are consistent with each other since the variation of light attenuation for measured mass of soot produced from each fuel is almost similar as tabulated in Table 2.

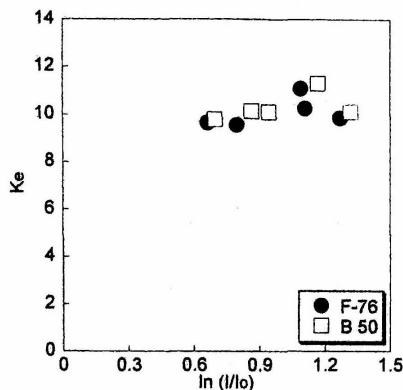


Figure 4: Measured values of K_e versus magnitude of light attenuation, $-\ln(I/I_0)$ for F-76 and B-50 at 632.8 nm

Table 2: Measured mass of soot collected, m_s , for F-76 Diesel and B-50 at 632.8 nm.

Fuel	F-76	B-50
m_s (mg)	4.4	4.5
$-\ln(I/I_0)$	1.27	1.32
m_s (mg)	3.7	3.58
$-\ln(I/I_0)$	1.1	1.7
m_s (mg)	3.4	3.4
$-\ln(I/I_0)$	1.09	0.945
m_s (mg)	3.0	3.02
$-\ln(I/I_0)$	0.796	0.865
m_s (mg)	2.4	2.37
$-\ln(I/I_0)$	0.662	0.697

However, the measured values of K_e for soot produced from both fuels are more than twice the value (4.89) that is typically calculated using the Rayleigh-limit solution of the Mie analysis with complex refractive index obtained from the literature [22]. Additional experiments are planned using different mixtures of B100 and F-76 diesel and near-infrared and infrared laser light sources.

Table 3: Measured K_e values for F-76 Diesel and B-50 (Biodiesel) at 632.8 nm.

Fuel	K_e	STDV.
F-76 Diesel	10.2	± 0.5
B-50 (Biodiesel)	10.2	± 0.5

5. CONCLUSION

The dimensionless extinction constant, K_e , for soot generated from F-76 diesel and B-50 biodiesel flames was measured in the present study. The measured value of K_e for both F-76 and B-50 soot at 632.8 nm is 10.2, which is consistent with previously measured values for JP-8. The measured values will be valuable in the interpretation of light extinction data for soot volume fraction measurements and in the interpretation of pyrometry data for temperature measurements using these fuels.

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