

A Comparative Study of Two Kinds of Biodiesels and Biodiesel-DEE Blends in a Common Rail Diesel Engine

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ABSTRACT

Ultrafine particles and NO_x emissions of two kinds of biodiesels and their blends with diethyl ether (DEE) as an additive were compared under two engine speeds and three loads on a turbocharged, high-pressure, common rail diesel engine. A single spray injection and equivalence ratio distribution are used to explain the results. The study shows that biodiesel and biodiesel-DEE blend consume more fuels than diesel but slight variation in thermal efficiency. NO_x emissions of waste cooking oil biodiesel are less than those of soybean biodiesel. At low and medium loads, DEE blending reduces the NO_x emission. At all engine loads and speeds, the shape of ultrafine particle number distribution curve is unimodal, and fuel type slightly affects the shape of distribution curves. The number/mass distribution curves shift to fewer particles when operating on biodiesel and the curves further move to downward when DEE is added. Nanoparticles do not increase when operating on biodiesel or biodiesel-DEE blend. Total number concentration of ultrafine particle is decreased in biodiesel and it's further decreased in the presence of DEE. The equivalence ratio distributions of waste cooking oil biodiesel and its DEE blend are shrink compared with soybean biodiesel and its DEE blend, this could explain the reason for waste cooking oil biodiesel emits fewer particles than those of soybean biodiesel.

INTRODUCTION

Fossil fuel plays an important role in the development and need of human being. However, it is limited and depleted day by day as globe consumption increase rapidly. Moreover, environment pollution, which is caused by using fossil fuel, forces researchers to find an alternative fuel. Biodiesel, which is produced from renewable resources, receives more and

more attention as an alternative fuel. Research demonstrated that properties of biodiesel were similar with those of diesel [1]. Therefore, biodiesel fuel can be used in diesel engine with few or without modifications [2]. Over past years, lots of investigations have been conducted to study performances and emissions of biodiesel. Due to biodiesel contains no aromatics and more oxygen compared to diesel, operating biodiesel in diesel engine reduces emissions of PM, HC, and CO [3, 4, 5, 6, 7, 8, 9].

However, engines fuelled with biodiesel were found to increase NO_x emission at most of operating conditions [3, 5, 10, 11]. The increase in NO_x emission fuelled with biodiesel is known as the biodiesel-NO_x effect and might need further approach to decrease NO_x in engines [12]. Therefore, many methods had been tried to decrease NO_x emission in the utilization of biodiesel. Exhaust gas recirculation (EGR) strategy is practically used to decrease NO_x without fuel economy penalty [3, 13]. Turbocharging, intercooling and electronic control are widely used in diesel engines to decrease NO_x emission [3]. Retarding fuel injection timing can reduce NO_x with a penalty of fuel economy [3, 14, 15]. Adding cetane number improver into the biodiesel to reduce NO_x emission is also used [3].

Nuszkowski et al. studied the effects of cetane improvers on NO_x emissions from heavy-duty diesel engines. They reported that additives had the most impact on reducing emissions at low engine powers [16]. Icingur and Altiparmak investigated that effect of fuel cetane number on NO_x emissions and found that NO_x were reduced when fuel cetane number was increased for the standard injection pressure [17]. Diethyl ether (DEE), which can be easily converted through ethanol, has high cetane number (approximates to 125) and could be used as a cetane improver. Meanwhile, it is

liquid at ambient condition, which makes it well handled [18]. Anand and Mahalakshmi investigated the effect of EGR and DEE on the emission of diesel in a single-cylinder DI diesel engine and found NO_x reduced with the increase of DEE [19]. Purushothaman and Nagaraj an compared NO_x emissions of orange oil-DEE blend and diesel in a DI diesel engine and reported that diesel emitted more NO_x [20]. Cinar et al. studied the effects of the premixed DEE and diesel on exhaust emissions in a HCCI-DI engine and they reported that the introduction of premixed DEE could decrease NO_x emissions compared with that of diesel combustion [21]. Kumar et al. investigated an engine fuelled with vegetable oil in a single-cylinder DI diesel engine and demonstrated that NO_x was decreased by DEE addition [22]. However, Kapilan et al. observed that the addition of DEE into diesel resulted in higher NO_x emission, especially premixing with 5% of DEE [23].

Particles produced by diesel engines have an impact on environment, engine durability and human health [24]. Current emission regulations do not include the restrictions of particulate size distribution, but it is likely to cover it in the more stringent engine exhaust regulations [25]. The effects of particles on environment, human health and aftertreatment devices depend on the particle size. In practice, finer particles are more harmful to human beings and could decrease the efficiency of the particle trap [24, 26]. Diesel exhaust particles mainly consist of solid carbon, volatile organic and sulfur compounds. Lapuerta et al.[6] summarized some effect of biodiesel on particle size distribution from various studies. Di et al. [7] studied the particulate number concentration of diesel engine fuelled with cooking oil and observed more nanoparticles in biodiesel operation. Park et al. [25] studied nanoparticles emissions of biodiesel-diesel blends and found that both total number and total mass reduced when blending biodiesel, meanwhile, numbers of fine particle were found increased. Tsolakis [27] examined EGR effects on particulate size distribution on RME biodiesel and showed small influence on particulate distribution in the case of EGR. Lapuerta et al.[28] studied the particulate emission of diesel engine fuelled with the biodiesel from waste cooking oil and found that mean particle size was decreased in biodiesel but numbers of small particles did not greatly influenced. Lin et al. [29] studied the particle size distribution of diesel engine fuelled with the palm-biodiesel-diesel blends and found that an increased number of particles with low aerodynamic diameters in biodiesel and biodiesel-diesel blends compared with that of diesel. Kim et al. [30] investigated nanoparticles from a CRDI engine operated on biodiesel-diesel blends and found that biodiesel operation would reduce total number but produce more fine particles. Ning et al. [31] studied the exhaust gas cooling effect on particle number and size distribution. Fontaras et al. [32] applied biodiesel to modern passenger cars and found a reduction in non-volatile particle numbers. Heikkilä et al. [33] ran alternative fuels on a heavy-duty engine and analyzed the nanoparticle emissions.

A major barrier in commercialization of biodiesel production from vegetable oil is its high manufacturing cost, which is due to the higher cost of original vegetable oil. Waste cooking oil, which is less expensive than pure vegetable oil, is a promising alternative to vegetable oil for biodiesel production. Restaurant waste cooking oil is less expensive than soybean oil [34]. Approximately 1.1 billion kg of waste cooking oil are collected annually from restaurants and fast-food establishments in the U.S. [35]. There are a lot of restaurants in China, thus, the usage of waste cooking oil in China is promising. The management of waste cooking oil is necessary, because disposing waste cooking oil at random could contaminate the environment. Thus, the transition of waste cooking oil to fuel is very important for environment and fossil fuel depleted.

Although previous studies revealed the particle and NO_x emissions of diesel engine operated on biodiesel and/or biodiesel-diesel blends, there is few report on ultrafine particle emission characteristics when engine operates on biodiesel-DEE blends, especially on a turbo-charged, high-pressure common rail injection diesel engine, meanwhile, a comparison of emissions of waste cooking oil biodiesel and edible soybean biodiesel is less than enough investigated. Thus, the effects of addition of DEE on engine NO_x and ultrafine particles and the comparison are worthy to be studied. Ultrafine particles and NO_x emissions of two kinds of biodiesels and their blends with diethyl ether (DEE) as an additive are compared under two engine speeds and three loads in a turbocharged, high-pressure, common rail diesel engine.

EXPERIMENTAL SETUP AND PROCEDURES

A four cylinder, four-stroke common rail, water-cooled, turbocharged diesel engine is used. Engine specifications are listed in Table 1. Figure 1 illustrates the schematic diagram of the experimental setup. Engine is connected to an eddy-current dynamometer and engine speed/load are controlled by an engine testing control system (Powerlink FC 2000) with accuracy of 1 rpm and 0.01 N·m. A pressure sensor (Kistler 6055C) is used to measure the cylinder pressure with 0.1 crank angle degree resolutions and the pressure is recorded by a digital data acquisition system (Yokogawa DL750 Scopecorder). Fuel flow rate is measured by an electronic weighting apparatus with accuracy of 0.1g and a stopwatch. NO_x is measured by Horiba NO_x analyzer (MEXA-720 NO_x) with accuracy of 1ppm. Particulate size distribution is measured by ELPI (Dekati Ltd. electrical low pressure impactor) with the size range of 7nm to 10μm with a filter stage. This device is a real-time particle size spectrometer, which is used for measuring the aerosol particle size distribution. It is composed of three main parts: a corona discharge charger, a low pressure cascade impactor and an

array of electrometers. Two diluters are applied in the system. Table 2 gives the specifications of ELPI and diluters.

Table 1. Specifications of the engine.

Injection system	Common rail
Compression ratio	17.2: 1
Rated torque/speed	70 kW /3600 rpm
Maximum torque/speed	225 N·m /1600~2600 rpm
Stroke	102mm
Bore	93mm
Displacement	2.771L
Type of injector	Bosch CR1P2
Type of common rail	Bosch LWR

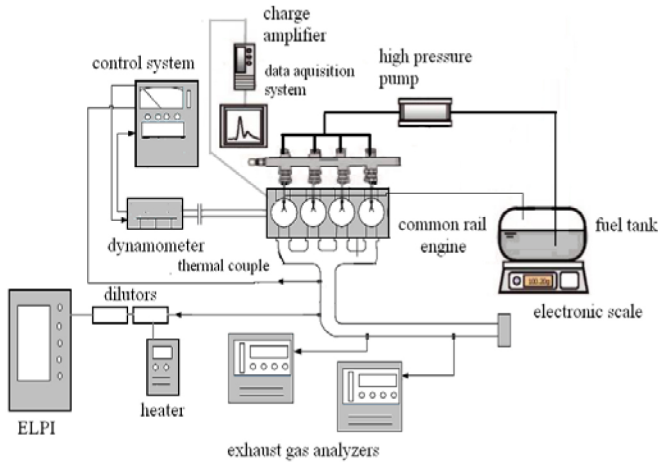


Figure 1. Schematic diagram of the experimental setup.

Table 2. Specifications of ELPI and diluters.

ELPI	
Description	Specification
Particle size range	0.03-10 μ m with 12 channels
Time resolution	2-3 s
Diluter (ejector type)	
Diluter	Diluter ratio
1st	8.43 (heating up to 200°C)
2nd	8.45

During the whole experimental process, engine speed is maintained at 1600 rpm or 2600rpm and loads are set at 25%, 50%, and 75% of the full load. Diesel oil, soybean biodiesel, waste cooking oil biodiesel, 90% soybean biodiesel and 10% DEE in volume and 90% waste cooking oil biodiesel and 10% DEE in volume are used in this experiment, denoting by D100, SB100, WB100, SB90E10 and WB90E10. Fuels blends are well mixed without separation. There was an occurrence of knocking when DEE percentage exceeds 10% in energy ratio [21]. Thus, in this study, DEE percentage is 10% in volume percentage, which equals to 7.5% in energy ratio. The fuels specifications are listed in Table 3.

Table 3. Specifications of fuels.

Fuel	D100	WB100	SB100	DEE
Density (kg/m ³)	853.8	872.8	881.4	713.4
Viscosity (mm ² /s)	3.223	5.164	4.269	0.3266
Oxygen (wt.%)	-	11.29	10.97	21.6
Carbon (wt.%)	86.70	76.46	77.10	64.9
Hydrogen (wt.%)	12.71	12.25	11.81	13.5
Sulfur (wt.%)	~0.023	~0.005	~0.005	0
Cetane number	45	62.5	51.5	> 125
T50 (°C)	~327	-	~336	-
T90 (°C)	~346	-	~340	-
Latent heat of	290	-	-	351.16
Low heating value	42.4	37.1	37.4	33.9
Sat. (%)	-	38.67	16.26	-

Before every actual measurement, the engine and exhaust gas analyzers are warmed up. The results of three replications are averaged. Horiba NO_x analyzer (MEXA-720 NO_x) is warmed up for 3min according to its manual. Temperature of cooling water is controlled at approximate 80-85°C. Pressure acquisition system is checked whether it is operated smoothly. The ELPI is set by monitoring flow rate, charger, outlet pressure and gas temperature according to manufacturer's set value. Zeroing should be made before ELPI measurement. Previous reports showed that if the exhaust gas was sampled directly, the electrometers of ELPI might be overloaded. In case of overloading, the exhaust gas is diluted before being sampled in experiment [36]. As mentioned in Table 2, two diluters are used with constant dilution ratio of 8.43 and 8.45 respectively. The first diluter is heated to 200°C in case of nucleation and condensation of the volatile materials. For the second diluter, the air is kept at ambient temperature. Dilution ratio is kept constantly for all tests to prevent the the particle distribution from changing.

RESULTS AND DISCUSSION

Figure 2 gives BSFC versus load at two engine speeds. The results show that BSFC of diesel is the lowest among all fuels. Without exception, BSFC is higher for biodiesels and biodiesel-DEE blends owing to the decreased heating value of oxygenated fuels, and this behavior is consistent with the previous studies [6, 18, 22, 23].

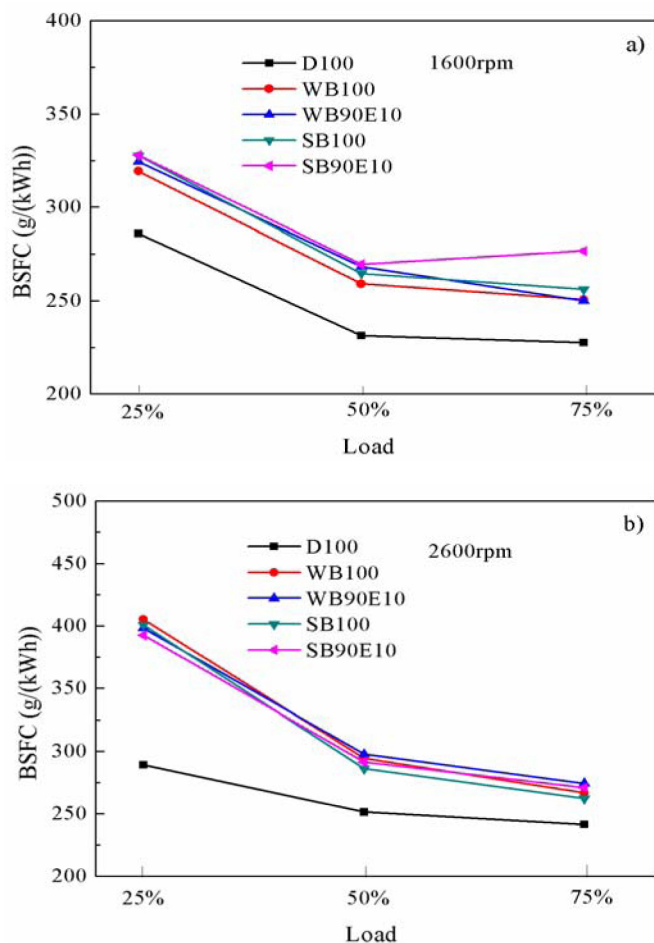


Figure 2. BSFC versus load at different engine speeds.

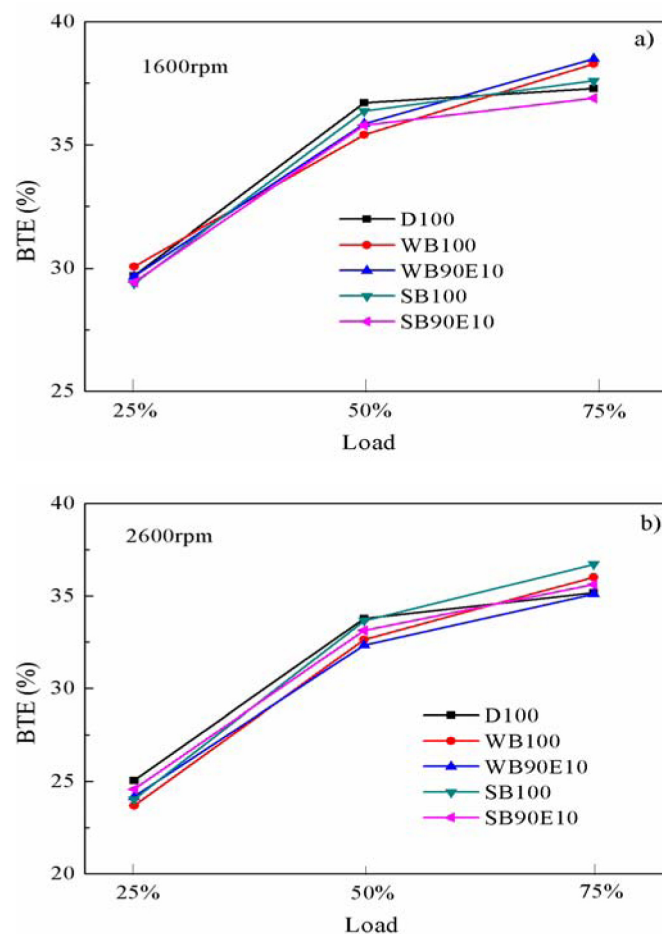


Figure 3. BTE versus load at different engine speeds.

Figure 3 shows the BTE versus load at two engine speeds. When comparing the performance operating on different fuels, BTE is more appropriate than fuel consumption [6]. As shown in Figure 3, BTE of biodiesel and biodiesel-DEE blends show a slight variation compared to that of diesel. This may be caused by the available oxygen contained in the biodiesel which improves the combustion process despite the fact that oxygenated fuel has lower heating value. The slight effect of biodiesel and/or DEE on BTE indicates that the increase in fuel consumption results from the decrease in heating value of fuels as oxygenated fuel is added.

Figure 4 shows net heat release rate (NHRR) versus crank angle at different loads and engine speeds. As indicated in Figure 4, the shapes of the NHRR curve are almost the same using the five different fuels. At the low load, early heat release decreases and the heat release is faster as DEE is premixed regardless of the biodiesels used; however, when the load becomes medium or high, early heat release varies not that significantly though DEE is premixed. These phenomena may be caused by the opposite effect of high cetane number and high latent heat of vaporization of DEE. Ignition delay tends to be shortened by high cetane number [37]. Nevertheless, cylinder temperature is decreased as DEE is evaporated which tends to increase the ignition delay. At the low load, less DEE is injected and in this condition, the high cetane number may become a dominant factor, leading to a short ignition delay and small premixed fuel during the ignition delay. In contrast to this case, at the high load, more DEE is injected. The higher latent heat of vaporization may become the dominant factor. DEE evaporation will have great influence on the decrease in cylinder temperature and increases the ignition delay, the premixed mixture will increase during the ignition delay and it will lead to an increase in peak pressure of biodiesel-DEE blend.

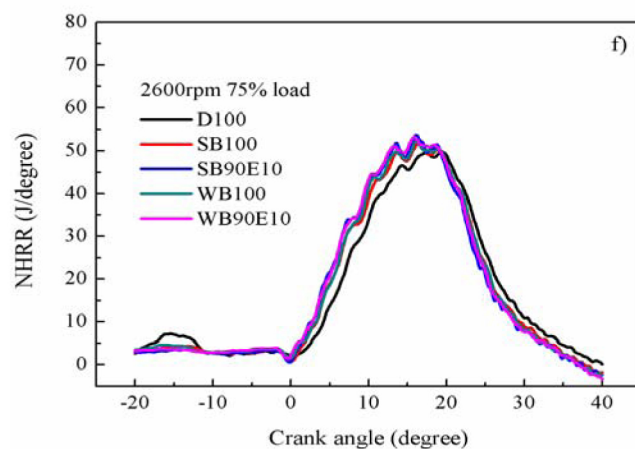
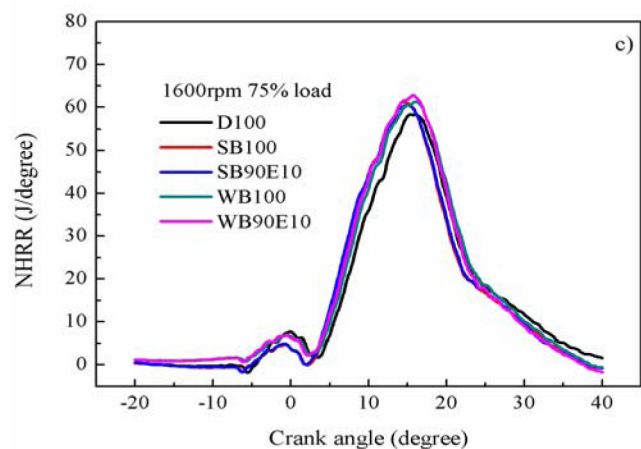
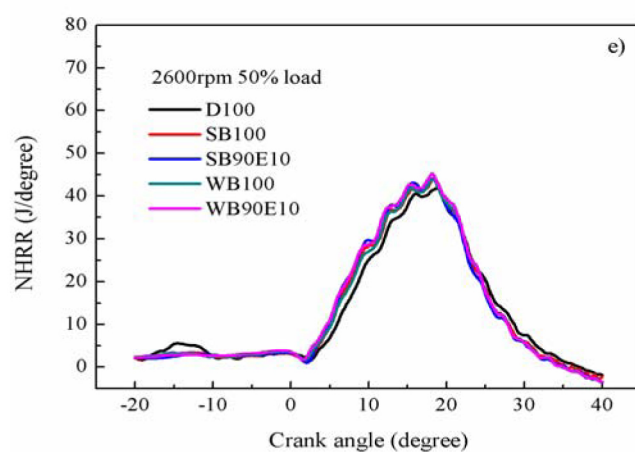
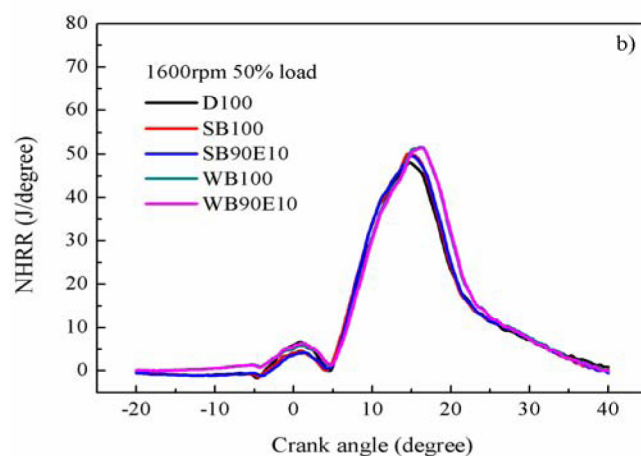
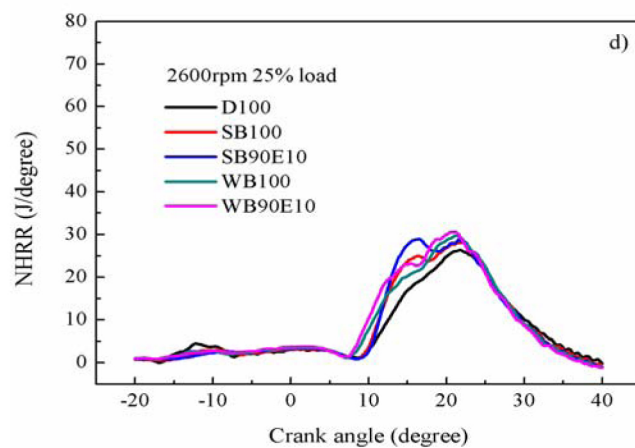
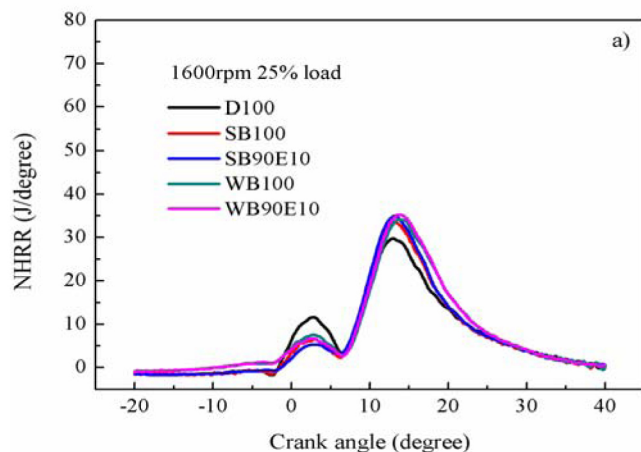


Figure 4. NHRR versus crank angle at different engine speeds and loads.

Figure 4 (cont.). NHRR versus crank angle at different engine speeds and loads.

Figure 5 shows that comparison in NO_x emissions at different loads and engine speeds. For all experimental conditions, NO_x emissions of waste cooking oil biodiesel are less than those of soybean biodiesel. At the low and medium loads, NO_x emission of biodiesel-DEE blends show a slight decreasing trend compared to that of neat biodiesels. Sun et al. reported that it was better to say several parameters seem