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Stabilization performance of methanol-diesel emulsified fuel prepared using an impinging stream-rotating packed bed

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ABSTRACT

A new continuous process for preparing methanol–diesel oil emulsified fuel is proposed using an impinging stream–rotating packed bed. The combustion of methanol–diesel oil emulsified fuel is significantly affected by its stability. Thus, the stabilization of the methanol–diesel oil emulsified fuel was investigated by varying numerous factors, including high-gravity factor, impinging distance, hydrophilic-lipophilic balance value, liquid flow rate, co-surfactants, content of methanol and emulsifier, and so on. The stabilized time and size of dispersed phase of methanol-diesel oil emulsified fuel were 762 h and 12 μm separately at the operating conditions of liquid flow rate of 70 L/h, an impinging distance of 30 mm, a hydrophilic–lipophilic balance value of 5.4, a high gravity factor of 208.1, a methanol volume content of 15%, co-surfactants of 1-butanol, an emulsifier amount of 3%, and consecutive recycle time of 3. The proposed technology can be applied in industries because of the use of relatively less emulsifier as well as its continuity, processing efficiency, and ease of application in large-scale production.

1. Introduction

Diesel engines have gained increasing attention in transportation, industry, and agricultural applications because of their high efficiency and reliability. Diesel vehicles are important all over the EU, and their market share reaches 42% of the entire vehicle market [1,2]. However, diesel engines still suffer from high PM2.5 particulates and nitrogen oxide (NO_x) emissions [3]. The rapid increase in fuel costs and stringent regulations on exhaust emissions have encouraged the search for cleaner fuel and more efficient combustion technology. The major pollutants emitted from diesel engines include particulate matter (PM), NO_x, carbon monoxide (CO) and unburned hydrocarbon, etc. These pollutants damage the ozone layer, enhance the greenhouse gas effect, and produce acid rain. These pollutants accumulate in the atmosphere, undergo physical, chemical, and biological reactions, and can then be transformed into other noxious substances that are detrimental to the environment and a threat to human health. Therefore, improving the performance of engines and reducing their emissions could improve fuel economy and reduce environmental pollution. With increasing concern for environmental protection and stringent exhaust gas regulations, reducing engine emissions has become an important research objective in engine development.

Several methods are available to reduce emission pollution from diesel engines during the combustion process. These methods include strategies such as improving engine design, enhancing the maintenance of the engine and fuel system, installing components to treat exhaust gases, and utilizing clean alternative fuels.

The emulsification technique [3] is an effective approach to improve the fuel economy and reduce the pollutants emission of diesel engines. Emulsion is mainly composed of two kinds of liquids, i.e., oil phase and water phase, one of which is dispersed in the other by liquid drop. Given that the boiling point of water is lower than that of the oil, when a water phase core is surrounded by oil phase, drops of water phase reach their boiling point first and swell rapidly through the enveloping oil layers. The vaporization of the water phase expands the oil layer to form smaller oil droplets, which results in an increase in the surface-to-volume ratio of the oil phase. The increase in mixing and contact surface between air and the smaller fuel droplets would lead to both a considerable improvement in burning rate and fuel efficiency. The substances in the water phase include methanol, ethanol, ethers, butanol [4–7].

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Methanol is easy to produce by coal-to-methanol and gas-to-methanol technology. Therefore, it is considered as one of the promising alternative fuels or oxygen additives for diesel engines because it is cheap and possesses high oxygen content. The interest in methanol-in-diesel oil emulsions is based on the fact that micrometer-sized methanol droplets positively affect fuel combustion. When an emulsion fuel is heated, the methanol droplets are vaporized first because methanol is more volatile than diesel oil at high-temperature. As an oxygenated fuel, methanol has several attractive features, and several of its properties are listed in Table 1.

The performance of methanol–diesel oil emulsified fuel depends on two main factors, i.e., the emulsified device and surfactants. However, phase separation occurs in methanol–diesel oil emulsified fuel with a single surfactant. At the same time, emulsified fuels with nitrogenous surfactants produce NO_X during the combustion process. In addition, the traditional emulsified device needs the higher content of surfactant (be over 5%) as the lower emulsified efficiency, which leads to the increasing cost of the emulsified fuel. Much of the emulsification equipment, such as the mechanical stirrer, homogenizer and colloid mill, are available to prepare emulsified fuel [8–11]. However, such equipment has several disadvantages, such as large volume, high energy consumption, unsatisfactory dispersion, and batch operation, which influence on the development of methanol–diesel oil emulsified fuels. Ultrasonic-assisted emulsification could be used effectively to prepare emulsion to generate high mechanical energy and produce fine droplets. However, ultrasonic-assisted emulsification [12–14] constrains the development of the methanol-diesel emulsified fuel because of its high cost, high energy consumption and batch operation. To satisfy the requirements of the methanol-diesel oil emulsified fuel, novel surfactants and highly efficient and continuous emulsification devices must be developed.

Ramshaw and Burns [15] invented a rotating packed bed (RPB) to enhance the gas–liquid mass transfer process, and this unique technology is referred to as “Higee” (or high gravity). In the RPB operation, gas–liquid mass transfer is usually enhanced by a high gravity factor of 10–100, which has been extensively studied in many systems such as mass transfer [16–18], distillation [19,20], absorption [21] reactive precipitation [22,23] and environmental protection [24,25]. The experiment indicated that liquid tend to wander less in the lateral direction through the packing in comparison with its radial motion. Therefore, the initial liquid distribution would have an important effect on micromixing and mass transfer characteristics. As mentioned above, based on the uniformity of mixing and transfer characteristics of the RPB, the impinging stream and RPB are carefully combined in the impinging stream–rotating packed bed (IS–RPB). The liquid/liquid combination yields better micromixing and mass transfer, with higher dispersion and turbulence. Rendering increased dispersion and turbulence, this high-gravity technology can be used in a wide range of applications from gas/liquid to liquid/liquid fields, such as micromixing, extraction, liquid membrane separation, emulsion, and precipitation reaction [26–29].

Table 1
Properties of methanol and diesel oil.

Property	Methanol	Diesel oil
Formula	CH_3OH	$C_{12}H_{26}$–$C_{14}H_{30}$
Molecular weight, kg/kmol	32	170–198
Boiling point, °C	65	180–360
Autoignition temperature, °C	392	315
Cetane number	3.8	47
Density, kg/m^3	796	840
Octane number	108	30
Kinetic viscosity at 20 °C, mPa s	0.7	3.4
Flash point, °C	11	78
Fraction of oxygen, wt%	50	0
Ignition temperature, °C	470	235

In recent years, many studies [30–34] have reported the optimization of formulation of emulsifier and the emulsification process. The effects of the optimized conditions such as yield behavior, viscosity, and lower pollutant emissions, on methanol–diesel oil emulsified fuel have been determined but the most critical characteristic of the methanol–diesel emulsified fuel is its stability. Only a few reports on the stabilization performance of such fuel are available. Therefore, investigating the stabilization performance of methanol–diesel oil emulsified fuel is imperative. In addition, the study of stabilization performance of methanol–diesel oil emulsified fuel not only has important academic value but also presents potential industrial application in improving the air–fuel mixture and burning rate, thereby reducing NO_x and PM emissions (i.e., decreasing environmental pollution) and alleviating the energy crisis.

2. Experimental

2.1. Materials and equipment

Commercial diesel oil was purchased from a gas station in the city of Taiyuan, China. The cloud point of $0^{\#}$ diesel oil used in experiment is 0 °C. In other words, $0^{\#}$ diesel oil will become muddy and not be used below 0 °C. Industrial-grade anhydrous methanol (99.8% purity) was also obtained from Tianjin Chemical Company in China. The compound surfactants were composed of non-ionic lipophilic and hydrophilic emulsifiers consisting of C, H, and O elements, such as Span 80, Span 85, Tween 80, Tween 85, and so on. The hydrophilic–lipophilic balance (HLB) value of the compound surfactants varied from 4.5 to 7.0 by adjusting the ratio and quantity of the hydrophilic and lipophilic surfactants. The methanol–diesel oil emulsified fuel was prepared using a novel continuous emulsified mixer – IS - RPB device.

2.2. Principles of IS-RPB

The IS-RPB reactor used in this study (Fig. 1) consists of a rotor, shell, liquid inlet and outlet, and motor. Stainless steel wire mesh

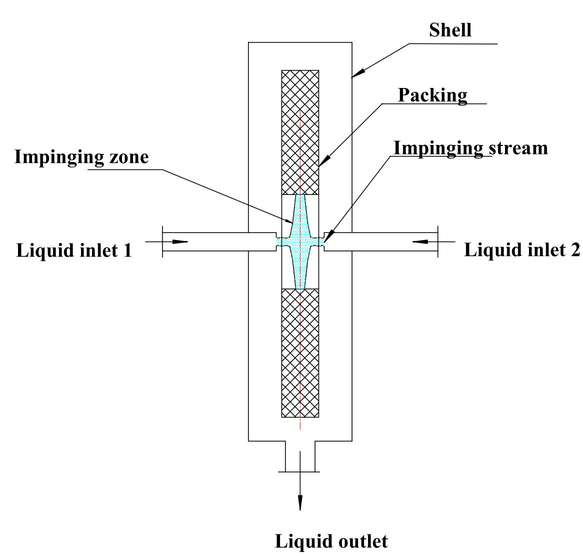

Fig. 1. Schematic of the rotating packed bed unit.