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Effects of nanoparticle additives to diesel on the combustion performance and emissions of a flame tube boiler

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ABSTRACT

This paper presents an experimental study about the effects of nanoparticles added to diesel fuels on the combustion performance and emissions of a flame tube boiler. Nanodiesel fuels were prepared by adding aluminum oxide (Al_2O_3) and titanium oxide (TiO_2) nanoparticles. The performance and emissions measurements were realized in a residential, water-cooled, reversal flame tube boiler. The temperature distributions in the combustion chamber, combustion performance and exhaust gas emissions of nanodiesel with 100, 200 and 300 ppm nanoparticles were studied and these were compared with the neat diesel fuel. The results showed that addition of nanoparticles decreased the size of the peak temperature zones and increased the thermal efficiency slightly from about 90.4% to 90.9% with addition of nanoparticles up to 300 ppm. CO emissions decreased up to 200 ppm from 275 to 75 ppm by using 300 ppm Al_2O_3 nanoparticles, and decreased up to 50 ppm from 275 to 225 ppm by using 300 ppm TiO_2 nanoparticles. It was observed that nanodiesels did not affect the NO_x emissions significantly, which were about 47–51 ppm. The results of Al_2O_3 and TiO_2 nanoadditives showed similar trends, but Al_2O_3 nanodiesel has a bit better performance and emission characteristics compared to TiO_2 nanodiesel.

1. Introduction

A nanofluid is a fluid containing nanometer-sized particles or carbon nanotubes [1]. Nanoparticles addition enhances the heat transfer characteristics of the original fluid. In the similar way, the nanoparticles have been added to diesel fuels as base fuel. This type of new fuel is called as nanodiesel. Metallic based and oxygen containing compounds, such as alumina (Al_2O_3), titanium oxide (TiO_2) and copper oxide (CuO) act as a combustion catalyst for hydrocarbon fuels and enhance the heat transfer properties. Therefore, nanodiesel has a potential to improve the combustion efficiency and to reduce the air pollutants carbon monoxide (CO), hydrocarbons (HC) and nitric oxides (NO_x). If combustion efficiency is increased, this will lead indirectly to a reduction of CO_2 and SO_2 because of the reduced fuel consumption [2–19]. Diesel is one of the main fossil fuels and generally consumed in internal combustion engines. Diesel fuel is also used for heat and electricity production. Nanoparticles have sizes less than 100 nm. The nano-sized particle provides an important advantage to the fuel in comparison to micron-sized particles; because there is no chance for fuel injector and filter clogging as in the case of micron sized particles. Kuo et al. [2] showed that there are multiple advantages of adding nanoparticles to propellants and solid fuels such as shortened ignition delay, increase in energy density, and high burn rates. DeLuca et al. [3] studied that nanoparticle presence in the liquid fuels increases the surface-area-to-volume ratio and thus allows more fuel to be in contact with the oxidizer to produce potential output. Shaafi et al. [4] provides an overview of the investigation advances in diesel engines in the use of dispersion of various nanoadditives (Al_2O_3, TiO_2, MnO, CuO etc.) for the engine performance increment and emission reduction. They reported that diesel engine performance improves appreciably, NO_x emissions increased because of increased peak temperatures and CO emissions decreased due to complete combustion of the fuel with nanoadditives. Sabourin et al. [5] examined the burning rates of nanofluids which consist of nitro methane and nano scale big surface area metal oxides of silicon dioxide (SiO_2) and Al_2O_3. Their results showed that by addition of nanoparticles the burning rates were increased. Tyagi et al. [6] investigated the addition of Al or Al_2O_3 nanoparticles on the ignition properties of diesel fuel. Their results showed that the radiative heat and mass transfer properties of diesel fuel improved by adding nanoparticles. They also

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concluded that the addition of the nanoparticles increases significantly the hot plate ignition probability of the diesel fuel. Kao et al. [7] examined experimentally engine performance, exhaust emission, and combustion characteristics of aqueous aluminum nanofluid combustion in a single-cylinder diesel engine. They said that at lower engine speeds less than 1800 rpm, adding aluminum nanofluid to diesel fuel reduces fuel consumption and NO_x emissions. Yetter et al. [8] have critically reviewed the reports on the metal particle combustion and nanotechnology. They concluded that the nano energetic particles possess high specific surface area and could lead to high reactivity. Gan and Qiao [9] carried out investigation on the burning characteristics of n-decane and ethanol fuel droplets containing aluminum particles with nano and micron sized dimensions. They claimed that nano suspensions remain stable for a much longer time than micron suspensions because of the higher surface-to-volume ratio. Also, for the same particle concentration and surfactant concentration, the disruption and microexplosion treatment of the micron sized suspension occurred later than nano sized suspension. Basha and Anand [10] prepared biodiesel emulsion fuel which consist of 83% of Jatropha biodiesel, 15% of water, and 2% of surfactants. They mixed the prepared biodiesel emulsion fuels with alumina nanoparticles. The authors indicated that the performance and the emission characteristics of diesel engine are improved with the prepared biodiesel emulsion-alumina nanoparticle fuels. Sajeevan and Sajith [11] performed experiments on the effect of cerium oxide nanoparticles on performance and emissions of diesel engine. They reported that with increasing the concentration of cerium oxide in diesel fuel the flash point, fire point, kinematic viscosity and the efficiency increased. Especially at higher loads they observed a reduction on HC and NO_x emissions by 45% and 30%, respectively. Lenin et al. [12] investigated the effect of manganese oxide and copper oxide nanoadditives to the performance and emission characteristics of a diesel engine. They reported that manganese has much effect than copper additive which provides 37% CO reduction and 4% NO_x reduction. Mehta et al. [13] experimentally investigated the effect of aluminum, iron and boron nanoparticles to the burning characteristics, engine performance and exhaust emissions in a single cylinder compression ignition engine. They observed volumetric reduction of 25–40% in CO emission, 8% and 4% hydrocarbon emissions, and marginal rise in NO_x emission by using aluminum and iron nanoparticles. Balamurugan and Sajith [14] investigated the effects of Oleic acid as a dispersant on the stability of zirconium–cerium oxide (Zr-CeO_2) nanoparticle suspended in diesel. They found that the optimum concentration of dispersant was 0.6% by volume in diesel. Ozgur et al. [15] investigated the effects of addition of MgO and SiO_2 nanoparticle additives to biodiesel on fuel properties and effects on engine performance and emission characteristics. They reported that the NO_x and CO concentration decreases and engine performance values slightly increases with the addition of nanoparticle additives. Ozgur et al. [16] also investigated the effects of addition of nine different oxygen containing nanoparticle additives on NO_x emissions of diesel fuelled test engine. They used nanoparticle additives namely aluminum oxide (Al_2O_3), magnesium oxide (MgO), titanium oxide (TiO_2), zinc oxide (ZnO), silicon oxide (SiO_2), iron oxide Fe_2O_3, nickel oxide (NiO), nickel iron oxide ($NiFe_2O_4$) and nickel zinc iron oxide $Zn_{0.5}Ni_{0.5}Fe_2O_4$ at the dosages of 25, 50 and 100 ppm. Their results showed that NO_x emissions were decreased with the addition of nanoparticles. Mirzajanzadeh et al. [17] investigated the effects of a hybrid nanocatalyst containing cerium oxide on amide-functionalized multiwall carbon nanotubes using two types of diesel–biodiesel blends (B5 and B20) at three concentrations (30, 60 and 90 ppm). They found that all pollutants i.e., NO_x, CO, HC and soot were reduced by up to 18.9%, 38.8%, 71.4% and 26.3%. Basha et al. [18] investigated the alumina and carbon nanotube nanoparticles blended biodiesel fuel on the working characteristics of a diesel engine. Their results demonstrated that using nano blended biodiesel fuels have a positive effect in the brake thermal efficiency and in the pollutants compared to neat biodiesel fuel. Gumus et al. [19] examined aluminum oxide and copper oxide nanodiesel fuel properties and usage in a compression ignition engine. Their results showed that the stability of nanodiesel can be increased by regulating pH and using dispersant. The addition of Al_2O_3 and CuO as nanoadditives increase the ignition probability, promotes complete combustion, improves the efficiency, and reduces the HC, CO and NOx emissions due to their chemical composition (oxygen content), catalytic properties and nano dimensions.

Literature survey showed that there are many studies on the use of nanodiesel blends in internal combustion engines. Research objectives of nanodiesel usage are generally focused on the effects of physicochemical properties and performance improvements in internal combustion engines. Such research studies are completely missing in the field of boilers. The objective of this study is to investigate the combustion performance and emissions of a flame tube boiler by using nanodiesel with Al_2O_3 and TiO_2 nanoparticles with different mass fractions. For all experiments, combustion chamber temperature distribution, exhaust gas emissions and thermal efficiencies were determined and compared.

2. Materials and methods

Nanodiesel preparation was performed at the laboratory of the Mechanical Engineering Department. Al_2O_3 and TiO_2 are used in this study, especially, because of their large surface area, low cost, thermal stability, higher thermal conductivity, and higher oxygen content. Al_2O_3 and TiO_2 nanoparticles can play a role as a catalyst and an energy carrier. In addition, they are insoluble in water, also relatively non-toxic and environmentally stable. Al_2O_3 (from 27 to 43 nm), TiO_2 (size ranged from 30 to 50 nm) nanoparticles and a commercial diesel fuel were used to produce nanodiesel fuels. The nanoparticles were supplied by the NanoAmor and were used as-received. The preparation of nanodiesel begins by direct mixing of the diesel fuel as base fluid with the nanoparticles and ultrasonicated for 1 h at 40 Hz.

The experimental setup is shown schematically in Fig. 1. A residential hot water boiler (up to 50 kW) with reverse flame and smoke tubes was used for the combustion analysis. It was equipped with an ALARKO ALM-5 diesel burner, which has a high pressure swirl atomizer. The injected fuel in the co-flowing air formed a solid cone spray of droplets with a cone angle of 60°. Then the droplets warmed up, evaporated and burned simultaneously. Ignition was caused by electrodes with an electric arc, which was switched off after the flame became self-sustaining. The technical characteristics of the burner are presented in Table 1. A schematic diagram of the reverse flame smoke tube boiler is shown in Fig. 2. The combustion chamber had a length of 60 cm and an inner diameter of 34 cm. Twelve smoke tubes surrounded the combustion chamber circularly. The length and the inner diameter of the smoke tubes were 70 cm and 7 cm, respectively. The heat generated by the fuel combustion was transferred to the water in the boiler and then the circulated water was cooled by two air-water heat exchangers. The flue gases exited the boiler via an exhaust pipe, with a 13 cm inner diameter, to the chimney.

The measurement positions of the boiler are shown in Fig. 2. The temperatures in the combustion chamber were measured simultaneously by the mineral-isolated Ni-Cr-Ni (Type K) thermocouples T1, T2 and T3. Their axial positions from the combustion chamber front were 10, 30 and 50 cm, respectively. Type K thermocouples were used because of the high temperatures in the combustion