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An experimental investigation of ignition probability of diesel fuel droplets with metal oxide nanoparticles

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ABSTRACT

The aim of this study is to investigate the effects of nanoparticles type, nanoparticles size, and droplet size on the ignition probability of the diesel fuel. Also, the effect of metal oxide nanoparticles on the ignition delay of diesel fuel droplets is studied. A series of hot plate ignition tests are conducted for diesel fuel with and without Al_2O_3, TiO_2 and Fe_3O_4 nanoparticles at different concentrations (up to 0.05 wt.%). The experimental results show that the ignition probability of the diesel fuel significantly increases in the presence of metal oxide nanoparticles. The ignition probabilities of diesel/Al_2O_3 and diesel/Fe_3O_4 nanofuels are almost similar and higher than that of diesel/TiO_2 nanofuel. Results for diesel/Al_2O_3 show that the nanoparticle size does not affect the ignition probability of nanofuel. Moreover, results indicate that the ignition probability decreases by increasing the droplet size. Investigations show that the ignition delay for diesel fuel droplets decreases in the presence of Al_2O_3 nanoparticles.

1. Introduction

Fuel modification has become an attractive concept in recent years. Nanoparticles with their interesting features can be used as fuel additives to improve combustion properties of traditional liquid fuels. Due to the high surface area of nanoparticles and depending on the properties of the added nanoparticles, nanofuels can offer better performance than pure fuels [1]. Previous studies indicate that the addition of nanoparticles changed the ignition and combustion characteristic of liquid fuels. In this regard, Tyagi et al. [2] by using a hot-plate experiment showed that adding aluminum and aluminum oxide nanoparticles to the diesel fuel significantly improved the ignition properties of the diesel fuel. They found that the ignition probability of diesel fuel containing a small amount of aluminum nanoparticles was higher than that of pure diesel. Beloni et al. [3] studied the combustion behavior of decane based slurries using a lifted laminar flame burner, considering Al, $Al_{0.7}Li_{0.3}$and 2B + Ti as additives. They found that $Al_{0.7}Li_{0.3}$and 2B + Ti nanoparticles ignited readily and burned within the hydrocarbon flame, causing an increase in flame temperature and length. Jones et al. [4] conducted an experimental investigation on the heat of combustion of ethanol fuels containing Al nanoparticles. They reported that the amount of heat release from nanofuels increases almost linearly with the Al nanoparticles concentration, while Al_2O_3nanoparticles do not participate in combustion reactions and cannot change the total heat release. Gan and Qiao [5] experimentally studied the burning characteristics of ethanol and *n*-decane based fuel droplets containing nano and micron-sized aluminum particles. They observed that the five distinctive stages (preheating and ignition, classical combustion, micro explosion, surfactant flame, and aluminum droplet flame) occurred for an *n*-decane/nano-Al droplet, while only the first three stages observed for micron-Al particles. In another study, Gan et al. [6] investigated the combustion behavior of nanofuels containing boron and iron particles at dilute and dense concentrations. Mehregan and Moghiman [7] numerically studied the combustion characteristics and emission performance of ethanol and *n*-decane liquid fuels containing aluminum nanoparticles. They reported that in the presence of aluminum nanoparticles, the flame temperature decreases and the maximum temperature location shifts slightly toward downstream. Tanvir and Qiao [8] developed a droplet stream combustion experiment to investigate the effect of droplet size on the burning behavior of ethanol fuel containing Al nanoparticles. They found that the droplet burning rate increases by adding Al nanoparticles. Huang et al. [9] experimentally studied the hot-plate ignition probability of the ethanol containing nanoparticles. They observed that the effect of nanoparticles on the ignition probability is related to the number and geometry of nanoparticles but independent from the nanoparticle chemical compositions. Javed et al. [10] investigated the autoignition and combustion behavior of heptane/Al nanofuel at various ambient temperatures. They found that the reduction in the ignition delay with increasing temperature depends on the concentration of nanoparticles. Recently, Ooi

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et al. [11] studied the effect of graphite oxide, aluminum oxide and cerium oxide nanoparticles on the combustion characteristics of diesel fuel by using the single droplet experiment.

Metal oxide nanoparticles can improve the thermo-physical properties of the base fluids [12–15]. Also, metal oxide nanoparticles such as aluminum oxide, iron oxide and titanium oxide can be used as an oxygen donating catalyst which can provide oxygen for the oxidation of CO and HC or absorb oxygen for the reduction of NOx. Despite the various advantages of using metal oxide nanoparticles as the fuel additive, it is urgent to consider their potential environmental impacts and biological effects. Previous studies show that aluminum oxide, iron oxide and titanium oxide nanoparticles are less toxic compared to other metal oxide nanoparticles [16–18]. In this studyAl_2O_3, $Fe_3O_4$and TiO_2nanoparticles are chosen due of their large surface area, high thermal conductivity, high oxygen content, availability, low cost, and relatively non-toxic.

Considering the importance of evaluating the ignition characteristic of liquid fuels, the aim of this study is to investigate the ignition probability of the diesel fuel containing metal oxide nanoparticles (Al_2O_3, TiO_2, Fe_3O_4). The hot plate experiment is used to study the performance of the diesel fuel droplets with and without nanoparticles. In addition, the effect of aluminum oxide nanoparticles on the ignition delay of diesel fuel is examined. The effects of droplet size on the ignition probability and the ignition delay are also investigated in this study.

2. Experimental method

2.1. Fuel preparation and characterization

The preparation of nanofluid fuels is an important issue in developing nanofuels. The various physical and chemical techniques have been used to achieve the homogeneous and stable suspension [19]. In this study, the diesel-based nanofuels were prepared using a two-step method. First the nanoparticles were mixed with the base fuel by hand, and then an ultrasonication was used to disperse the nanoparticles in the base fuel uniformly. The amount of nanoparticles required for each dosing level was measured using a precision electronic balance with an accuracy of 0.1 mg. This was followed by sonication of the mixture in an ultrasonic disrupter (Ultrasonic Probe/f: 20 kHz, 400 W) for about 20 min to disperse particles evenly. The addition of a surfactant is not considered in this study because the surfactant can affect the characteristics of nanofuel. In order to prevent any agglomeration or sedimentation of the nanoparticles, the nanofuels were used immediately after preparation. In this study, the diesel fuel was considered as the base fluid. The composition of the pure diesel is given in Table 1. Three types of metal oxide nanoparticles Al_2O_3, TiO_2, Fe_3O_4 (purchased from US Research Nanomaterials, Inc.) were used as additives. The TEM images of Al_2O_3, $TiO_2$and Fe_3O_4 nanoparticles are shown in Fig. 1. The size distributions of $Al_2O_3$and TiO_2nanoparticles are in the range of 15–80 nm and 10–50 nm, respectively, with average diameter of most probable particles 20 nm. The size distribution of Fe_3O_4 nanoparticles is in the range of 10–45 nm with average diameter of most probable particles 20–30 nm. In addition, some tests were conducted on the diesel fuel containing aluminum oxide nanoparticles in another size of 80 nm (size ranged from 65 to 100 nm). The technical specifications of the nanoparticles are presented in Table 2.

Table 1
Composition of pure diesel.

Component	C	H	S	N
Mass fraction (%)	83.450	16.200	0.365	0.100

2.2. Experimental setup and procedure

The schematic of the experimental set-up is shown in Fig. 2. The tests were conducted on an electrically heated steel plate. In order, to avoid dispersion of droplets on the hot plate, a small concave curvature in the center of test surface was created. The temperature of the center of test surface was continuously measured using the laser digital infrared thermometer (GM900) with the maximum operating temperature of 900 °C and the accuracy of ± 1.5 °C. Single droplets were dispensed with a 1 ml pipette which was mounted directly above the surface such that the droplet fell as close as possible to the center of the plate. The distance between the pipette and the hot plate was 2.5 cm for all tests. The average droplet size was determined based on the number of droplets generated by a specified volume of the fuel in the pipette.

Experiments were carried out as a following procedure. The experiments were carried out in a closed room at atmospheric pressure of 90.56 kPa. The temperatures of the ambient air and the fuel were respectively 27.4 ± 1 °C and 32 ± 2 °C, measured by using K-type thermocouple with accuracy of 0.1 °C. At each surface temperature, the test was done by dispensing a single droplet on the hot plate. Before testing each fuel, the hot plate was carefully cleaned and polished to remove any residue from the surface. The ignition tests were carried out 50 times for each sample. The experiments were repeated three times at any surface temperature. Experiments were started at 400 °C and then repeated at different surface temperatures by 20 °C consecutive increments of the surface temperature. Several types of diesel based nanofuels containing different volume fraction of Al_2O_3, TiO_2 and Fe_3O_4 nanoparticles were prepared. The ignition time delay is defined as the time interval between the instant of contact and the appearance of the flame. The ignition delay was measured for each droplet and the average value was taken as the ignition delay. The ignition time delay was measured with an accuracy of 0.01s. The standard uncertainty in the hot surface temperature and droplet diameter were found to be 4 °C and 0.1 mm, respectively. The uncertainty in the ignition probability and the ignition delay were calculated using the Student-*t* method with a confidence level of 95%. This method can be used to determine the confidence interval of sample mean value for experimental data with small sample size [20]. The uncertainties in the ignition probability and the ignition delay were found to be 7.6% and 0.04s, respectively (with 95% confidence level).

3. Results and discussion

This study investigates the ignition behavior of diesel fuel with and without nanoparticles. The ignition probability of pure diesel was studied first as a baseline. Fig. 3 presents the effect of hot surface temperature on the ignition probability of the pure diesel. It can be seen that there are low temperatures in which ignition does not occur (ignition probability is 0%) and high temperatures in which ignition always occurs (ignition probability is 100%). Between these cases, by increasing the hot plate temperature, the ignition probability gradually increases in a transition regime. This observation is in agreement with the previous studies [2,21,22].

3.1. Effect of Al_2O_3 nanopaticles on the ignition properties of the diesel

Fig. 4 shows the ignition probabilities of diesel fuel containing 0.03 wt.% and 0.05 wt.% of Al_2O_3 nanoparticles (20 nm). The results demonstrate that the addition of Al_2O_3 nanoparticles to diesel fuel increases the ignition probability of the diesel fuel. This increase is more pronounced at relatively low temperatures of the hot plate. It can be observed that the ignition probability increases from 18% for pure diesel to 50% for 0.03 wt.% Al_2O_3/diesel at the surface temperature of 500 °C. Also, the ignition probability of diesel/0.03 wt.% Al_2O_3 is about 76% at 520 °C which is much higher than that of the pure diesel (42%). Similar results can be seen for diesel/0.05 wt.% Al_2O_3. Results indicate