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Combustion characteristics of a 300 kW_{th} oil-fired furnace using castor oil/diesel blended fuels

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HIGHLIGHTS

- A 300 kW_{th} oil-fired furnace was fueled with blends of castor oil and diesel.
- Excellent stable combustion was observed with the blended fuels.
- Furnace temperature only slightly dropped with increasing castor oil content.
- CO emissions in the five burning conditions were close to zero.
- NO emission was almost unaffected by the addition of castor oil in the diesel.

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ABSTRACT

In the ever-increasing demand for alternative fuels, one promising solution is the partial substitution of conventional fossil fuel with biofuel rather than completely replacing it. In this experimental study, a 300 kW_{th} (thermal power) oil-fired furnace is fueled with blends of crude castor oil and diesel to examine the feasibility of using these blends as a substitute for pure diesel in industrial applications. Castor oil is derived from castor seeds, which possesses low heating value, high oxygen content and high viscosity. A furnace test was conducted for pure diesel and castor oil/diesel blends with various mixing ratios. Pure diesel and blends with 5%, 10%, 20% and 30% castor oil were comparatively investigated by focusing on wall temperatures in the radiative section of the furnace, gas temperatures in the convective section and emission products from combustion. All experiments were performed under the operating condition of optimum (minimum) excess O_2 concentration in the flue gas. The air supply rates for the minimum excess oxygen requirement were 245, 241, 240, 237 and 236 Nm^3/h, respectively, for pure diesel and 5%, 10%, 20% and 30% blended castor oil at the fixed liquid-fuel supply rate of 20 L/h. Excellent stable combustion was observed during the experiments with the castor oil/diesel blended fuels. Both the wall temperature and gas temperature dropped slightly with increases in castor oil content in the blends; nevertheless, they were very close compared with pure diesel. Additionally, with increasing castor oil content in the blends, NO and CO emissions only slightly decreased and increased, respectively. Accordingly, it is verified that the use of 5–30% castor oil in the blends produces similar furnace temperature distributions and comparable emission levels of CO, NO and SO_2 when compared to pristine diesel.

1. Introduction

Fossil fuels (coal, oil, and natural gas) are nonrenewable resources. The burning of such fuels has raised many environmental problems, including global warming, air pollution, and acid rain, among others. In recent years, attention to alternative fuels has increased dramatically, driven by critical shortages of fossil fuels and rising levels of greenhouse gas emissions. The utilization of biofuels as alternative fuel sources is one of the most promising solutions to the problems of depleted fossil fuels and the associated negative environmental impacts [1].

Biomass resources can be converted directly into promising renewable liquid fuels such as bioethanol, biodiesel, bio-oils, or other bioliquids (BLs). Liquid bio-based fuel has the potential to

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replace conventional fuel oils, and offers many advantages, for instance, clearly positive CO_2 balance; high-energy density compared to atmospheric biomass gasification; the possibility of utilization in both small-scale power generation systems and large power stations; and, the potential of using pyrolysis liquid as fuel in existing power plants [2]. Liquid biofuel can be co-fired with fuel oil, natural gas or coal, especially in large power stations. In addition to the advantages of higher overall plant efficiencies and reduced investment costs in comparison with 100% biomass plants in existing industrial sites, co-firing bio-oil with conventional fossil fuels has several environmental benefits such as reduced emissions of CO_2, NOx and SOx [3]. Bio-oil can also be employed as a start-up or back-up fuel for industrial facilities [4].

Numerous studies have placed particular emphasis on the production, upgrade and application of these biomass-derived liquids as fuels for transportation purposes, particularly biodiesel and bioethanol in conventional engines [5–8]. Other studies have targeted combustion characteristics for the introduction of liquid biofuels or their blends as fuels in small-scale facilities [9–15] and commercial plants [16]. However, relatively few studies have focused on crude (unrefined) BLs for use in engines or boilers due to the modification requirements of these systems [17].

Numerous research efforts have been devoted to investigating the prospects of the substitution of petrodiesel with liquid biofuel (especially biodiesel) in diesel engines. Research on liquid biofuels for use in furnaces or boilers is relatively rare. Lee et al. [18] examined the combustion performance of a blend with 20% soy bean methyl ester (SOME) in No. 2 fuel oil using a residential-scale hot water boiler. They reported that although NOx emissions were comparable, about 20% less SO_2 emissions were released compared with pure No. 2 fuel. Zheng et al. [19] investigated the spray combustion characteristics of fast pyrolysis bio-oil produced from rice husk. It was found that despite a slight increase of measured NOx concentration being observed at the higher fed air, the measured SOx concentration was very low (smaller than 30 ppm). Bazooyar et al. [20] investigated the combustion performance and gas emissions of diesel and biodiesels made from various feedstocks, including grape seed, corn, sunflower, soybean, olive and rice bran oils in a semi-industrial boiler. It was revealed that the boiler performance of the biodiesel were similar to that of diesel at higher energy rates and lower air-fuel ratios, and that besides NOx, the biodiesels emitted much lower emissions than diesel. Ghorbani and Bazooyar [21] evaluated the potential for blends of soy bean methyl ester (SOME), B100, B5, B10 and B20, rather than diesel, as alternatives for non-modified burners in a semi-industrial boiler. The results showed that the thermal efficiency of the boiler using the various fuels was similar under the same operating conditions. In addition, SOME and its blends exhibited lower emissions of CO_2, NOx and SO_2 than diesel. Daho et al. [22] investigated the combustion characteristics of heating fuel oil and cottonseed oil in a modified burner, and concluded that non-condensable gases (CO, O_2, CO_2, NOx and SO_2) and PAHs emissions were similar for these two fuels under optimized atomization and granulometry conditions. Allouis and Chiariello [23] experimentally investigated the effects of oxygen enrichment and CO_2 dilution on the flame stability and emitted pollutants (CO, NOx) of rapeseed oils and their blends with diesel in a stationary burner. They found that while the effect of oxygen enrichment increased NOx emissions due to the higher furnace temperature, CO emissions increased only slightly. In contrast, the effect of CO_2 dilution was found to reduce the NOx emissions due to the lower furnace temperature under a fixed oxygen concentration. Park et al. [24] investigated the combustion characteristics of heavy fuel oil (HFO) and palm-based bioliquid (BL) in a 100 MWe-capacity (electrical power) boiler using computational fluid dynamics (CFD). The BL-firing case exhibited more uniform gas temperature and heat flux distributions in the combustion zone than did the HFO-firing case. Also, BL emitted much lower SOx and NOx emissions due to the inherently low S and N content.

Castor (*Ricinus communis* L.) is an important non-edible oil seed crop and has high annual seed production and yield due to it being suitable to grow on marginal land and in semiarid climates. Oil content in the castor seed is considerable (around 50%), and is a renewable and clean fuel that is classified as a vegetable oil. In particular, castor oil is a non-edible bioliquid, and so its application in the biofuel industry, unlike the use of sustainable feedstock for biodiesel production via conventional transesterification technologies [25–29], does not create food crises or raise critical environmental concerns. In addition, castor oil is less expensive when compared to other vegetable oils since it is soluble in alcohol and undergoes the transesterification reaction with minimum heating under ambient temperature [30]. Moreover, castor oil has a greater cetane number, leading to better ignition quality for diesel engines, and contains more oxygen but little, if any, sulfur, thereby enabling the combustion to be more complete and much cleaner than diesel alone. However, few studies have been devoted to investigating emission and performance of diesel engine using castor biodiesel [31,32]. Especially, research on combustion of blended fuel of crude castor oil and diesel in furnaces or boilers has not been previously documented in literature.

In response to the ever-increasing demand for alternative fuels, a promising solution is the partial substitution of conventional fossil fuel with biofuel, rather than completely replacing it. In this study, the combustion characteristics and emitted pollutants of castor oil/diesel blends were studied experimentally in a 300 kW_{th} (thermal power) oil-fired furnace without any modifications to the system. We aimed to examine the feasibility of using these blends as a substitute for diesel in industrial applications.

2. Experimental apparatus and method

2.1. Combustion system with a vertically down-fired furnace

Fig. 1 shows a schematic of the combustion system [33], while Fig. 2 illustrates the vertically down-fired furnace with a maximum thermal loading of 300 kW_{th}. kW_{th} or kilowatts thermal means kilowatts of thermal power. Its overall structure can be divided into three parts, namely the radiative, convective and flue gas sections. The vertical cylindrical refractory-lined radiant combustion chamber has an inner diameter of 0.56 m and a length of 3.05 m, and can be supplied with various types of fuel, such as diesel, HFO, emulsion fuel, pulverized coal, and solid/liquid biofuel, etc.

The radiative section (vertical combustion chamber) contains 5 sub-sections, each of which is equipped with an R-type thermocouple to measure the wall temperature of the chamber, an observation window to facilitate observation of the flame appearance and combustion stability, and a port to allow access to the combustion chamber. The set of two burners for burning solid and liquid fuels installed on top of the vertical furnace were designed and manufactured by C&C Engineering, Inc., with each one having a maximum thermal loading of 300 kW_{th}. Both burners are equipped with a pilot flame, flame detector and pressure gauge for igniting the flame and monitoring its behavior.

For liquid fuel, a low-pressure air-assisted atomizer (Fig. 3(a)) is employed for oil atomization and subsequent injection into the burner. The secondary air is injected into the burner via tangential injection while tertiary air is supplied through four inlet tubes at the top of the burner, as shown in Fig. 3(b). The tangential injection system introduces the air flow in a circumferential direction, thereby establishing a swirling-flow field in the centerline and providing the means to design and build practical tubular flames. The