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Liquid butane as an alternative fuel for diesel oil burners

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ABSTRACT

The experimental tests performed to study the combustion process of liquid butane employing a diesel oil burner are presented. For these tests, a dual pumping and injection system was designed to operate with pressures varying from 0.8 to 2.0 MPa. Five distinctive cases were tested for each fuel, obtaining a complete characterization of the combustion processes in comparable conditions. Flame geometries, temperatures and the main chemical products of the combustion process were recorded experimentally for both liquid butane and diesel oil. It was observed that liquid butane flames present elongated conical shapes, with low radiation cyan color at the base position, followed by a higher radiation zone in the core and flame front positions. Also, the temperatures and NO_x concentrations of liquid butane flames are lower than those of diesel oil flames. In general, it is feasible to modify the combustion technology of diesel oil burners to use liquid butane as an alternative fuel.

1. Introduction

In the last two decades, with the worldwide energy crisis, the price of diesel oil has sharply increased, imposing a huge economic burden to produce power at a reasonable cost for residential needs, commercial facilities and industrial production. This situation demands a constant search for alternatives that ensure a highly efficient power generation at the lowest possible cost. Thus, it is vital to analyze the feasibility of modifying the technology currently used for combustion processes to introduce alternative fuels that substitute diesel oil.

Diesel and fuel oil are the most consumed fuels in the industrial facilities and thermal power plants, which represents a major problem due to the permanent price increments and high speculation in oil markets. Additionally, as pointed out by Martyr and Plint [1], the hazardous pollution caused by handling and consumption of diesel oil has contributed to the rapid environmental degradation, which turns unfeasible the use of these fuels in the nearby future. Therefore, an opportunity to introduce alternative fuels has motivated detailed studies of biofuels, fuel blends, polluting exhaust emissions and comparative analysis of fuel prices.

Generally speaking, biofuels seem to be attractive substitutes to petroleum-based fuels, mostly because the majority of biofuels are obtained from renewable sources and the greenhouse effect gases are reduced. Nonetheless, experimental studies, such as the ones presented by Yoon and Lee [2] and Crookes et al. [3], have proven that some biofuels, under certain conditions, may retard the ignition phase and reduce the combustion performance, compromising any cost-effective power generation. In the case of biodiesel blends from vegetable oils, Agarwal et al. [4] explain that, without much chemical processing, usually these blends present high viscosities and fairly low volatility, causing high droplet size due to poor fuel atomization and jet-mixing. Hence, operational performance and durability of combustion technology are severely reduced.

Also, as clarified by Atsbury [5], the high soot formation from the combustion of some biodiesel blends and the flammable/explosive nature of biogases, bioethanols and hydrogen-based fuels may become safety hazards and environmental drawbacks to their complete approval for commercial thermal machines. Nonetheless, with the appropriate treatment and manipulation, biofuels still are good alternatives which mostly improve in the emission reduction of carbon monoxide (CO), unburned hydrocarbons (HC) and particulate material (PM) as demonstrated in the studies by Sayin and Canakci [6] and Rodrigues de Souza et al. [7].

From an economic point of view, an interesting result presented by Demirbas [8] indicates that, even though biodiesel blends have lower economic performance than diesel oil (in terms of plant capacity, process technology, raw material cost and chemical costs), they are strong competitors of natural gas and diesel oil for urban transportation and industries. Demirbas also remarks that biofuels provide the prospect of new economic opportunities by creating jobs for people in rural areas of developing countries, which usually are highly dependent in oil consumption. However, Chang and Su

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[9] clearly explain that the great paradox of the conventional biofuel production and consumption, in favorable periods of high oil prices, is the shortage of basic foods used as raw material (e.g., corn and soybean) that are fundamental part of the food security of humans and livestock. For that reason, they stress the need for a careful choice of the raw material to be used for biofuel production and suggest the selection of inedible algae-based feedstock.

Other researchers have focused on low sulfur gaseous hydrocarbons, such as *n*-butane, propane and natural gas, which generally are liquefied to be injected in dual-fuel technology. Studies by Huang and Sung [10], Huang et al. [11], Lee et al. [12] and Yamasaki and Iida [13] have identified *n*-butane as one of the main substitute fuels for diesel oil, mostly due to its similar thermo-physical characteristics (important factor for dual-fuel systems) coupled with the high combustion efficiency and low emissions achieved by the two-stage autoignition process (i.e., low heat release stage, LTR, and high heat release stage, HTR).

In fact, *n*-butane (C_4H_{10}) is the fuel with lowest carbon number of the paraffin family found to interchange well in combustion technology with higher hydrocarbons (such as diesel oil), and has proven to reduce significantly the CO and PM concentrations in exhaust gases [12]. Additionally, the small carbon number of *n*-butane is indicative of the fast chemical kinetics of its combustion process which aids the speed-up for autoignition and improves combustion performance. However, this last characteristic has challenged designers and combustion engineers, who need to control properly the ignition timing and combustion duration at very high temperatures and injection velocities [13].

Liquid *n*-butane (hereafter referred to as liquid butane) has inspired different inventions over the past 60 years (e.g., Schylander [14], Pillard [15] and Kaufman [16]) and is becoming the mainstream of substitute fuels in oil combustion technology [17,18]. As Fleisch et al. [18] point out, just until recent years gas-derived fuels could not compete with conventional petroleum-based liquid fuels because gas-to-liquid conversion has been and still is an expensive process. But now, a significant cost reduction from improved technologies and economies of scale has raised the competitiveness of liquefied gas fuels for commercial applications. Either for small-scale indoor purposes (such as the case presented by Ghosn et al. [19]) or large-scale industrial purposes (such as metal piece heating discussed by Wang et al. [20]), commercial developers and users can benefit from the quick gasification and ignition of liquid butane for a more efficient combustion.

Consequently, the main objective of this study is to design and test of a dual system for liquid butane and diesel oil injection in a Joannes® diesel oil burner, aiming for the optimization of this combustion technology to facilitate the introduction of liquid butane as the alternative fuel. For that purpose, firstly, the fuel injection, jet-mixing and ignition systems are fully studied, and a new system of liquid butane injection complementary to that of diesel oil is proposed. Secondly, the experimental setup is implemented on a horizontal isothermal vessel, which includes instrumentation for mass flux, pressure and temperature measurements, flue-gas analysis, PLC automation, solenoid valves, water pumping, fuel injection and security systems. Finally, diesel oil and liquid butane combustion are investigated, respectively.

This research article presents the final results obtained with the new dual injection system. In Section 2 the general set-up of the testing bench is detailed. Then, the simplified radiation model used for thermal performance assessment is presented. The experimental results for both fuels are discussed in Section 3, emphasizing on the main features and benefits of liquid butane combustion. Finally, in Section 4 the concluding remarks are presented.

2. Experimental setup and methodology

2.1. Isothermal reactor and instrumentation

For this study, a horizontal vessel of 550 mm in diameter and 1650 mm long, with a 180 mm diameter exhaust pipe, was adapted to operate as an isothermal reactor. Its furnace interior, which has high alumina refractory coating, is surrounded by a cooling water circuit which maintains a stable temperature profile, aided by a two-step heat exchanger that removes heat transported by the cooling water. Additionally, the AZ14 Joannes® diesel oil burner, designed to generate a maximum power of 180 kW, was installed to test the dual-fuel system.

The schematic design of the dual injection system is presented in Fig. 1. Diesel oil is stored in a 45 L tank and is injected with a Suntec® fuel pump at 0.8, 0.9 and 1.0 MPa. Liquid butane is fed from a low-pressure cylinder (0.25 MPa) into a variable flux fuel pump that rises the fuel pressure between 1.0 and 2.0 MPa. These high-pressure lines are connected to a liquid accumulator and pressure reduction valves that adjust the final injection pressure. The fuel flow is controlled primarily by automated solenoid valves which obey to a sequence program launched by a PLC and monitored from a remote computer. Whenever a change in time or operating sequence is needed, the program is modified, recompiled and reloaded into the PLC.

Diesel oil and liquid butane flow rates are measured by a rotameter calibrated in situ, and a digital volumetric flow-meter is used in the cooling water circuit as well. Also, to adapt the power output to the reactor's capacity, the original burner nozzle of 3 GPH was replaced for a 1.75 GPH nozzle. This is a major change in the burner's system based on the need of a low power range control. For this experiments, a Danfoss® pressure-swirl nozzle (of 2.94 kg/h, HR hollow cone, 60 degrees spray) was employed to obtain the desired 1.75 GPH fuel injection. A schematic diagram of this nozzle, with its components and dimensions, is presented in Fig. 2.

Five type R thermocouples of 0.75 mm in diameter and platinum–rhodium coating (13% rhodium) were used to scan the furnace wall temperatures along the combustion chamber. Also, a type K mobile thermocouple (1.5 mm in diameter and chrome–alumel coating) was installed to measure the flame temperature at five positions along the centerline and flue-gas temperatures at 1500 mm from the exhaust pipe entrance. The flame and wall temperatures at the burner's exit (first position, 0 m) were obtained with a LumaTech® infrared pyrometer (measuring range: -30 to 750 °C) and two flue-gas meters (TESTO® 350-S and Bosch® BEA 250-EU) were used in order to assess and control combustion parameters in real time. A smoke meter, Bosch EFAW 68A, was used to measure soot emissions.

For the flame geometry characterization and monitoring, a Sony® HDR-FX1000 professional camcorder was employed for multiple imaging and footage recording. The captured images were post-processed with the Adobe® Premier Pro toolkit (Photoshop® CS5), using the furnace's dimensions as reference for the sizing of the flames, obtaining the integral scales of length and radius at the flame's base, core and front positions discussed in Section 3.

The operation sequence of this experimental hybrid system was defined as follows:

- Air pre-cleaning of the combustion chamber is set to 10 s to drag any remaining unburned hydrocarbons from previous tests. In case of an emergency, the sweeping procedure continues for 3 min;
- Turning-on the ignition spark is set for 13 s;
- Preheating the reactor and nozzle with a diesel oil flame is done for 35 min;