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Comparison of hydrogen and hydrogen-rich reformate enrichment of JP-8 in an open flame

Michael Seibert*, Sen Nieh

US Army RDECOM CERDEC Command, Power & Integration Directorate, Aberdeen Proving Ground, MD 21005, United States
Department of Mechanical Engineering, The Catholic University of America, 620 Michigan Ave. NE, Washington, DC 20064, United States

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ABSTRACT

Hydrogen enhanced combustion of JP-8 provides an additional control parameter for external combustion based power sources. When supplied as part of a “reformer gas” mixture, hydrogen provides similar benefits as pure hydrogen, given sufficient oxygen mixing. Previous work showed benefits of hydrogen enhanced combustion for external combustion based power sources. As a step closer to practical applications, the present work examines the use of hydrogen rich reformate. This mixture of hydrogen, carbon monoxide, carbon dioxide, and nitrogen is produced by fuel reforming of JP-8 and other logistics fuels.

Tests evaluated the temperature profiles of dual fueled flames using JP-8 and either hydrogen or a bottled mixture representing fuel reformate. Both supplemental fuels move combustion earlier, allowing more stable combustion and potential for reduced size. JP-8 flow rate was reduced to maintain fuel energy input at a constant 5.5 kWth. In comparing two cases, the important factor was the total energy contribution. The ratio of hydrogen and carbon monoxide had little effect on the flame structure.

This research also compared methods of hydrogen addition. It was added with either the atomizing air or the secondary air which reiterated the importance of oxygen availability. For example, hydrogen through the nozzle produces additional changes to the flame structure due to the combustible mixture of hydrogen and air in the nozzle. The equivalent flow rate of reformate in the nozzle does not produce the same effect because the air in the nozzle is replaced by the other gases in the reformate (CO, CO_2, and N_2).

Hydrogen enrichment tests establish the benefit of dual firing hydrogen and JP-8. These reformate tests show the variables that must be considered in implementing this technique in a practical system.

1. Introduction

Hydrogen enrichment has been presented as a control parameter to enable JP-8 combustion based portable power sources [1,2]. The present study demonstrates that hydrogen-rich reformate can serve the same function as pure hydrogen if it does not displace the necessary oxygen. This approach is motivated by the US Military mandate that only one fuel, JP-8, be taken to the battlefield, and the increased capability of soldier-carried electronic devices which drives increased power demand without increasing weight. Diesel engines can operate on JP-8; however, given their weight, portable power under 1 kW requires innovative alternatives.

Technologies such as Stirling engines, thermo electric and thermophotovoltaic generators are potential alternatives but require reliable JP-8 combustion. These power sources can all produce power of 250 W to 2000 W, and all use an external combustion heat source. Techniques enabling the combustion of heavy liquid hydrocarbon fuels, such as JP-8, would fill this power gap.

To address this need, Coombe [3] examined the effect of oxygen enriched air on the combustion of JP-8 in small combustors. Hydrogen enriched combustion has been considered as another approach to improve combustion. It has shown success with a variety of other hydrocarbon fuels and applications. Experiments adding hydrogen to natural gas and other light hydrocarbons show improved flame stability, flame speed, and lean blow off limit [4–9]. Emissions reductions have also been shown in kerosene fueled gas turbine combustors [10,11].

Hydrogen addition to spark ignition engines has shown improved emission performance and cyclic variability [12–15]. Hydrogen has been used in compression ignition engines both as an additive to diesel type fuels and as the main fuel ignited by diesel injection [16–19,33]. In most cases, hydrogen showed improved emissions performance in NO_x and particulates with some researchers reporting reduced fuel consumption. However, some results concluded that the cost of hydrogen

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* Corresponding author.
E-mail address: michael.l.seibert.civ@mail.mil (M. Seibert).

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production outweighed the benefit [20]. Banerjee et al. provide a thorough review of hydrogen and EGR as an approach to meet competing requirements in particulate emissions, NO_x and fuel efficiency [21] while Verhelst et al. examine work done in hydrogen combustion as a pathway to hydrogen fueled engines [22].

Following these successes, the possibility and advantages of dual firing of hydrogen and JP-8 was previously investigated numerically [1] and experimentally [2] by the authors.

DuBois [23] studied autothermal catalytic reforming of JP-8 for solid oxide fuel cell applications which allows the generation in situ of hydrogen on the application site from JP-8. This logistic availability of hydrogen produced from JP-8 guided the present research to compare the use of pure hydrogen with the more realistic use of hydrogen-rich reformate. Similar mixtures of hydrogen and carbon monoxide are also known as “syn-gas,” which can be produced more economically than pure hydrogen from a variety of sources. These mixtures have been studied for industrial burners, internal combustion engines, gas turbines and other applications. The hydrogen fraction is shown to increase flame speed and reduce combustion instability in engine conditions [24,25]. Numerical investigations show reduction of CO and NO_x with increasing hydrogen for industrial applications [26]. Hydrogen reduces CO despite CO being added with the hydrogen.

In diesel engines, hydrogen-rich reformate has been used with exhaust gas recirculation (EGR) to reduce emissions and improve fuel efficiency. Exhaust gas fuel reforming has been demonstrated as a method of on-board hydrogen production in diesel engines with improvements in efficiency and emissions performance [27,28]. Using hydrogen in conjunction with EGR provides a path around the NO_x-particulate trade-off [29]. Shan et al. combined EGR with port injection of hydrogen rich bio gas. They identified 50% EGR and 15% hydrogen as the best combination of engine efficiency and emissions performance [30].

Burguburu et al. studied hydrogen addition to kerosene fueled gas turbine combustors. The improvement is present to a lesser degree with hydrogen rich reformer gas which can be produced from jet fuel on board [31]. It was also noted that the hydrogen/carbon monoxide proportion in the reformer gas did not substantially change the lean blow out limit or CO emissions performance.

While JP-8 combustion has been studied extensively for turbine and engine applications, low power combustion at atmospheric pressure is a novel application driven by military logistics requirements. This work examines an open, atomized JP-8 droplet flame for external combustion power system applications. Previous experiments by the authors show earlier combustion and improved flame stability with pure hydrogen addition to the open JP-8 flame [2]. In an effort to move the research closer to practical applications, additional tests were done using mixtures of simulated reformate. These consist of gas mixtures containing the major components of the products of fuel reformation: hydrogen, carbon monoxide, carbon dioxide, and nitrogen. In the reforming process, the fuel, such as JP-8, is partially oxidized with air. A fraction of the air needed for full combustion reacts with the fuel. The reaction breaks the longer hydrocarbon chains, but since there is insufficient air for full combustion, the reaction does not proceed all the way to carbon dioxide and water. CO_2 and water are formed, but carbon monoxide and diatomic hydrogen are the more dominant products.

2. Experimental set-up

Measurements are made of a 5.5 kWth open flame. The test stand is designed around an air siphon nozzle which uses pressurized air to spray JP-8 droplets upward, as shown in Fig. 1. Approximately 10% of the air required for combustion is supplied through the nozzle. This air is used both to atomize the fuel and pull it from the fuel tank. The nozzle is mounted within a 1.5″ (3.8 cm) tube supplying secondary combustion air. Hydrogen and hydrogen-rich reformate can be introduced to either the atomizing air or the secondary air supply. Temperature is measured using 1/16″ (1.6 mm) K-type thermocouples mounted to a linear slide with a DC motor. Vertical temperature profiles are measured directly over the center of the fuel nozzle. Temperature is measured laterally through the flame by three thermocouples sweeping through the flame at 1.4 cm, 3.1 cm, and 12.7 cm. The thermocouples are held at each location for 30 s. The first 15 s allow the thermocouple to reach thermal equilibrium. Then, temperature is averaged over the last 15 s. A string potentiometer measures and records the thermocouple locations. The combined location and temperature data provide a detailed thermal profile of the flame.

Hydrogen and simulated hydrogen-rich reformate are supplied by two compressed gas cylinders reflecting different balances between reformate products. The compositions are shown in Table 1. The R2 reformate is based on an autothermal reformer with 34.5% hydrogen, 18.1% carbon monoxide, 7.3% carbon dioxide with the balance nitrogen. This is similar to the work of Scenna [34] who produced a reformate stream with approximately 35% hydrogen and 16% carbon monoxide. A water-gas shift reaction would transfer an oxygen atom from water to carbon monoxide increasing the fraction of hydrogen and carbon dioxide, and reducing carbon monoxide. This produces concentrations similar to R1 with hydrogen increasing to 42%, carbon monoxide reduced to 2%, and carbon dioxide increased to 18%.

When hydrogen or hydrogen-rich reformate is added to the nozzle air, the air is reduced to maintain a constant back pressure in the nozzle. The constant nozzle back pressure produces a constant liquid flow rate, independent of the gas mixture [32]. Total fuel energy is maintained during hydrogen addition by reducing the JP-8 flow rate with a metering valve.

3. Results

Vertical temperature profiles with reformate are shown in Fig. 2. These scenarios were generated to have 10 and 20% of the fuel energy come from “R1” reformate. This gives 7.2 and 14.5 slpm reformate and 3 and 6 slpm hydrogen. At the centerline, temperature increase occurs earlier with reformate addition. The JP-8 only case reaches 600 K at 1.94 cm, while the 14.5 slpm reformate (6 slpm hydrogen) case is above 600 K at 1.63 cm. Hydrogen addition moves combustion earlier in the flame, even when diluted in reformate. Above 6 cm, the temperatures run together. This is to be expected because all three flames have the same total amount of fuel energy, and approximately the same mass of air to heat up. The primary change is the shift towards earlier combustion. This enhances stability and can reduce size.

The reformate in secondary air mixture is 4.5% hydrogen, slightly above its listed lower flammability limit. As droplets spread into the secondary air flow and evaporate into this reformate/air mixture, flammability conditions are met sooner than in the case without reformate.

Lateral temperature sweeps give further insight into the effect of hydrogen on the flame structure. Temperature profiles at 1.4 and 3.1 cm show the early flame structure with the “R1” simulated reformate in Figs. 3 and 4. The hydrogen rich reformate shifts combustion earlier as the two diffusion flame temperature peaks increase with increasing hydrogen/reformate. At 1.4 cm, temperatures at the edge of the flame are raised by approximately 100 K relative to a JP-8 only flame. As expected, increasing the energy fraction from reformate increases the temperature. At 3.1 cm, the temperature increase at the edge of the flame is less pronounced, but the center temperature increases by 200 K with 20% energy contribution. The earlier shift in temperature is most evident in the shallower temperature dip in the center of the flame.

General structural similarity is seen between reformate and hydrogen enriched flames when compared on the basis of hydrogen flow rate. At 10% and 20% energy contribution, the R1 reformate is at 7.2 and 14.5 slpm respectively, which amounts to 3 and 6 slpm of hydrogen. The temperature profile of these flames is compared to a JP-8/