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PGAE - TR – 12 – 02

Simulation of Dual Firing of Hydrogen and JP-8 in a Swirling Combustor

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14. ABSTRACT
Flame control, particularly at very lean conditions, is a critical requirement for external combustion power sources such as thermoelectric and thermophotovoltaic generators. The availability of in-situ produced hydrogen from JP-8 fuel reforming presents a potential supply of hydrogen on the battlefield without adding a second fuel to the logistics system. Dual firing of hydrogen with light hydrocarbons has been investigated to reduce the lean flammability limit, allowing improved flame control and reduced emissions. This research investigates the use of small amounts of hydrogen co-fired with jet fuel for improved energy efficiency, operational flexibility and environmental protection. Simulations were conducted using a computational fluid dynamics model of a 6 kW (thermal), swirling flow combustor. The simulations use hydrogen and a single hydrocarbon surrogate for JP-8 with a 4 step reaction mechanism. Follow up simulations examined the effect of using reformed fuel containing hydrogen, carbon monoxide and other gases dual-fired with JP-8. Varying levels of reformate and air were examined. The results show that at lean conditions, the dual firing of hydrogen or reformate with JP-8 provides improved fuel conversion, demonstrating better flame stability and providing higher fuel burning efficiency. Dual firing with hydrogen provides little benefit to JP-8 combustion under stoichiometric or fuel rich conditions because they are limited by mixing rather than chemical kinetics. These results indicate that dual firing of hydrogen with JP-8 is a promising method for improving lean flame stability and control. This has the potential to enable small scale power applications with specific temperature requirements such as thermoelectric and thermophotovoltaic generators.

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Simulation of Dual Firing of Hydrogen and JP-8 in a Swirling Combustor

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Abstract: *Flame control, particularly at very lean conditions, is a critical requirement for external combustion power sources such as thermoelectric and thermophotovoltaic generators. The availability of in-situ produced hydrogen from JP-8 fuel reforming presents a potential supply of hydrogen on the battlefield without adding a second fuel to the logistics system. Dual firing of hydrogen with light hydrocarbons has been investigated to reduce the lean flammability limit, allowing improved flame control and reduced emissions. This research investigates the use of small amounts of hydrogen co-fired with jet fuel for improved energy efficiency, operational flexibility and environmental protection. Simulations were conducted using a computational fluid dynamics model of a 6 kW (thermal), swirling flow combustor. The simulations use hydrogen and a single hydrocarbon surrogate for JP-8 with a 4 step reaction mechanism. Follow up simulations examined the effect of using reformed fuel containing hydrogen, carbon monoxide and other gases dual-fired with JP-8. Varying levels of reformate and air were examined. The results show that at lean conditions, the dual firing of hydrogen or reformate with JP-8 provides improved fuel conversion, demonstrating better flame stability and providing higher fuel burning efficiency. Dual firing with hydrogen provides little benefit to JP-8 combustion under stoichiometric or fuel rich conditions because they are limited by mixing rather than chemical kinetics. These results indicate that dual firing of hydrogen with JP-8 is a promising method for improving lean flame stability and control. This has the potential to enable small scale power applications with specific temperature requirements such as thermoelectric and thermo-photovoltaic generators.*

Keywords: hydrogen; fuel reforming; external combustion; jet fuel.

Introduction

To simplify logistics, the US Military has mandated that only one fuel be taken to the battlefield. The chosen fuel, JP-8, is a middle distillate hydrocarbon mixture slightly lighter than diesel fuel. Like diesel fuel, it has a low octane rating and can not be used in unmodified spark ignition engines. Compression ignition engines do not work well at small scales because the increasing ratio of cylinder surface area to volume leads to flame quenching on the cylinder wall. As a result, there is a lower limit to the power sources that can be supplied by heavy hydrocarbon fuels. For example, the military does not have any diesel or JP-8 fueled electric power sources smaller than 2 kW. The largest batteries can power up to 250 W. This leaves a power gap between 250 and 2000 W. This power range includes loads such as laptop computers, radios, power tools, and battery chargers.

This need opens the door for Stirling engines, thermoelectric generators and thermal-photovoltaic generators which would not be able to compete directly with internal combustion engines at higher power levels. These power sources can all produce power in the 250 to 2000 W range and all use an external combustion heat source. Technology improving the combustion to provide energy to these systems would fill this power gap.

Previous work in small combustors examined the effect of oxygen enriched air on the combustion of JP-8[1]. This work showed increased burner capacity and temperature at increased levels of oxygen enrichment.

Recent advances in fuel reforming for fuel cell applications allow the generation of hydrogen on the battlefield from JP-8[2]. Due to this availability of hydrogen, the possibility of dual firing hydrogen and JP-8 was investigated.

Previous work in hydrogen enriched combustion has shown success in other areas. Schefer at Sandia National Labs added hydrogen to methane-air flames and found that it improved lean flame stability and reduced NO_x emissions[3]. Kumar and Mishra added hydrogen to liquefied petroleum gas (LPG) flames which lowered NO_x emissions while increasing CO[4]. Several researchers have used hydrogen as a supplementary fuel for diesel engines with mixed results[5,6]. Most researchers have reported reduced specific fuel consumption but the impact on NO_x emissions is mixed.

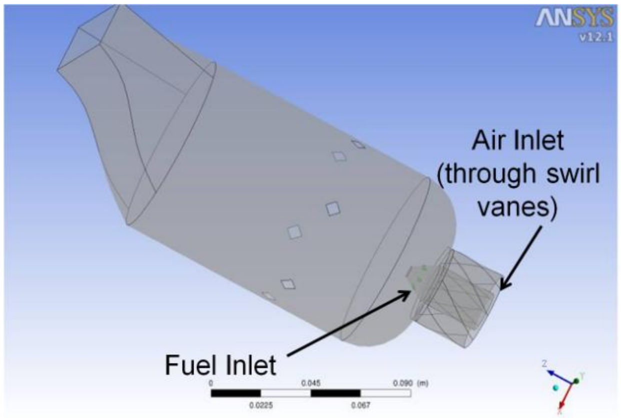

Figure 1. Geometry of the combustor used in the simulations described in this paper. The overall combustor length is 22 cm and diameter is 8 cm.

Simulation

This research simulated a 6 kW (thermal), swirling flow combustor with various levels of hydrogen enrichment. The combustor geometry is shown in Figure 1. Jet fuel is approximated by a single hydrocarbon $C_{12}H_{23}$ with a four step combustion mechanism.

$$C_{12}H_{23} + 6O_2 \rightarrow 12CO + 11H_2$$

$$CO + 0.5O_2 \rightarrow CO_2$$

$$H_2 + 0.5O_2 \rightarrow H_2O$$

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

Air is introduced through the end of the burner, passing through swirl vanes before entering the combustion region. Fuel is introduced immediately downstream of the swirl vanes. JP-8 and hydrogen are both introduced as gases. Simulations were completed using the Ansys CFX computational fluid dynamics software.

The total Lower Heating Value of the fuel mixture is maintained at a constant 6 kW. Simulations were conducted using a JP-8 and hydrogen mixture containing 0%, 1% and 10% hydrogen gas composition by mass. Air flow rate is identified based on the equivalence ratio, Φ. Φ is the stoichiometric air to fuel ratio, divided by the actual air to fuel ratio. $\Phi<1$ indicates a fuel lean or excess air condition. $\Phi>1$ indicates a fuel rich condition. For each level of hydrogen enrichment, air flow rate was varied from the lean flammability limit to $\Phi=1.2$. Burner performance was quantified by combustion completeness, outlet temperature, and lean flammability limit.

Figure 2 shows the percentage of fuel which is consumed before the outlet. At low equivalence ratios, that is, fuel lean, the increased hydrogen addition increases the percentage of fuel consumed. The increased hydrogen also reduces the lean flammability limit. Without hydrogen added, combustion is not sustained at flames leaner than 0.42 equivalence ratio, while mixtures containing 1% and 10% hydrogen by mass burn as lean as 0.35 and 0.10 equivalence ratio respectively. This enhanced lean burning provides increased control of the burner, improving operational flexibility. At higher equivalence ratios, passing into the stoichiometric and fuel-rich condition, hydrogen addition reduces the amount of JP-8 consumed.

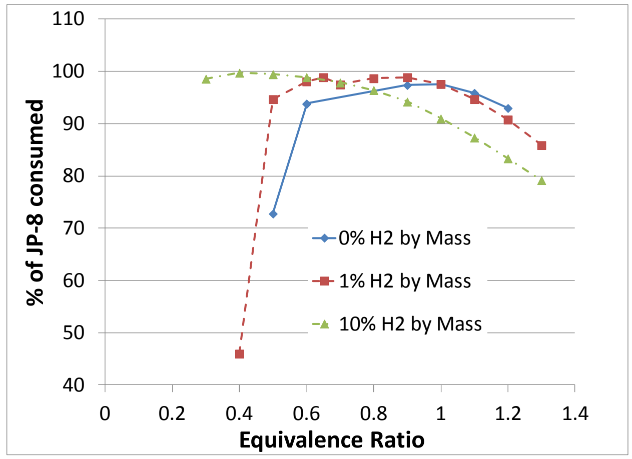

Figure 2. Combustion completeness with pure hydrogen dual-fired with JP-8

These simulations show benefits to dual firing JP-8 with pure hydrogen. A JP-8/hydrogen mixture with 1% hydrogen by mass is 46% hydrogen by volume while a JP-8/hydrogen mixture with 10% hydrogen by mass is 90% hydrogen by volume. It may also be advantageous to examine less pure hydrogen streams. In general, fuel reformers do not produce pure hydrogen without additional purification, adding size and power consumption.

Additional simulations were conducted using data from an autothermal reforming system to supply a realistic fuel reformate stream as the source of hydrogen. The data is based on a representative autothermal fuel reformer using a steam to carbon ratio of 2.0 and an oxygen to carbon ratio of 1.05. Using this reformer, 6 ml/min of JP-8 produces 30 standard liters per minute of reformate. This stream contains the following:

Table 1. Autothermal reformer product components

Species	H_2	N_2	CO	CO_2	CH_4
% Volume	32	43.9	12	12	0.1

In these simulations, the reformate stream was introduced at the air inlet. Levels of enrichment were identified based on the fraction of fuel diverted to create the reformate stream.

The combustion completeness of dual fired JP-8 and reforming product is shown in Figure 3. The effect of added hydrogen is still present when it is diluted by other reformate components. Again, at lean conditions, diverting fuel to the reformer leads to increased

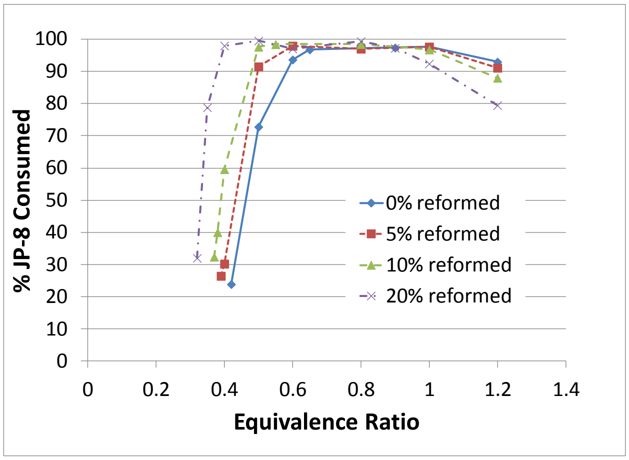

Figure 3. Combustion completeness with reformed JP-8 dual-fired with JP-8. The percentages indicate the percent of JP-8 that passed through a fuel reformer before entering the combustor

combustion and flame stability, extending the lean flammability limit. The more fuel is reformed prior to the combustor, the more fuel is consumed. At fuel rich conditions, reforming part of the fuel reduces the amount that is actually consumed.

The use of reformate also reduces the lean flammability limit. Without reformate added, combustion is not sustained at flames leaner than 0.42 equivalence ratio, while reforming 5% burns as lean as 0.4, and 10% burn as lean as 0.37 equivalence ratio. Flames using 20% reformed fuel burn as lean as 0.32 equivalence ratio.

The improved operation at lean conditions allows greater operational flexibility and the opportunity to reduce pollutant emissions.

Figure 4 shows the temperature profiles of the four levels of fuel reforming (0, 5, 10 and 20%) at the leanest equivalence ratio that each will sustain near complete combustion. At 5% fuel reforming, the higher temperature region is slightly larger than the flame without reforming. At higher levels of fuel reforming (10 and 20%), a leaner flame is sustained. Figure 4c and 4d show the lower temperature burning which is possible under leaner conditions. This provides greater flexibility in combustion control.

Figure 5 shows the axial temperature distribution for the same lean flames as Figure 4. In each case, there is a peak temperature followed by a gradual decline down the length of the combustor. Higher levels of fuel reforming move the peak to the left of the graph, or earlier in the combustor, and reduce the downstream temperature and lowering the overall average temperature. In principle, lowering the average temperature and shortening the peak temperature region should be expected to suppress the formation of thermal NO_x.

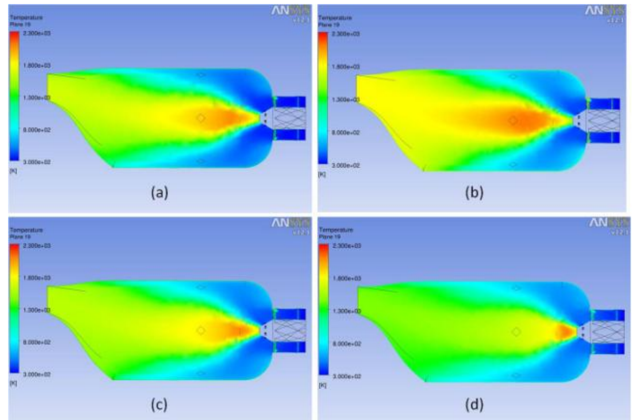

Figure 4. Temperature profiles of flames at the leanest equivalence ratio that will sustain a quality flame (>95% burned). A) no reforming, equivalence ratio 0.6, b) 5% of fuel reformed, equivalence ratio 0.6, c) 10% of fuel reformed, equivalence ratio 0.5, and d) 20% of fuel reformed, equivalence ratio 0.4.

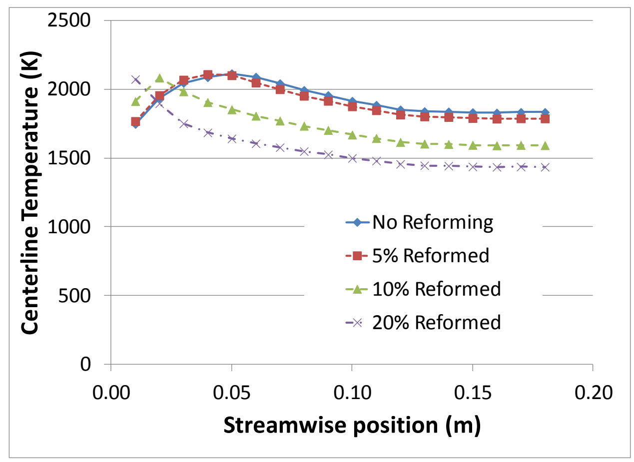

Figure 5. Axial temperature distribution in the leanest case allowing full combustion for each level of reforming: With no reforming, this lean equivalence ratio is 0.65, for 5% reformed it is 0.6, for 10% it is 0.5 and for 20 % reformed it is 0.4

Discussion

There is a contrast in the performance of dual firing hydrogen (or reformate) with JP-8 at fuel-lean and fuel-rich conditions. The hydrogen provides a benefit in the lean, but not the rich condition. In lean burning, a well mixed flame has enough oxygen to complete the combustion of all the components; however, the additional mass of air dilutes the thermal energy, lowering the temperature. The reduced temperature slows the reaction kinetics and reduces the number of reactive radicals present in the mixture.

The faster kinetics of hydrogen provide heat, energy and radicals to continue the JP-8 reaction. The results show that this increases the flame stability, particularly in lean flames with lower temperatures. Increased flame stability could provide improved temperature control. The increased flame stability also helps to insure complete combustion of the JP-8, improving fuel efficiency and reducing emissions.

The temperature profiles demonstrate the flame stability of hydrogen or reformate enhanced flames at lower temperatures. Lower temperatures or reduced time at high temperatures are a major method of pollutant control, particularly for NO_x. Many external combustion driven systems such as thermoelectric generators, have specific hot side temperature requirements. The improved lean-flame stability can widen the range over which the temperature can be controlled.

JP-8 has high volumetric energy density, but is composed of relatively complex hydrocarbon chains which give it slower combustion kinetics than lower order hydrocarbons. Hydrogen has fast and simple combustion kinetics, but has very low volumetric energy density. This research indicates the possibility of combining the benefits of both fuels by adding a small amount of hydrogen to JP-8 combustion.

Summary

The simulations completed in this research demonstrate the feasibility and benefits of using hydrogen or reformed fuel as a supplement to JP-8 in an external combustion based power application. Small amounts of hydrogen or reformed JP-8 at lean conditions provide good improvement to the flame stability and combustion completeness, improving fuel efficiency and reducing emissions. The enhanced combustion is due to the higher reactivity of hydrogen, improving the thermal environment and increasing radical concentrations. The improved stability allows more flexible flame control for better power system performance and operational flexibility. Given the success of this research, experiments will be conducted to more fully understand the impact of hydrogen on flame controllability, combustion completeness and pollutant formation. It is also possible that additional advantages can be gained by fuel staging and other methods of introducing the reformed fuel. Further investigation is also warranted in optimizing the weight and power cost of the reformer with the performance improvement of the burner.

Acknowledgement

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