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Impact of H_2 addition on flame stability and pollutant emissions for an atmospheric kerosene/air swirled flame of laboratory scaled gas turbine

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ARTICLE INFO

Article history:
Received 4 December 2008
Received in revised form
23 February 2009
Accepted 24 February 2009
Available online 5 April 2009

Keywords:
Laboratory turbine
Scaled burner
Kerosene
Hydrogen
Premixed combustion
Combustion stability diagram
Flame structure
Pollutant emissions

ABSTRACT

The purposes of this study are to compare the stability domains and the pollutant emissions when combustion occurs with and without addition of H_2 to a kerosene (Jet A1)/air premixed prevaporised mixture injected in a lean gas turbine combustor. Chemiluminescence of CH*, pollutant emissions (NO_x and CO) and pressure fluctuations data are simultaneously collected in order to determine the effects of H_2 addition on the stability of the combustion and on the flame structure for an inlet temperature of 473 K, atmospheric pressure and for a large range of equivalence ratio (from 0.3 to 1). Addition of hydrogen enables keeping stable combustion conditions when, for the same kerosene mass flow, the flame becomes lifted and very unstable. As for pollutant emissions, results show that the equivalence ratio is the key parameter to control NO_x emission even in the situation where the combustion power is increased due to H_2 addition. As H_2 addition strongly increases the flammability limits and the combustion stability domain, stable combustion can occur at leaner equivalence ratio and then decreases CO and NO_x emissions. This is an important fact since no substitution effect takes place in the reduction of NO_x and CO emissions. Study at constant combustion power and equivalence ratio by adjusting hydrogen and kerosene mass flow shows again a decrease in the pollutant emissions. Hydrogen injection in power generation systems using combustion seems to be a promising way in combustion research since due to the combined effects of enlarging combustion stability domain and reducing NO_x emissions by substituting kerosene to the benefit of H_2.

1. Introduction

The strong dependence (of industry and financial places) on kerosene or oil, the increase of these costs coupled with the thinning down of hydrocarbons fossils resources and reduction of pollutant emissions limits, such as NO_x, CO or soot tend to decrease the use of fossil hydrocarbons. This is the beginning of a new research phase in the combustion domain and more precisely in the aircraft combustion.

In the objective aiming at reducing NO_x, CO emissions and reducing use of fossil oil, aircraft industry develops several strategies: injection, chemical and fuel strategies.

Injection strategies are based on an improvement in the atomization efficiency. At the moment there are two technologies of injectors. The first one, called ''air blast injector'',

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0360-3199/$ – see front matter
doi:10.1016/j.ijhydene.2009.02.059

needs high values of air velocity compared to the fuel velocity to atomize the fuel. The second one, called "mechanical injector" uses a pressurised tank of fuel. The fuel under pressure is then injected in the combustor via the very short outlet section of the injector (less than 1 mm diameter). This sudden widening of the section leads to atomise the fuel. This second type of injector is the most employed. A new injection system is expected to be most used: the multi staged systems. Their efficiency is ensured thanks to the possibility of modifying the fuel injection repartition according to the desired operating conditions. Nevertheless, all these technologies are used under conditions near from the stoichiometry, which lead to produce NO_x emissions but with few CO and unburned hydrocarbons.

Chemical strategies are also used to strongly reduce these NO_x emissions rates and one promising way is to burn in lean conditions thanks to LPP (Lean Premixed Prevaporized) burners. This way has been used to strongly decrease the thermal NO_x. Lean combustion which is currently developed to reach the NO_x emissions reductions targets, leads to instabilities combustion which are not acceptable in the operating conditions [1–4].

The last strategy deals with fuels. Nevertheless, the course of the drastic reduction of CO_2 emissions can be made only in replacing a fossil fuel by a fuel not containing carbon [5–7]. In that sense, hydrogen is one of the possible ways considered to date. Although an aircraft fully propelled by hydrogen is not a realistic objective for at least several decades because of technical difficulties (such as hydrogen production that could cover the whole growing aircraft traffic or developing new materials that could resist to the high temperature of the hydrogen combustion in the max take-off phase), introducing small amount of hydrogen in the kerosene combustion seems to be nowadays a promising way for these three points:

- pollutant emissions reduction,
- decrease of fossil hydrocarbons' use to the profit of cleaner sources of energy production,
- improvement of re-ignition efficiency in high altitude.

The solution investigated in this paper considers the last strategy, where gaseous hydrogen is injected in a prevaporized kerosene/air mixture.

As far as we know, very few experiments or numerical simulations have been performed to demonstrate the interest of H_2 addition in kerosene/air mixtures for aeronautical approaches, even if the effects of hydrogen onto gaseous fuel/air mixtures have been already demonstrated.

A study concerning injection of hydrogen in a gaseous methane/air mixture has proved that stable combustion domain is extended towards the lean limits without hydrogen addition [8].

Similarly, the effect of hydrogen injection on propane/air combustion in a gas turbine has been investigated [9]. The authors found that hydrogen injection tends to decrease pressure fluctuations amplitude but increases CO emissions. Nevertheless, from these measurements burnt gas are not diluted in their case that can lead to difficulties in pollutant emissions measurements.

An experimental set-up operating with liquid kerosene has been tested with an air blast atomizer [10]. They found that the blow-off limit of the flame shifts to the lean side of the air–fuel mixture in the hybrid combustion. Hybrid combustion results in a slight decrease in NO_x emission and a remarkable decrease in soot emission. When hybrid ratio ($m_{H_2}/m_{kerosene}$) is under 10%, the flame stability is improved by the hybrid combustion. Increasing the hybrid ratio from 10% to 50% produces an increase in combustion efficiency and reductions of soot and NO_x. While the hybrid ratio is over 50%, the characteristics of the hybrid combustion flame become similar to those of hydrogen gas flame

Experimental studies are also needed to study hydrogen injection in a kerosene/air flame in complex flow configurations, such as high turbulence level, swirling flow, two-phase flow and dilution air which are representative of realistic conditions in the aircraft engines.

A feasibility analysis of hydrogen as additional fuel has already been done [11]. A commercial aircraft configuration is considered in the long and very long-range class (30% of the airlines representing 25% of the reservations). A study based on hydrogen addition in the kerosene/air combustion has been carried out and the results show a gain on total weight of fuel loaded in the aircraft for the same conditions of power during the maximum take-off phase and for the same distance of fly. A decrease of gas combustion temperature at the outlet of the combustion chamber (in the cruise and take-off phases) has been observed. The decrease of specific fuel consumption becomes more important when high mass fraction of hydrogen is injected: almost 16% for 10% of hydrogen (mass fraction) and for a same total mass fuel (for different hydrogen introduction) the more hydrogen is injected and the longer the fly-distance can be.

The aim of this study will be to characterize the effect of hydrogen addition to a kerosene (JET A1)/air mixture in terms of flame stability and pollutant emissions. First, the results concerning the combustion diagram in terms of stability domain are displayed. Then, the flame structures and the spectral densities of frequencies occurring during combustion are linked in the combustion diagram in order to characterize the impact of hydrogen addition. Finally the measurements of pollutant emissions, i.e. CO and NO_x, will be discussed with respect to the hydrogen injection rate and to the operating conditions in the gas turbine combustion chamber.

2. Laboratories & experimental apparatus

2.1. *Scale gas turbine*

The experimental apparatus is a laboratory scale gas turbine combustion chamber [12–15] in a LPP configuration (Fig. 1). Thanks to electrical heater ($P = 2$ kW) the primary air can be heated up to 473 K. In this study fuel injection is realised thanks to an oil nozzle (DANFOSS 030F7912, 0.6 US Gal/h – 60° – S). Combustion air is swirled by means of a radial swirler composed of 6 channels inclined by 45° (Fig. 2). The Swirl number, S_n, based on the following relation is estimated to 1.74: