IMPACT OF HYDROGEN ADDITION ON THE THERMO-ACOUSTIC STABILITY OF A METHANE FUELLED MICRO GAS TURBINE

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Abstract

In recent years great efforts have been made on the use of hydrogen (pure or mixed with standard hydrocarbons) as a fuel in combustion systems, in order to enable a greater penetration of renewable energy sources in the actual energy mix. In this context, micro gas turbines (mGT) are an emerging technology for achieving an efficient cogeneration of heat and power (CHT) considering their higher efficiency, flexibility and environment friendliness. Unfortunately, although these systems can be designed to operate with different fuels (natural gas, syngas, biogas, etc.), the substitution in fuel composition may lead to the onset of unwanted phenomena such as thermo-acoustic instabilities which limit system stable operation and raise safety problems. To prevent these damaging events, it is essential to be able to predict the onset of such instabilities at the design stage. In the present study, the impact of hydrogen addition on the stability map of a typical mGT, i.e., the AE (ex Turbec) T100, is numerically investigated. The results show that the introduction of hydrogen in the mixture leads to an increase in instabilities in the combustion chamber.

Introduction

The production of CO_2 is strongly related to combustion processes involved in transportation, industry, heating applications, and power generation sectors. The current energy generation and supply system must support the growing demand for a drastic reduction of CO_2 emissions. In the future power generation market, the trend is shifting toward decentralized power generation technology. Micro gas turbines currently represent the most promising technology in order to decentralize power generation. Integration of green hydrogen in micro gas turbines (mGT) will encourage the upcoming energy transition. However, the hydrogen enrichment in gas turbine burners might cause the displacement of combustion instabilities. Combustion instability is a physical phenomenon that happens during the combustion process due to the interaction between acoustic waves propagating inside the combustion chamber and thermal release fluctuations. Even if there is an increasing number of experimental and numerical studies on gas turbine burners fueled by pure hydrogen and methane-hydrogen blends, the investigations on the thermoacoustic behavior of these mixtures are very few. On the numerical level, a linear analysis of the flame acoustic perturbation and a detailed modeling of the acoustic damping of the system is required in order to predict correctly the thermoacoustic behavior of burner designed for methane-air mixture in case that hydrogen is used as fuel. Three basic methods, low-order numerical models, CFD (Computational Fluid Dynamics) models, and Helmholtz solver models, are used to examine thermoacoustic instability. Low-order models divide the thermoacoustic system into a network of basic acoustic domains (such as pipes, burners, flames, etc.), where the acoustic field is modeled as a Helmholtz equation solution [1] [2]. CFD methods (for example, soling RANS, URANS, and LES techniques) allow for a more realistic characterization of the thermo-fluid dynamic flow fields inside the combustor; nevertheless, this comes at a significant computational cost [3] [4]. By using the Fourier transform, Helmholtz solvers are used to translate time domain-based differential equation problems into eigenvalue issues in the frequency domain [5] [6]. Simulations based on Helmholtz solvers offer the possibility to account for the real geometry of the burner with the fluid-dynamic properties obtained by CFD simulation. Indeed, this approach requires information on the heat release, time delay, flow field, pressure, and temperature distribution, in order to correctly model instabilities during the combustion process. This method has not been frequently utilized to calculate instabilities within mGT burners.

In the present study the thermoacoustic influence of hydrogen as a component of a mixture with hydrocarbons, in micro gas turbine burners has been presented. Specifically, the AE T100 combustor has been used as a case study. Indeed, this mGT was designed to work with only methane. With the aim to adapt these machines to work with methane/hydrogen blends for the energy transition phase, it is important to understand their thermoacoustic behavior caused by hydrogen enrichment. In this framework, this study presents a thermo-acoustic stability analysis of the AE T100 combustor. In details, RANS simulations have been carried out on the combustor fueled both by methane and methane enriched with hydrogen at 30%v (on volume basis). The results from CFD simulations have been used in a Helmholtz solver in order to understand the influence of hydrogen addition on the thermoacoustic stability map of the combustor.

Geometry AE-T100

The geometry of combustion chamber of the AE-T100 [7] [8] [9] investigated in this study is shown in Fig. 1. Combustion air enters in counter-current in the gap between the outer casing and inner walls. A portion of air reaches the pilot injector through the 12 jet holes of swirler 1 consumed in diffusion mode. The 15 radial vanes of swirler 2 and 30 jet holes of swirler 2', allow residual air to mix with the main fuel resulting in a premix flame. At the exit of the combustor, burned gasses are diluted with fresh air coming through dilution holes to reach the desired turbine inlet temperature (TIT) of 950°C.

CFD simulations of AE-T100

In the RANS study on the burner of AE-T100, the aim is to develop the field of fluid-dynamic quantities in order to use it in the thermoacoustic simulations, as well as studying the impact of increase of hydrogen in the fuel blend. Starting with a constant air flow rate of $\dot{m}_{air} = 690\ g/s$ and a constant thermal power of $P_{th} = 333\ kW$, the fluid-dynamic parameters of RANS simulations for the two mixtures are set. The parameters of the analyzed cases are summarized in Table 1.

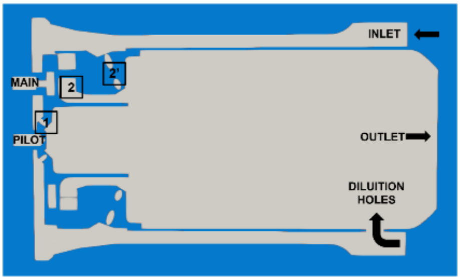
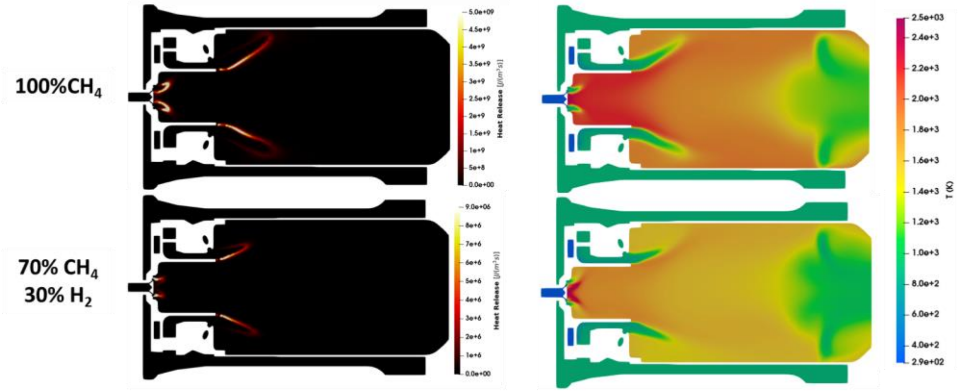


Figure 1. Burner geometry of AE-T100: (a) Fuel injection system main and pilot through plane highlighting the counter-flow air inlet, the pilot (1) and main (2,2') swirlers, and the dilution holes.

Table 1. Parameters of CFD simulations of AE-T100.

Parameters	100 % CH_4	70 % CH_4 + 30% H_2	Units
T_{air} = air inlet temperature	300	300	K
Ø = equivalence ratio	0.38	0.31	-
$\dot{m}_{fuel}$= mass flow	6.65	6.20	g/s
p = pressure	$4 \text{ x } 10^{-5}$	$4 \text{ x } 10^{-5}$	Pa
LHV=lower heating value	50.1	53.7	kJ/g

The 3D RANS CFD simulations on the burner of AE-T100 have been carried out by means open source code OpenFOAM. The reactingFoam solver has been used to perform reacting flow simulations. The turbulence model employed was the k-ε model. For all mixtures, the simulation of the AE-T100 burner has been performed by using the GRI-mech 3.0 chemical mechanism that consists of 53 chemical species and 325 reactions. Fig. 2 shows the results of this analysis in terms of contours of heat release rate (Fig. 2(a)) and temperature (Fig. 2(b)) in the combustion chamber of AE-T100 fueled by pure methane and 70%$_v$ CH_4-30%$_v$ H_2 mixtures. The hydrogen-enriched flame is shorter with respect to pure methane flame of burner fueled by pure methane, due to the higher burning velocity of the hydrogen. The temperature distribution is clearly influenced by the addition of hydrogen in the mixture: particularly, a higher temperature peak is observed close to the pilot flame whereas the temperature slightly drops further inside the combustor as shown in Fig. 2(b). This may be explained by the fact that in the two cases the air mass flow rate and thermal power are kept constant resulting in a leaner mixture characterized by a lower adiabatic flame temperature.



(a) (b)

Figure 2. Contour on Longitudinal Plane for two mixture (100% CH$_4$ and 70%$_v$ CH$_4$ -10%$_v$ H$_2$): (a) Heat release, (b) temperature.

The thermo-acoustic model

For the thermo-acoustic analysis, only the combustion chamber and pilot duct were considered, as the area variation between the swirlers/injectors and dilution holes was deemed sufficient to achieve acoustic decoupling. The inlet sections are considered to behave like a hard-acoustic walls (u'=0), while a pressure node (p'=0) is imposed at the outlet section of the combustion chamber.

The thermo-acoustic stability study was performed using the Acoustic Pressure and Frequency Domain model in COMSOL Multiphysics. This solves the acoustic differential equations problem converting it into a eigenvalues problem in the frequency domain. Three-dimensional mean fields of speed of sound and density are taken from CFD simulations. In the frequency domain, in the case of small perturbations, the local flame response to an acoustic perturbation can be represented by the Flame Transfer Function (FTF). This is a complex function that depends only on the excitation or angular frequency $\omega = 2\pi f$, where f is the frequency. This function is defined as the ratio of the heat release rate fluctuation $\hat{\dot{Q}}(\boldsymbol{x})/\bar{\dot{Q}}(\boldsymbol{x})$ to the velocity fluctuation $\hat{u}(\boldsymbol{x})/\bar{u}(\boldsymbol{x})$ taken at a reference position i:

$$\frac{\hat{\dot{Q}}(\boldsymbol{x})}{\bar{\dot{Q}}(\boldsymbol{x})} = FTF\,\frac{\hat{u}_i(\boldsymbol{x})}{\bar{u}_i(\boldsymbol{x})} = nexp(-i\omega\tau)\,\frac{\hat{u}_i(\boldsymbol{x})}{\bar{u}_i(\boldsymbol{x})}$$

where n is the gain factor and τ the time delay between the two fluctuations, and **x** is the spatial coordinate. In the present work, only dynamics of the main flame is considered. The time delay was computed using a particle tracking technique: released at the exit of main swirler (reference location i), particles are tracked and a mean convective time computed until the flame front is reached. The value of this time was set equal to 7 ms and 2 ms in the pure methane and methane/hydrogen case, respectively.

Results

Results from the linear stability analysis show that when adding hydrogen, the system becomes more instable (see Fig. 3 and Table 2).

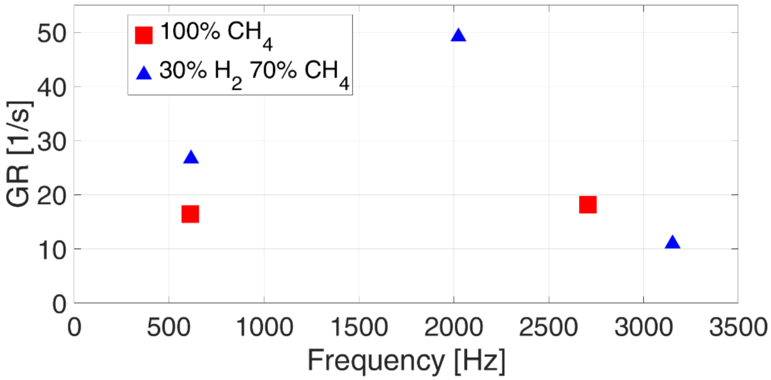
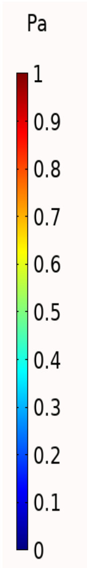
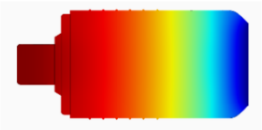
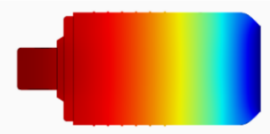
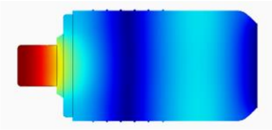
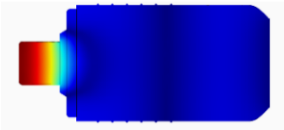
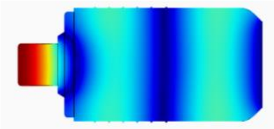


Figure 3. Frequencies and Growth Rate for the AE-T100 burner fueled by three different mixtures.

The first mode at 600 Hz is more unstable observed when hydrogen is injected. The modes of the burner, in each case, are longitudinal. In particular in the burner fueled by pure methane the first mode is a mode of the combustion chamber and the second is related to the pilot chamber. When hydrogen is injected, the second mode of the methane case is split into two modes for the combustion chamber. These differences are due to the different flame shape of the two mixtures, which result in a difference in the convection times of the burner operating with the two different mixtures. This causes a different iteration between velocity and heat fluctuations within the burner. In the future, the development of the Flame Transfer Function, in order to forecast in a more precise way the thermoacoustic response of these burners, may be appointed.

Table 2. Acoustic pressure between the burner fueled by two mixtures for first longitudinal e fourth azimuthal mode. In particular, an increase of the growth rate of

100% CH_4	70% CH_4+30% H_2	
611.18+16.45 [Hz] 	615.22+26.63 [Hz] 	
	2024.35+49.13 [Hz] 	
2705.92+18.63 [Hz] 	2781.18+10.96 [Hz] 	

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