THE EFFECT OF HYDROGEN ENRICHMENT ON SATURATED OSCILLATIONS AMPLITUDE IN A SIMPLE THERMOACOUSTIC SYSTEM

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Abstract
The use of hydrogen to enrich or replace hydrocarbons–based flames represents an appealing perspective to reduce the emission of pollutants in gas turbine combustors. This implementation is, however, not straightforward, as the properties of hydrogen consistently differ from those of the most widely used gaseous fuels, resulting in a change in the characteristics and stability of the combustion of the mixture. The present paper investigates, by the means of a Reduced Order Model, the non–linear stability of a simple thermoacoustic system composed of a perfectly premixed, laminar, conical flame enclosed in a Rijke tube, and fuelled by two different mixtures, a pure methane–based mixture and a hydrogen–enriched one. For both mixtures the mean heat release rate of the flame was kept constant, and a Flame Describing Function was derived making use of a Level Set Method, allowing to confirm a direct connection between the hydrogen enrichment level of the mixture and the reduction in the non–linear properties of the corresponding flame dynamics. Stability was assessed using the position of the flame holder as a control parameter. The hydrogen–enriched system was proven to achieve, without the need of any major triggering perturbation, limit cycle oscillations of larger amplitude than the pure methane case – eventually resulting in flame flashback –, thus manifesting a greater tendency to jeopardize the operation of the combustion chamber.

Case study, modelling, and results
The case study consists of a Rijke tube confining a perfectly premixed, laminar, conical flame, analogous to the one analysed in **[1]**. The total length of the chamber is $L = x_1 + x_2 = 3$ m, and its radius is $r = 0.11$ m. Ambient conditions are used at the inlet to define temperature and mean pressure in the region upstream the flame, $T_1 = 293$ K, $\bar{p}_1 = 1$ atm. Two mixtures with different hydrogen enrichment levels but identical equivalence ratio ($\phi = 1.08$) are considered. The hydrogen enrichment level is described by the means of the parameter $\chi = X_{H_2}/(X_{H_2} + X_{CH_4})$, where X is the mole fraction, that is varied from 0 to 0.8, causing the growth of the laminar flame speed of the mixture from 0.3859 to 1.2175 m/s **[2]**. The temperature downstream of the flame T_2 is supposed to not modify either in space or in time, and a mean isobaric heat capacity is considered to be representative in the temperature range envisaged

in this work. The perfect gas law is held to be valid. For the methane–based mixture, the mean inlet velocity is $\bar{u}_1$ = 2.12 m/s and T_2 = 1000 K, while for the hydrogen–enriched one $\bar{u}_1$ = 2.22 m/s and T_2 = 1018 K. In both cases, the same mean heat release rate is attained. The inlet and outlet reflection coefficients for the acoustic boundaries of the chamber are both fixed to -0.99.
As the length of the combustion chamber is much greater than its transversal dimension and laminar burners operate at low Mach numbers, a linearised one–dimensional model is used to describe the acoustics **[3]**. This allows decomposition of every fluid dynamic variable into mean and fluctuating components, and to express the latter in the form of superposition of two waves propagating downstream and upstream the ducts of the chamber. At the flame position, with the assumption that the flame is compact, a relationship among the fluid dynamic variables is provided by linearisation of the quasi–one–dimensional Euler equations in the low Mach number regime **[3]**. The flame is supposed to be perfectly premixed, and it is hence assumed to be solely velocity sensitive. A non–linear model for the combustion dynamics is provided by the kinematic level set method of the *G*–equation **[1-4]**, which allows tracking the evolution of the flame front under the effect of a general upstream velocity perturbation. For laminar flames, the flame front area *A(t)* is assumed to be proportional to the heat release rate $\dot{q}(t)$ **[1-4]**, allowing to connect velocity perturbation to heat release rate perturbation. The perturbation component of the velocity vector is derived from the acoustic velocity fluctuation upstream of the flame making use of the incompressible–convective model **[3]**. The *G*–equation was solved using an in–house numerical code, whose results have been validated by comparison with both numerical and experimental data. Both flames were forced up to a maximum perturbation amplitude equal to half the value of the respective mean flow velocity. This figure corresponds to the lowest perturbation amplitude at flashback of the two flames (that of the hydrogen–enriched one). A summary of the results is presented in Fig. 1 in terms of gain of the Flame Describing Function (*FDF*) **[1-4]** of the two mixtures for different values of a, the ratio of the perturbation amplitude to the mean flow velocity.

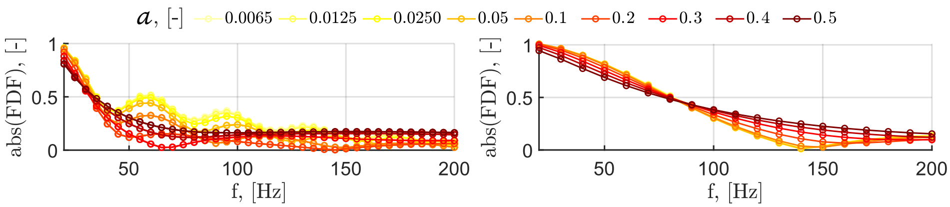

Figure 1. *FDF* gain of the methane (left) and hydrogen (right) flames.

The broadening of the range of the perturbation amplitude with respect to the case study of **[2]** allows to confirm that hydrogen enrichment results in a reduction in the non–linear behaviour of the flame. This behaviour is crucial to determine the final state of the system. Once an unstable thermoacoustic mode is triggered, the growth of the oscillations is limited by the fact that, as their amplitude increases, the gain and phase shift of the *FDF* reduce until the heat release response saturates, the growth rate of the mode reaches a null value, and saturated amplitude oscillations establish **[3, 4]**. If the gain and phase shift of the *FDF* remain relatively unchanged in response to increasing acoustic perturbations, the propensity for the heat release rate to reach saturation might be diminished. Hence, acoustic perturbations of substantial magnitude might be required to achieve heat release rate saturation, resulting in a limit cycle of great amplitude. To address this hypothesis, the expression of the *FDF* is plugged into the acoustics, and the stability of both systems is readily assessed **[1, 3, 4]**. The morphology of the resulting stability maps (Fig. 2) can be put in analogy with that of the *FDFs* of the mixtures. The gain of the methane–based *FDF* displays an extremely jagged appearance (featuring numerous peaks and drops along the frequency axis and increasing the perturbation amplitude) the pattern of which is reflected in the shape of the associated stability map – with several unstable zones distributed in the *a*–*f* plane. On the contrary, the FDF of the hydrogen–enriched flame features a less elaborated shape, resulting in fewer changes in the stability of the system. Accordingly, whereas a multitude of stable limit cycles are encountered for the methane–based system, the hydrogen–enriched system presents vast regions for which instability does not need to be triggered by consistent disturbances, and no stable limit cycles are found in the perturbation amplitude range considered in this work, ultimately resulting in flashback and combustor impairing.

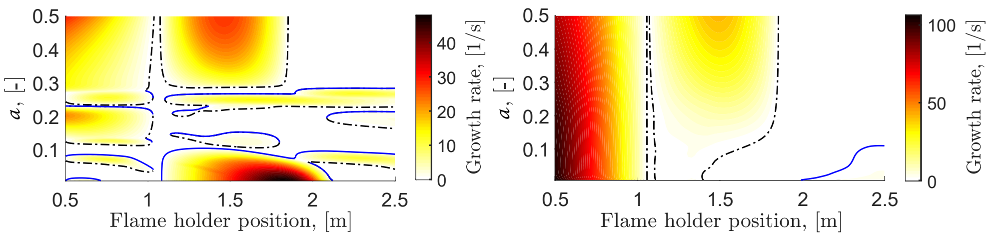

Figure 2. Stability map of the methane (left) and hydrogen (right) systems. Only positive growth rates of the first two modes are presented. Stable limit cycles are indicated by blue continuous lines, unstable ones by black dotted lines.

References

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