Numerical studies on the impact of equivalence ratio oscillations on lean premixed flame characteristics and emissions

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Abstract: In this work, the numerical investigation of laminar and turbulent one-dimensional lean premixed methane-air flames subject to equivalence ratio oscillations is presented. Harmonic perturbations at various frequencies and with various amplitudes are regarded and their influence on CO and NO emissions, heat release fluctuations, and burning velocity is evaluated. The results indicate a strong non-linear behavior of the flame response for high forcing amplitudes attributed partly to the extension into the stoichiometric and rich combustion regime and partly to non-linear effects imposed due to the interaction of burning velocity and equivalence ratio oscillations. Furthermore, the turbulent considerations expose decreasing mean burning velocities and heat release rates with increasing amplitudes due to damping of turbulent fluctuations induced by the oscillations.

1 Introduction

Lean premixed combustion is used in gas turbine processes being able to operate under moderate temperatures and reduce emissions, such as NO_x and CO. A major drawback of lean premixed flames, especially when turbulent, is their susceptibility to combustion instabilities.

Equivalence ratio fluctuations lead to heat release fluctuations and were detected by Lieuwen et al. as one of the major causes for combustion instabilities at lean conditions [1].

In the present work, we numerically investigate the influence of periodic equivalence ratio oscillations on one-dimensional lean premixed flames. We compare laminar and turbulent simulations and evaluate pollutant formations of NO_x and CO, heat release rate fluctuations, and species displacement speeds. The numerical method utilized for the studies is the one dimensional Linear Eddy Model [2].

2 Linear Eddy Model

In the LEM, molecular diffusion is implemented deterministically whereas turbulent stirring is given by a sequence of statistically independent rearrangement events, representing eddies. Each eddy is governed by three random variables: the location and the size of the eddy, and the time when the eddy occurs. The eddy size is determined from a distribution of domain sizes, $f(l)$, and the occurrence time is calculated from a Poisson distribution and a rate parameter, λ.

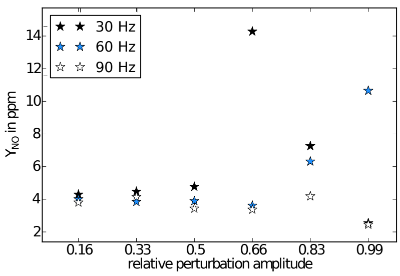
$$\lambda = \frac{54}{5} D_t L^{-3} \frac{\left[1-(\eta/L)^{-5/3}\right]}{\left[(\eta/L)^{4/3}-1\right]}, \qquad f(l) = \frac{-5/3}{L^{-5/3}-\eta^{-5/3}} l^{-8/3},$$

D_t ... turbulent diffusivity, L ... integral length, η ... Kolmogorov length.

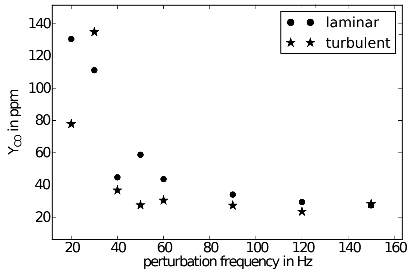
The model reproduces important key features of turbulent mixing [2] and proved itself to be a valid model in studies on various research fields, amongst them LEM simulations on turbulent premixed combustion and pollutant formation by Menon et al. [3].

3 Results

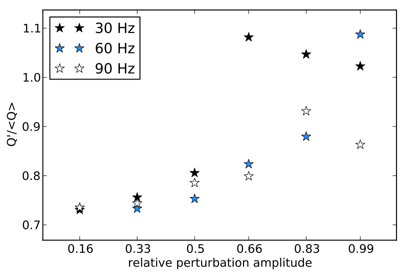
Equivalence ratio oscillations are studied as they may occur in gas turbines under combustion instabilities. A methane-air mixture with an equivalence ratio of 0.6 preheated to 425 K is investigated. The Kolmogorov and integral lengths were taken from measurements; their values are 1e-4 m and 0.025 m, respectively. The simulations are conducted for a frequency range of 20 Hz to 150 Hz and the amplitudes are varied in a wide range for representative frequencies. The flame response was characterized by evaluating NO and CO emissions, heat release fluctuations, and displacement speeds in dependence on forcing frequencies and amplitudes. The inflow velocity was set to the instantaneous burning velocity. It was found that emissions of NO as well as CO increase with forcing amplitude up to a certain value of forcing amplitude (Fig. 1(a)). This behavior correlates with the convex relation of NO and CO on the equivalence ratio. Laminar and turbulent simulations show the same tendencies although differences in absolute values and in the frequency dependence are present (Fig. 1(b)). Decreased NO and CO emissions for higher forcing amplitudes are caused by the complex interaction of burning velocity with equivalence ratio oscillation leading to non-linear effects. Fluctuations in the heat release rate exhibit an increase with amplitude and saturation for certain frequencies (Fig. 1(c)) which are attributed to equivalence ratio dependecies and the same non-linear effects as for the emissions. The mean displacement speeds were considered separately for reactants, products and the intermediate species NO. Quite different behavior is observed for the different groups. For the laminar case an increase of the reactants displacement speed, no distinct behavior for the products displacement speed and an increase in NO-displacement speed is found. The turbulent considerations expose damping of turbulent fluctuations in the displacement speed when forcing is applied which becomes more distinct with higher forcing amplitudes and lower forcing frequencies (Fig. 1(d)). This damping leads to a decrease of displacement speeds which superposes on the characteristics found for the laminar case. The burning velocity therefore decreases with forcing amplitude for the turbulent case which also results in decreasing mean heat release rates.



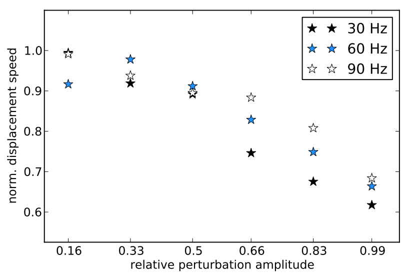
(a) NO mass fraction, turbulent



(b) CO mass fraction, laminar vs. turbulent



(c) Heat release fluctuation, turbulent



(d) Displacement speeds for CO_2 and H_2O, turbulent

Figure 1: Amplitude dependence of NO mass fraction (a), heat release fluctuations (c) and averaged CO_2 and H_2O displacement speeds (d) for turbulent simulations and frequency dependence of CO mass fraction for turbulent and laminar simulations (b).

References

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