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Response of curved premixed flames to single-frequency and wideband acoustic waves

Hemdan Shalaby [a,*], Kai H. Luo [a], Dominique Thévenin [b]

[a] Department of Mechanical Engineering, University College London, London WC1E 7JE, United Kingdom
[b] Lab. of Fluid Dynamics and Technical Flows, University of Magdeburg "Otto von Guericke", Universitätsplatz 2, D-39106 Magdeburg, Germany

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ABSTRACT

The dynamic response of a premixed curved flame interacting with sinusoidal acoustic waves has been numerically studied in the present work. Flame/acoustic interactions are particularly important both from a theoretical point of view and for practical purposes, as a possible trigger mechanism for combustion instabilities. Flames found in practical devices show a complex geometry, far from the planar configuration usually considered in theoretical studies. The particular purpose of the current study is to assess quantitatively the effects of acoustic waves on curved premixed flames, considering both single and wideband frequencies in order to mimic the conditions encountered in practical systems. The interaction process is studied by using Direct Numerical Simulation (DNS) including detailed physicochemical processes and differential molecular diffusion. The chemical reactions are modeled by a 25-step skeletal scheme involving 16 species to describe methane oxidation. The numerical results show strong flame front oscillations back and forth during interaction of the wave with the curved premixed flame. Moreover, the results demonstrate that a single-frequency acoustic wave has a magnifying effect on the preexisting wrinkling of the flame. This extending flame front leads to increasing fuel consumption rate. The effect is found to be maximum at an intermediate excitation frequency of 500 Hz. Interestingly, a wideband excitation from 100 to 1000 Hz leads to significant flame oscillation and the fuel consumption rate is highly increased in that case. As a whole, this study shows that curved flames are much more sensitive to acoustic excitations compared to planar flames, due to the baroclinic torque in combination with other inherent instabilities. An oblique acoustic wave has a similar but slightly enhanced disturbance to the premixed flame. Moreover, non-unity Lewis numbers have significant effects on curved flame-acoustic interaction, even in the present stoichiometric methane flame. However, it presented highly sensitive to the interaction.

1. Introduction

In practical applications, curved flames are the rule and planar flames the exception. This is also true even in simple configurations used for most fundamental studies. A simple premixed flame in a closed tube is a good example of the spontaneous formation of a curved flame due to various modes of instabilities [1–5]. One of the striking phenomena observed under such conditions is the well-known "tulip flame". Curved flames with a shape close to a tulip are found to be fully developed when taking into consideration flame-hydrodynamic interactions [6].

Curved flames of direct relevance for flame-acoustic interactions have been encountered for instance in the experiments by Searby [7], Searby and Rochwerger [8] and then explained analytically by Bychkov [9]. These studies have highlighted two key, competing effects for flame-acoustic interaction: (i) stabilization of the flame instabilities by acoustic waves of moderate amplitudes and (ii) excitation of the parametric instability at the flame front at higher acoustic amplitudes. Later experimental and theoretical works by Aldredge and Killingsworth [10] and Yáñez et al. [11] have built on top of these results. Violent folding of a flame front due to flame-acoustic resonance has been also predicted, obtained and studied by Bychkov [12] and Petchenko et al. [13,14]. Such a resonance may be responsible for the acoustic flame turbulization observed by Searby [7] or Aldredge and Killingsworth [10]. A review concerning premixed flames interacting with acoustic waves can be found in [15].

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* Corresponding author.

E-mail addresses: k.luo@ucl.ac.uk (H. Shalaby), k.luo@ucl.ac.uk (K.H. Luo), thevenin@ovgu.de (D. Thévenin).

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As a precious complement to experimental studies, Direct Numerical Simulations (DNS) combined with accurate physico-chemical models have been successfully used to study flame-acoustic interaction for premixed [16–18] as well as nonpremixed [19] flames, using different fuels (hydrogen [16,17,19] and syngas [18]). Such studies have delivered essential information to understand the coupling between turbulent flames and acoustic waves [20,21].

Teerling et al. [23] investigated numerically the response of slightly corrugated premixed flames to oscillatory pressure waves using single-step chemistry and unity Lewis number. They observed that the pressure waves can magnify the flame wrinkle due to the Rayleigh–Taylor instability. The present study is intended as an extension of the work by Teerling et al. [23], using more complex physicochemical models in addition to non-unity Lewis number in a DNS. It is important to check if the previous observations would be modified in that case, and how the curved flame will respond quantitatively to single and wideband acoustic waves. In order to isolate the acoustic effects, we study in the present work a curved flame interacting with acoustic waves in an open domain, avoiding any possible influence of solid walls. This interesting aspect of wall influence, obviously encountered in practical applications, will be the subject of future work. The DNS results can in particular be used to answer following questions:

- What is the qualitative response of the curved flame to single and wideband acoustic waves?
- What is the effect of the acoustic wave amplitudes on fuel consumption rate?
- What is the difference between the curved and planar flames with respect to the acoustic energy enhancement?
- What is the effect of an oblique acoustic wave compared with a planar wave disturbance on the curved flame?
- What is the effect of non-uniform Lewis number compared with unity Lewis number?

The rest of the paper is arranged as follows. The mathematical equations are presented in Section 2, followed by a description of the essential computational parameters in Section 3. The outcomes are shown and discussed in Section 4, before the conclusions are drawn.

2. Mathematical equations

In the present work, the employed DNS code is the parallel flame solver, *ParComb* [24–26], which solves the full compressible reactive Navier–Stokes system coupled with detailed chemistry and multicomponent transport models via coupling with the *chemkin* [27], *transport* [28] and *eglib* [29] libraries. Using classical notations [30–32] and ignoring all external forces, the conservation equations solved in *ParComb* are as follows:

Mass conservation

$$\frac{\partial\rho}{\partial t} + \frac{\partial(\rho u_j)}{\partial x_j} = 0 \tag{1}$$

Momentum conservation

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_j u_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}; \qquad i = 1,2,3 \tag{2}$$

Species balance

$$\frac{\partial(\rho Y_k)}{\partial t} + \frac{\partial[\rho(u_j + V_{kj})Y_k]}{\partial x_j} = \dot{\omega}_k; \quad k = 1, N_s \tag{3}$$

Energy conservation

$$\frac{\partial(\rho e_t)}{\partial t} + \frac{\partial[(\rho e_t + p)u_j]}{\partial x_j} = -\frac{\partial q_j}{\partial x_j} + \frac{\partial(\tau_{ij} u_i)}{\partial x_i} \tag{4}$$

Ideal gas law

$$\frac{p}{\rho} = \frac{R}{W} T \tag{5}$$

where ρ denotes mixture density, u_j the components of the hydrodynamic velocity, p the pressure, τ_{ij} the stress tensor, N_s the total number of species, V_{kj} the component of the diffusion velocity of species k in the direction j, $\dot{\omega}_k$ the chemical production rate of species k and q_j the jth-component of the heat flux vector.

The above system of governing equations, together with considered thermodynamical relations (e.g., the ideal gas law), chemistry and transport models described later are solved on a three-dimensional Cartesian grid with high-order numerical schemes. A sixth-order central scheme progressively reduced to a one-sided fourth-order scheme near the boundaries is used for spatial discretization. The improved skew-symmetric formulation [33] has been implemented for the convective terms in order to reduce numerical dissipation and increase stability. According to this scheme, the derivative of a general convective term can be written as:

$$\frac{\partial(\rho a u_j)}{\partial x_j} = \frac{1}{2}\frac{\partial(\rho a u_j)}{\partial x_j} + \frac{1}{2}\frac{a\partial(\rho u_j)}{\partial x_j} + \frac{\rho u_j}{2}\frac{\partial a}{\partial x_j} \tag{6}$$

Time integration is performed in an explicit manner with a fourth-order Runge–Kutta scheme, as implicit methods do not seem to be beneficial for the specific problems considered [34] and are difficult to parallelize efficiently. A Courant–Friedrichs–Levy (CFL) condition for the convective terms and a Fourier condition pertaining to the diffusion terms are treated to ensure the stability of the explicit integration and determine a suitable time-step. Boundary conditions are treated with the help of the Navier–Stokes Characteristic Boundary Condition (NSCBC) technique [41], extended to take into account multicomponent thermodynamic properties [35].

2.1. Chemistry

The resulting reaction rate comprising N_s species with an arbitrary number of elementary reactions N_r for reaction j is then the difference between the forward and backward rates, given (without third bodies) by

$$r_j = k_{fj}\prod_{i=1}^{N_s} n_i^{\nu'_{ij}} - k_{bj}\prod_{i=1}^{N_s} n_i^{\nu''_{ij}}, \qquad j \in [1, N_r] \tag{7}$$

where $n_i = \rho Y_i / M_i$ denotes the molar concentration of species i with k_{fj} and k_{bj} are respectively, while ν'_{ij} and ν''_{ij} are the forward and backward stoichiometric coefficient of the ith species in the jth reaction, classically expressed via the Arrhenius law [36]:

$$k = AT^{\beta}\exp\left(-\frac{E_a}{RT}\right) \tag{8}$$

The parameters A and β of the pre-exponential factor and the activation energy E_a are determined experimentally [36,37]. The two reaction constants are linked using the equilibrium constant $k_{j,eq}(p,T) = k_{fj}/k_{bj}$ which is suitably defined by the thermodynamic properties of the chemical components involved in the reaction.

Finally, the molar production rate of species i is given by taking the sum of all contributions from the elementary reactions:

$$\dot{w}_i = M_i\sum_{j=1}^{N_r}\nu_{ij} r_j, \qquad i \in [1, N_s] \tag{9}$$

where $\nu_{ij} = \nu'_{ij} - \nu''_{ij}$.

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