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A direct numerical simulation study of stretched laminar lean hydrogen-air flames

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ABSTRACT

Analyzed in the paper are data obtained in unsteady two-dimensional complex-chemistry Direct Numerical Simulations of (i) unstable lean (the equivalence ratio is equal to 0.35, 0.5, or 0.7) H_2 -air flames expanding in initially quiescent gas and (ii) counterflow twin laminar flames of the same mixtures. In the latter case, both natural development of instabilities without any imposed perturbation and flame response to large perturbations in the flow velocity or initial flame shape are explored. Time-dependent strain rates are also addressed. Results show that diffusional-thermal instability of lean hydrogen-air flames is suppressed by quite moderate (or higher) stretch rates (critical stretch rate normalized using flame time scale is substantially smaller than unity in all studied laminar flames). A higher stretch rate is required to stabilize a leaner flame. Computed values of critical strain rates that suppress instabilities of twin counterflow laminar flames (i) are weakly sensitive to time-oscillations of strain rate, (ii) are increased with increasing magnitude of inlet velocity perturbations, and (iii) are higher in the case of perturbation of flame shape when compared to perturbation of flow velocity. However, these variations in the critical strain rates are quite moderate even if perturbation magnitude is large.

Novelty and significance statement: Results of new unsteady two-dimensional complex-chemistry Direct Numerical Simulations of (i) unstable flame kernels expanding in initially quiescent lean H_2 -air mixtures and (ii) counterflow twin laminar flames of the same mixtures are reported. Diffusional-thermal instability is shown to be suppressed by quite moderate stretch rates. Computed values of critical strain rates that suppress flame instabilities remain low independently of perturbation type (upstream flow velocity or initial flame shape) and magnitude even if the perturbation magnitudes are high. The reported numerical results generate new fundamental knowledge about development of diffusional-thermal instability of stretched laminar premixed flames. These results and generated knowledge are significant for developing predictive models of turbulent combustion of mixtures susceptible to diffusional-thermal instability.

1. Introduction

Rapidly growing interest in sustainable transition to carbon-free fuels such as H_2 [1] strongly motivates research into diffusional-thermal instability of lean hydrogen-air laminar flames [2]. Direct Numerical Simulation (DNS) studies of such flames were performed by several research groups over the past decade, as reviewed elsewhere [3]. While those studies significantly advanced understanding

of diffusional-thermal instability of laminar flames in spatially uniform flows of unburned reactants, instability of stretched laminar flames has received less attention despite this problem is highly relevant to modeling turbulent combustion.

Indeed, first, positive stretch rates are known to statistically predominate in turbulent flows [4]. Second, theoretical studies of single-step-chemistry laminar flames characterized by asymptotically high

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activation energy have shown that instabilities of such flames are suppressed by strain rates in spatially non-uniform flows [5–7]. Third, suppression of laminar flame instabilities by turbulent stretch rates was recently hypothesized [8,9]. Accordingly, the issue of the influence of stretch rates on diffusional-thermal instability of a laminar premixed complex-chemistry flame is of great fundamental interest and of importance for developing high-fidelity models of turbulent burning of lean mixtures containing H_2 .

To the best of the authors' knowledge, numerical research into this issue was started quite recently [10] by running two-dimensional (2D) complex-chemistry simulations of lean H_2 -air strained laminar flames. The reported results showed that high strain rates stabilized laminar flames, but those simulations were restricted to a single mixture, a single flame configuration (reactant-to-product planar counterflow flame), and four strain rates. To lay a solid foundation for modeling interactions between flame instabilities and stretch rates in turbulent flows, research into instabilities of stretched laminar flames should be significantly extended. The present work responds to this call by reporting new numerical results obtained from two different configurations of lean H_2 -air laminar flames subject to various stretch rates and characterized by different equivalence ratios ϕ .

2. DNS databases

Unsteady 2D simulations of lean H_2 -air laminar flames were performed using solver PeleLMEx [11,12]. It employs the finite-volume method combined with the block-structured adaptive mesh refinement approach [13] to solve the reacting flow Navier–Stokes equations under low-Mach-number conditions. Since this well-established solver has been adopted extensively to simulate unstable laminar [14–18] or turbulent [15,17,19,20] flames propagating in boxes and lab-scale burners [21–24], detailed descriptions of the governing equations, numerical methodologies, and solver validation are not repeated here. The interested reader is referred to the cited papers.

The present simulations adopted a chemical mechanism by K  rom  n  s et al. [25] and a mixture-averaged transport model without Soret effect. It is worth noting that multi-component transport and Soret diffusion are known to quantitatively affect major characteristics of lean H_2 -air flames. For instance, Soret effect promotes laminar flame instability [26] and results in increasing burning rate [27]. However, the magnitude of such effects is moderate, and they do not change “qualitative observations” [27]. Since the focus of the present work is placed on qualitative trends and estimates, the aforementioned simplifications are invoked to reduce computational costs and explore more cases. These simplifications are not expected to alter major conclusions, especially conclusions drawn by comparing results obtained using the same model from different flame configurations.

Mixture characteristics, computed using open-source library Cantera [28] with the adopted transport model and chemical mechanism [25], are reported in Table 1, where S_L , $\delta_L = (T_b - T_u)/\max\{dT/dx\}$, and $\tau_f = \delta_L/S_L$ are unstretched laminar flame speed, thickness, and time scale, respectively; ϕ is the equivalence ratio; $\sigma = \rho_u/\rho_b$ is the density ratio; T is the temperature; subscripts u and b refer to unburned and burned gases, respectively. These three mixtures were explored because our previous DNS studies of turbulent flames [29–31] dealt with them. Critical stretched rates reported in the three rightmost columns in Table 1 will be explained in Section 3.

To explore the influence of different kinds of flame stretching on its instability, two canonical configurations were simulated, i.e., planar counterflow twin (reactant-to-reactant) flames and cylindrical kernels expanding in initially quiescent gas. The expanding flames are stretched not only by flow non-uniformities but also due to the flame curvature. In both configurations, the same grid size $\Delta x = 23.4 \mu m$ was adopted, e.g., about $\delta_L/40$ in case F035.

Simulations of the expanding flames were run in squares, with outflow boundary conditions, i.e., zero normal derivatives $\partial q/\partial n = 0$

Table 1

Characteristics of studied mixtures.

Case	ϕ	S_L , m/s	δ_L , mm	τ_f , ms	σ	Expanding		Twin
						$\tau_f K_S^{cr}$	$\tau_f K_S^*$	
F035	0.35	0.12	0.92	7.67	4.16	0.17	1.78	0.35
F050	0.50	0.58	0.41	0.71	4.95	0.09	0.55	0.17
F070	0.70	1.42	0.34	0.24	5.81	0.08	0.31	0.13

for various quantities q , being set on all sides of the computational domains. Three domain widths Λ were probed, i.e., $\Lambda = 4.8, 9.6$, or 19.2 cm. Since results computed at $\Lambda = 9.6$ and 19.2 cm are almost identical, the former results will be presented in the following. Initially, gas was uniform and quiescent, the pressure was equal to 1 atm, but the temperature was set equal to 2000 K in a centrally located circular hot spot and to 300 K outside of it. Flame instabilities developed naturally, i.e., without any initially imposed perturbation.

Radii $r_f(\theta, t)$ of expanding flames were computed for an iso-surface of $c(\mathbf{x}, t) = c^*$, where c^* was linked with the peak fuel consumption rate $\dot{\omega}_F^*$ in the unstretched flame. Here, θ is azimuthal angle. The effective flame radius is equal to $R_f = \sqrt{A_f/\pi}$, where A_f is the area enveloped by the flame circle. The flame speed $S_b = dR_f/dt$ and time t or stretch rate $K_S = R_f^{-1}dR_f/dt$ [32], reported in the following, are normalized using σS_L and τ_f , respectively.

Unsteady 2D simulations of the twin counterflow flames were run in a rectangular of $\Lambda \times \Lambda/2$. Here, $\Lambda = 9.6$ cm is distance between two identical nozzles, with the symmetry boundary condition being set at $y = \Lambda/2$. At the inlet ($y = 0$), the flow velocity was equal to $u_{in} = U + U' \sin(kx)$, where $U' = bS_L$ and $b = 0, 0.4, 1, 2$, or 4 . Thus, this study addresses not only natural development of flame instabilities triggered by infinitesimal perturbations ($b = 0$), but also response of strained lean H_2 -air laminar flames to significant velocity perturbations. At other boundaries, outflow conditions were used. In most simulations, initial conditions were set adopting steady one-dimensional (1D) strained laminar flame solution pre-computed using Cantera [28]. In some cases, the inlet velocity depended neither on x nor on time, i.e., $u_{in} = U$, but the initial 1D flame was wrinkled, i.e., $y_f(x, 0) = Y_f + \beta \delta_L \sin(k_0 x)$, where $\beta = 0.01, 0.08, 0.1$, or 0.5 . In all cases, the perturbation wavelength $k_0 \approx \delta_L^{-1}$, as the perturbation growth rates are highest at $k\delta_L \approx 1$ for the studied mixtures [3,10,30].

When simulating planar strained flames (1D or 2D), consumption velocity was evaluated as follows

$$S_c(t) = \frac{1}{\rho_u Y_{F,u} \Lambda^{n-1}} \int \dot{\omega}_F(\mathbf{x}, t) d\mathbf{x}, \quad (1)$$

where $n = 1$ or 2 in 1D or 2D case, respectively; Y_F is fuel mass fraction; and $\dot{\omega}_F(\mathbf{x}, t)$ is Fuel Consumption Rate (FCR). In the following, the 2D consumption velocity $S_c(t, K_g)$ computed at the bulk flame strain rate $K_g = 4U/\Lambda$ [33] will be normalized using the consumption velocity $S_c^{1D}(K_g)$ obtained from the stationary 1D strained flame subject to the same K_g . This rate and time t will be normalized using τ_f .

3. Results and discussion

3.1. Expanding flames

Fig. 1 shows evolution of the observed speeds S_b of expanding flames (the right end of a curve corresponds to the initial stage). In all cases, there is a local minimum of $S_b(K_S)$, followed by an increase in the flame speed with increasing R_f (decreasing K_S) for sufficiently small stretch rates (large flame kernels). The initial decrease in S_b at large $\tau_f K_S$ results from decreasing stretch rate of a growing flame kernel, as stretching is well known to increase speed of a lean H_2 -air flame [32,34]. The subsequent increase in S_b is caused by the flame instabilities. For expanding hydrocarbon-air laminar flames, such a phenomenon is well known to occur due to Darrieus-Landau (DL)

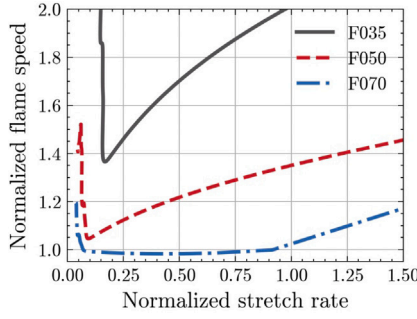


Fig. 1. Evolution of observed flame speeds $S_b/(\sigma S_L)$ with decreasing normalized stretch rate $\tau_f K_S$.

instability [35]. In the present study, diffusional-thermal instability plays the major role, at least at $\phi = 0.35$ or 0.5 . Normalized stretch rates $\tau_f K_S^{cr}$ corresponding to the minimum flame speeds are reported in the third-to-right column in Table 1.

While flame instabilities weakly affect its speed at $K_S > K_S^{cr}$ the expanding flames become unstable earlier, i.e., at K_S larger than K_S^{cr} . Indeed, Fig. 2(a) shows that harmonic perturbations of flame-circle radius $r_f(\theta, t)$ appear well before instabilities begin notably affecting S_b (results obtained in other cases are similar and not reported for brevity). Thus, there is an initial stage of instability development, associated with growth of its amplitude, e.g., cf. ordinate axes in Fig. 2(a) and (c), but weak effect on the flame speed. The point is that instabilities of expanding spherical (or cylindrical) flames weakly affect their speeds until the rate of growth of the flame surface perturbations becomes substantially larger than the rate of growth of the flame radius $R_f(t)$ [2].

Such an intermediate stage of instability development is illustrated in Fig. 3, which shows dependence of $d \ln A / d \ln Pe$ on the inverse Peclet number $1/Pe = \delta_L / R_f$. Here, the perturbation amplitude $A(t)$ is obtained by performing a Fourier transform on $r_f(\theta, t)$ and such a form of presentation of numerical results is taken following activation-energy-asymptotic theory of DL instability of single-step-chemistry spherical flames [35]. Fig. 3 clearly shows two phases on instability development; (i) $A \propto R_f$ at moderately large Pe and (ii) more rapid growth of the amplitude $A(t)$ when compared to the flame radius $R_f(t)$ at large Peclet numbers. Fig. 2(a) and (c) correspond to beginning of these two stages.

Competition between an increase in flame surface area due to (i) instabilities and (ii) growth of the flame itself is an important feature of expanding flames. This competition affects values of the normalized stretch rates $\tau_f K_S^{cr}$ reported in Table 1. Moreover, the influence of stretching of an expanding flame on its instability is subject to other transient effects. For instance, when a flame kernel grows, the range of perturbation wavenumbers k that can affect the kernel expands from large k associated with short wavelengths to smaller k . Due to such an increase in k , the instability growth rate $\omega(k)$ increases also (if k remains moderately large). As a result, (i) a balance between ωA and dR_f/dt can be established before $\omega(k)$ reaching its peak value (due to the increase in k with R_f) and (ii) stretch rate associated with such a balance can be smaller than the stretch rate required to overwhelm the peak $\omega(k)$. Due to such transient effects, the reported values of $\tau_f K_S^{cr}$ may be insufficient to characterize flame stabilization by stretch rates.

Accordingly, the next-to-right column in Table 1 reports significantly higher normalized stretch rates $\tau_f K_S^*$ associated with occurrence of instability, e.g., see Fig. 2(a). Both $\tau_f K_S^{cr}$ and $\tau_f K_S^*$ are increased with decreasing ϕ , i.e., diffusional-thermal instability is more pronounced in leaner H_2 -air mixtures, as expected. Indeed, first, when the equivalence ratio is decreased in lean H_2 -air mixtures, Lewis number $Le < 1$ decreases further but Zel'dovich number Ze increases (under atmospheric pressure), e.g., see Ref. [36, Fig. 2(b)]. Second, according to activation-energy-asymptotic theories of single-step-chemistry

flames, e.g., Ref. [37], the growth rate of diffusional-thermal instability involves a term of $(1 - Le)Ze$, i.e., is higher at lower Le or larger Ze . As stabilization of more unstable leaner flames is expected to be more difficult, the simulated increase in $\tau_f K_S^{cr}$ or $\tau_f K_S^*$ with decreasing ϕ is consistent with the theory.

Fig. 4 shows evolution of the following conditioned contributions $\langle \kappa S_d | \kappa > 0, S_d > 0 \rangle_S$ and $\langle \kappa S_d | \kappa < 0, S_d > 0 \rangle_S$ to the curvature term in the well-known expression for flame stretch rate [32,38]. Two other contributions to $\langle \kappa S_d \rangle_S$, i.e., $\langle \kappa S_d | \kappa > 0, S_d < 0 \rangle_S$ and $\langle \kappa S_d | \kappa < 0, S_d < 0 \rangle_S$ vanish in expanding cylindrical laminar flames. Here, $\kappa = \nabla \cdot \mathbf{n}$ is flame curvature; $\mathbf{n} = -\nabla c / |\nabla c|$ is unit vector normal to flame contour (in the simulated 2D case);

$$S_d = \frac{1}{\rho |\nabla c|} \left[\frac{\partial}{\partial x_i} \left(\rho D_F \frac{\partial c}{\partial x_i} \right) + \frac{\dot{\omega}_F}{Y_{F,u}} \right] \quad (2)$$

is displacement speed; $c = 1 - Y_F / Y_{F,u}$ is combustion progress variable; D_F is molecular diffusivity of fuel; and subscript S refers to quantities averaged over the flame contour $c(\mathbf{x}, t) = 0.94$ associated with the peak FCR in the unstretched laminar flame.

These contributions are analyzed following Berger et al. [39,40], who emphasized an important role played by the term $\langle \kappa S_d | \kappa > 0, S_d > 0 \rangle_S$ in lean H_2 -air turbulent flames and considered a large magnitude of this term to be “a distinct marker of” diffusional-thermal instability [39, p. 11]. However, in the expanding cylindrical laminar flames studied, this term is largest at small t/τ_f , i.e., well before appearance of any sign of that instability, see the left circle on black curve. Subsequently, at $3 < t/\tau_f < 4$, this term remains roughly constant despite development of the instability, see Fig. 2(a)–(c). Therefore, while a large magnitude of the term $\langle \kappa S_d | \kappa > 0, S_d > 0 \rangle_S$ may be a consequence of diffusional-thermal instability, this large magnitude is not a sufficient condition for claiming importance of this instability.

3.2. Twin counterflow flames

3.2.1. Lack of initial perturbations

Figs. 5 and 6 indicate mitigation of flame instabilities by strain rates. Specifically, first, comparison of curves plotted in black solid and red dashed lines in Fig. 5 shows that a small increase in $\tau_f K_g$ results in suppression of (i) an increase in $S_c(t)$ with time and (ii) oscillations in $S_c(t)$. At larger $\tau_f K_g$, the normalized consumption velocity is always close to unity. Small differences between $S_c(t, K_g)$ and consumption velocity $S_c^{1D}(t, K_g)$ in stationary 1D strained flame subject to the same K_g could be attributed to using different codes for simulations of the steady 1D and unsteady 2D strained flames, i.e., Cantera [28] and PeleLMEx [11], respectively. Second, Fig. 6 shows that flame contour is smooth if K_g is larger than a critical value K_g^{cr} .

The computed values of the normalized critical strain rate $\tau_f K_g^{cr}$ are reported in the right column in Table 1. Similar to $\tau_f K_S^{cr}$ or $\tau_f K_S^*$, $\tau_f K_g^{cr}$ is increased with decreasing ϕ . Moreover, Table 1 shows that $\tau_f K_S^{cr}$ is smaller than $\tau_f K_g^{cr}$, whereas $K_S^* > K_g^{cr}$, i.e., the cylindrical flame becomes unstable at larger stretch rates when compared to planar counterflow twin flames. The difference in $\tau_f K_g^{cr}$ and smaller $\tau_f K_S^{cr}$ is associated with transient effects discussed in the previous subsection. The difference in $\tau_f K_g^{cr}$ and larger $\tau_f K_S^*$ could be attributed to enhancement of flame instability due to flame curvature.

Table 1 also shows that both $\tau_f K_S^{cr}$ and $\tau_f K_g^{cr}$ are well below unity in all cases studied here, whereas DNS data obtained from turbulent flames imply a higher $\tau_f K_{cr}$, e.g., about 4 if $\phi = 0.5$ [30,31]. This value is significantly larger than $\tau_f K_S^*(\phi = 0.5) = 0.55$ also. Thus, the present numerical results obtained from stretched laminar flames not only support but even strengthen a hypothesis regarding suppression of flame instability by turbulent stretching. Accordingly, the present results and an earlier study [9] call for developing alternative approaches to modeling diffusional-thermal effects in lean H_2 -air turbulent flames, i.e., approaches that do not highlight diffusional-thermal instability, e.g., see a review article [8] or Refs. [41,42] as recent examples.

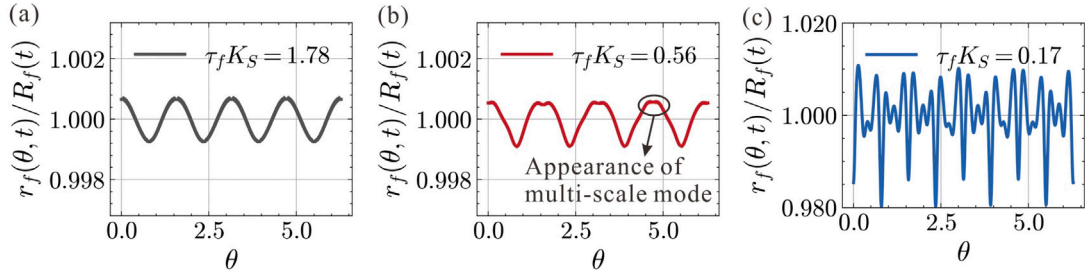


Fig. 2. Flame-contour perturbation $r_f(\theta, t)/R_f(t)$ at different stages of instability development. Case F035. (a) $\tau_f K_S = 1.78$, $t/\tau_f = 0.39$, (b) $\tau_f K_S = 0.56$, $t/\tau_f = 1.30$, (c) $\tau_f K_S = 0.17$, $t/\tau_f = 4.68$ (S_b begins growing due to instability).

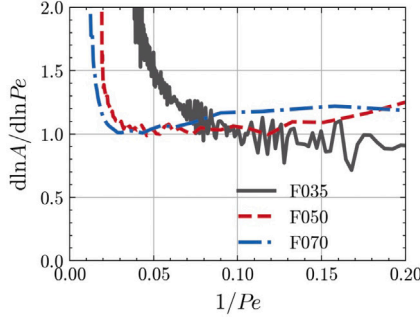


Fig. 3. Relative growth of perturbation amplitude in three flames specified in legends.

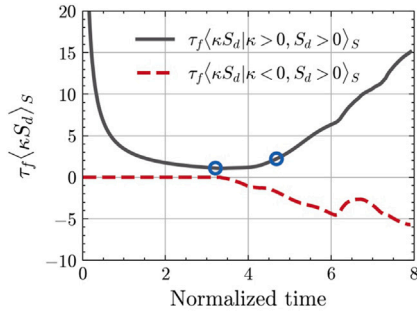


Fig. 4. Evolution of two normalized contributions, $\tau_f \langle \kappa S_d | \kappa > 0, S_d > 0 \rangle_S$ (black solid line) and $\tau_f \langle \kappa S_d | \kappa < 0, S_d > 0 \rangle_S$ (red dashed line), to the normalized curvature term $\tau_f \langle \kappa S_d \rangle_S$ in expanding cylindrical flame. Left and right circles show instants associated with $\tau_f K_S^*$ and $\tau_f K_S^{cr}$, respectively. $\phi = 0.35$.

Nevertheless, it is worth noting the following three substantial differences between turbulent flames and simple laminar flames simulated here: (i) turbulent strain rates are highly unsteady, (ii) perturbations can be much stronger in turbulent flows, and (iii) the highest stretch rates are created by the smallest turbulent eddies, whereas the present study of twin flames deals with large-scale externally imposed strain rates. Accordingly, addressed in the next two subsections is the influence of transit effects and magnitude of velocity perturbations on $\tau_f K_g^{cr}$.

3.2.2. Unsteady velocity perturbations

To explore point (i), extra simulations of the twin flames were run adopting $u_{in} = U[1 + \sin(2\pi f t)]$. Results obtained at $\phi = 0.35$, $\tau_f K_g = 0.35$, and $f = K_g$, $4K_g$, or $8K_g$ do not reveal appearance of flame instabilities. Fig. 7 shows that the computed curves $S_c(t)/S_c^{1D}$ exhibit very weak oscillations in the vicinity of unity, with the oscillation amplitude being decreased with increasing f .

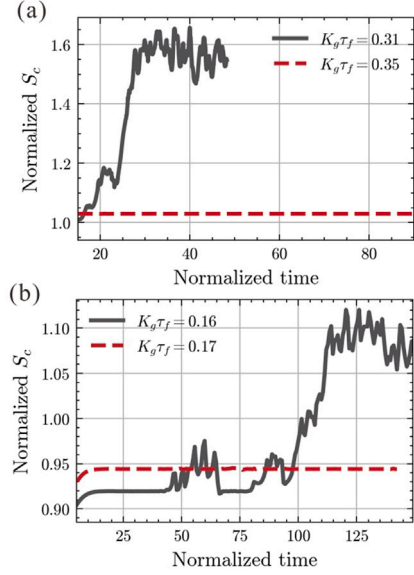


Fig. 5. Evolution of naturally developing instabilities of twin counterflow laminar flames under the influence of different strain rates, specified in legends. Burning velocity is normalized using its value $S_c^{1D}(K_g)$ in 1D strained flame subject to the same K_g . (a) $\phi = 0.35$, (b) $\phi = 0.5$.

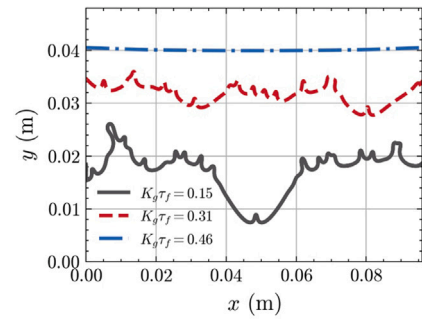


Fig. 6. Representative instantaneous flame contours at different strain rates K_g specified in legends. $\phi = 0.35$.

3.2.3. Large perturbations of inlet velocity

To explore point (ii), simulations of the twin flames were run by setting $u_{in} = U + U' \sin(kx)$ and increasing U' . Results plotted in Fig. 8(a) show that oscillations in $S_c(t)$ appear and are more pronounced at a higher U' . However, after a transition phase, a statistically stationary stage is reached and $S_c(t)$ weakly oscillates around a mean value. For the largest $U' = 4S_L$ and the critical strain rate $\tau_f K_g = 0.35$, see curve plotted in blue dotted-dashed line in Fig. 8(a), this mean value is about $1.4S_c^{1D}$ or $2S_L$. For comparison, our recent 2D simulations of unstable

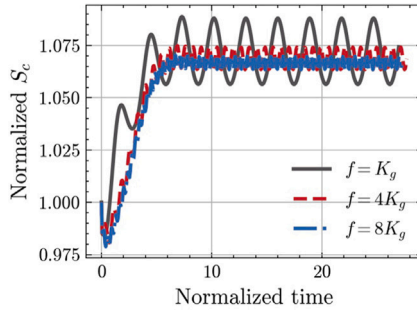


Fig. 7. Variations of the normalized consumption velocity $S_c(t)/S_c^{1D}$ computed for different perturbation frequencies specified in legends. Time is normalized using τ_f .

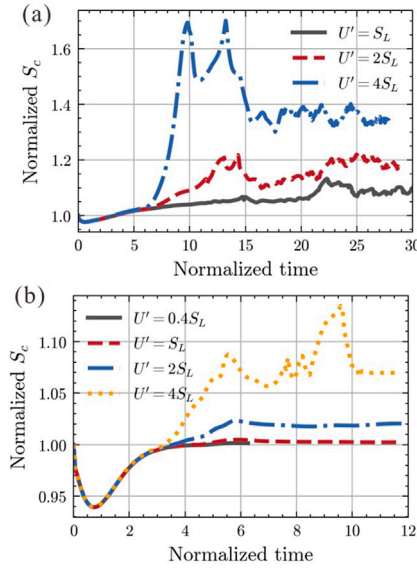


Fig. 8. Evolution of burning velocity normalized using $S_c^{1D}(K_g)$ under the influence of significant inlet velocity perturbations $u_{in} = U + U'\sin(kx)$, whose magnitudes U' are specified in legends. (a) $\tau_f K_g = 0.35$, (b) $\tau_f K_g = 0.77$. $\phi = 0.35$. Time is normalized using τ_f .

laminar flames in a box have shown that a ratio of $S_c(t)/S_L$ can be as large as 2.8 if $\phi = 0.35$ [30, Fig. 1(a)]. Even the peak $S_c(t) = 1.7S_c^{1D} = 2.65S_L$ in Fig. 8(a) is smaller. The difference between the two flame configurations is larger at a higher strain rate, e.g., curve plotted in yellow dotted line in Fig. 8(b) indicates that $S_c(t) < 1.15S_c^{1D} = 2S_L$. Note that Fig. 8(a) and (b) report results computed at different $\tau_f K_g$ and, accordingly, normalized using different S_c^{1D} (both $\tau_f K_g$ and S_c^{1D} are larger in Fig. 8(b)).

Fig. 9 indicates that large velocity perturbations upstream of twin laminar flames result in formation of a weakly perturbed curved flame front under the influence of the critical (for the infinitesimal perturbations) strain rate. While the overall flame shapes are broadly consistent with those observed in simulations of equidiffusive twin laminar flames subjected to similar inlet velocity perturbations, cf. curves plotted in black solid and red dashed lines, distinct small-scale structures are still present in the case of a low Lewis number. Due to such small-scale structures, $S_c(t)/S_c^{1D} > 1$, see curve plotted in blue dotted-dashed line in Fig. 8(a).

3.2.4. Perturbations of initial flame shape

Fig. 10 shows response of twin counterflow laminar flames to harmonic perturbations $y_f(x, 0) = Y_f + \beta\delta_L \sin(k_0 x)$ of the initial flame

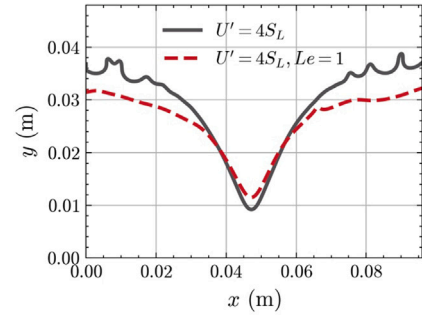


Fig. 9. Shape of quasi-stationary twin counterflow laminar flame at $\tau_f K_g = 0.35$ and $U' = 4S_L$. $\phi = 0.35$.

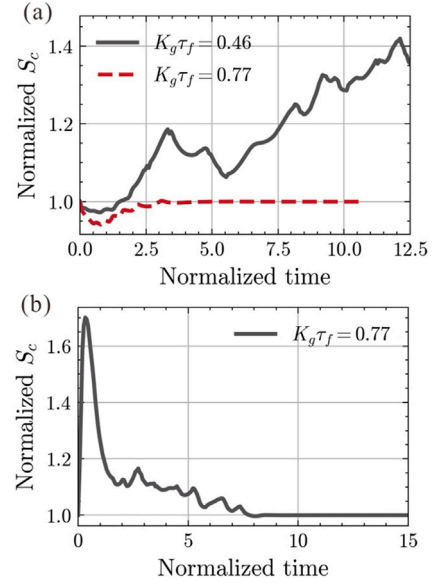


Fig. 10. Response of twin counterflow laminar flames to harmonic perturbations $y_f(x, 0) = Y_f + \beta\delta_L \sin(k_0 x)$ of the initial flame shape at different strain rates, specified in legends. $\phi = 0.35$, $\delta_L k_0 \approx 1$. (a) $\beta = 0.01$. (b) $\beta = 0.5$. Consumption velocity is normalized using its value S_c^{1D} in stationary 1D flame subject to the same K_g .

shape under the influence of different bulk strain rates K_g , specified in legends. Three findings are of interest.

First, while the flame is stabilized by strain rate, see curve plotted in red dashed line in Fig. 10(a), the normalized critical value $\tau_f K_g^{cr} = 0.77$ is larger when compared to the case of an initially planar flame. This difference holds even if flame-shape perturbations are weak, e.g., $\beta = 0.01$ in Fig. 10(a). Nevertheless, $\tau_f K_g^{cr} = 0.77$ is still significantly smaller than the normalized critical stretch rate associated with turbulent flames propagating in a box, e.g., about 7.0 [30].

Second, the phenomena emphasized in Ref. [10], i.e., (i) growth of perturbation wavelength, see Fig. 11(a), due to transverse velocity gradient, which stretches out the perturbation, and (ii) an initial increase in the perturbation amplitude, see Fig. 11(b), are also observed in the present study. However, in the case of $\tau_f K_g = 0.77$ and $\beta = 0.01$, these local phenomena weakly affect $S_c(t)/S_c^{1D}$, which is close to unity, see curve plotted in red dashed line in Fig. 10(a). In the case of $\tau_f K_g = 0.77$ and larger $\beta = 0.5$, the initial perturbation still disappears, but this takes time, see Fig. 10(b).

Third, the discussed local phenomena do play a role in the case of large perturbations ($\beta = 0.5$, see Fig. 10(b)). They result in a significant increase in the peak value of $S_c(t)$ up to $1.7S_c^{1D} = 3S_L$, which is larger than $\max\{S_c(t)\} = 2.8S_L$, computed by us for the unstable laminar 2D

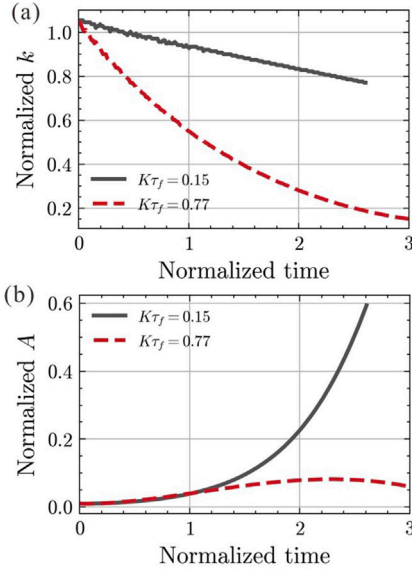


Fig. 11. (a) Decrease in instability wavenumber k and (b) increase in instability amplitude A at two different $\tau_f K_g$, specified in legends. $\phi = 0.35$, time is normalized with τ_f .

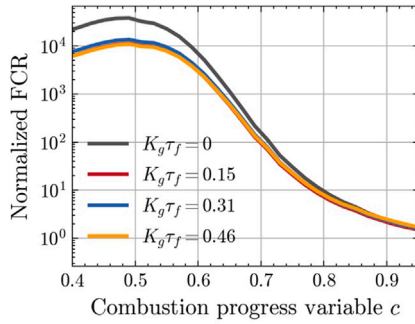


Fig. 12. Normalized conditioned profiles $\langle \dot{\omega}_F | c \rangle(c)$ of FCR, computed at various strain rates specified in legends. $y_f(x, 0) = Y_f + \beta \delta_L \sin(k_0 x)$, $\phi = 0.35$.

flame in a box [30, Fig. 1(a)]. Nevertheless, this large perturbation vanishes with time and the flame evolves to a stable stage.

While strain rates mitigate flame instability, an increase in K_g weakly affects local flame structure during the non-linear quasi-steady stage of instability development, i.e., when $S_c(t) > S_c^{LD}$ does not grow monotonously, but oscillates around a mean value. Indeed, Fig. 12 reports profiles $\langle \dot{\omega}_F | c \rangle(c)$, conditioned to the local combustion progress variable c and averaged over the non-linear stage of instability development at various K_g . These results are normalized point-wise using the FCR $\dot{\omega}_F(c)$ obtained from the unperturbed 1D laminar flame. Curves plotted in color lines show that profiles computed at three different strain rates are indistinguishable with the naked eye, with the results obtained from initially unperturbed flame (black line) being also close.

A similar trend is observed in Fig. 13, which reports dependencies of the local equivalence ratio and fuel consumption rate, conditioned to either local tangential strain rate $K_t = \nabla \cdot \mathbf{u} - \mathbf{n} \cdot \nabla \mathbf{u} \cdot \mathbf{n}$ or local flame curvature, on the conditioning variable. These results were (i) sampled along the flame contour $c(\mathbf{x}, t) = c^*$, where c^* corresponded to the peak fuel consumption rate in the unperturbed 1D laminar flame, and (ii) normalized using characteristics of that unperturbed flame. Fig. 13 shows that any of the four dependencies considered, i.e., $\langle \phi | K_t \rangle(K_t)$, $\langle \phi | \kappa \rangle(\kappa)$, $\langle \dot{\omega}_F | K_t \rangle(K_t)$, or $\langle \dot{\omega}_F | \kappa \rangle(\kappa)$, is weakly sensitive to variations in the bulk strain rate.

Thus, results presented in Figs. 12 and 13 indicate universality (i.e., independence of an externally imposed strain rate) of mean local flame structure during the non-linear stage of development of diffusional-thermal instability. Such results imply that mean local characteristics of laminar flames, computed during the non-linear stage of instability development, could be useful for modeling turbulent combustion, if turbulence is sufficiently weak and turbulent stretching does not suppress diffusional-thermal instability.

All in all, the reported results of simulations of cases of (i) time-dependent strain rate, (ii) large stationary perturbations of velocity upstream of a strained flame, and (iii) large perturbations of initial flame shape do not indicate a significant increase in $\tau_f K_g^{cr}$ when compared to the canonical case of a constant strain rate and infinitesimal perturbations. Thus, these results do not explain why diffusional-thermal instability of laminar flames could survive in turbulent flows characterized by significantly higher mean stretch rates, e.g., $4\tau_f^{-1}$ if $\phi = 0.5$ [30,31]. A wider range of frequencies of strain rate oscillations, types of perturbations, their length scales and magnitudes should be explored to clarify the issue. Moreover, in a turbulent flow, a flame is affected by a wide spectrum of stretch rates and this feature of turbulent combustion should also be addressed in future studies of the influence of stretch rates on flame instabilities.

4. Concluding remarks

Newly obtained results of unsteady 2D complex-chemistry simulations of lean H_2 -air laminar flames either expanding in initially quiescent gas or stabilized in counterflow (reactant-to-reactant) configuration show that diffusional-thermal instability of such flames is suppressed by quite moderate (or higher) stretch rates. These findings support a hypothesis that diffusional-thermal instability is suppressed by turbulent stretching [9] and call for developing alternative approaches to modeling diffusional-thermal effects in lean H_2 -air turbulent flames, i.e., approaches that do not highlight flame instabilities.

Computed values of critical stretch rates associated with suppression of diffusional-thermal instability are substantially different in expanding cylindrical and twin counterflow flames. These differences may stem from the cylindrical flame curvature and transient effects discussed in Section 3.1. There is another important difference between the two canonical flame configurations. Specifically, an expanding flame kernel is subject to a stretch rate created by the kernel itself, with the perturbation length scale being comparable with the flame thickness in a highly curved kernel. On the contrary, the twin flames are subject to an externally imposed strain rate whose length scale is much larger than δ_L . Both configurations have features associated with turbulent combustion, e.g., curvature and transient effects in expanding flames or large-scale externally imposed strain rate in twin counterflow flames. Further studies are required to reveal a model flame configuration that is best suited for developing models of turbulent combustion.

Under conditions of the present study, computed values of critical strain rates that suppress instabilities of twin counterflow laminar flames (i) are weakly sensitive to time-oscillations of strain rate, (ii) are increased with increasing magnitude of inlet velocity perturbations, and (iii) are higher in the case of perturbation of flame shape when compared to perturbation of flow velocity. However, these variations in the critical strain rates are quite moderate.

During the non-linear stage of development of diffusional-thermal instability of twin counterflow laminar flames, the mean local flame structure is weakly sensitive to the magnitude of externally imposed bulk strain rate if this strain rate is insufficient to suppress the instability.

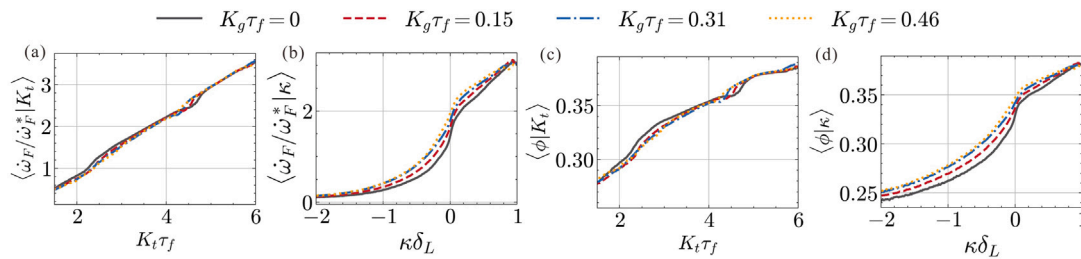


Fig. 13. Conditioned dependencies of (a)–(b) normalized fuel consumption rate and (c)–(d) equivalence ratio, computed at various bulk strain rates specified in legends, on normalized (a), (c) tangential strain rate or (b), (d) curvature. $y_f(x, 0) = Y_f + \beta \delta_L \sin(k_0 x)$, $\phi = 0.35$.

CRediT authorship contribution statement

Xuefeng Guan: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hsu Chew Lee:** Writing – review & editing, Formal analysis. **Tianhan Zhang:** Writing – review & editing, Supervision. **Peng Dai:** Writing – review & editing, Supervision. **Minping Wan:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Andrei N. Lipatnikov:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.proci.2026.106394>.

References

- [1] A. Dreizler, H. Pitsch, V. Scherer, C. Schulz, J. Janicka, The role of combustion science and technology in low and zero impact energy transformation processes, *Appl. Energy Combust. Sci.* 7 (2021) 100040.
- [2] Y.B. Zeldovich, G.I. Barenblatt, V.B. Librovich, G.M. Makhviladze, *The Mathematical Theory of Combustion and Explosions*, Consult. Bureau, New York, 1985.
- [3] H. Pitsch, The transition to sustainable combustion: Hydrogen-and carbon-based future fuels and methods for dealing with their challenges, *Proc. Combust. Inst.* 40 (1–4) (2024) 105638.
- [4] P.K. Yeung, S.S. Girimaji, S.B. Pope, Straining and scalar dissipation on material surfaces in turbulence: implications for flamelets, *Combust. Flame* 79 (3–4) (1990) 340–365.
- [5] G.I. Sivashinsky, C.K. Law, G. Joulin, On stability of premixed flames in stagnation-point flow, *Combust. Sci. Technol.* 28 (3–4) (1982) 155–159.
- [6] G. Joulin, G.I. Sivashinsky, On the linear hydrodynamic stability and response of premixed flames in stagnation-point flows, in: *Symposium (International) on Combustion*, Vol. 24, Elsevier, 1992, pp. 37–44.
- [7] Y. Kortsarts, I. Brailovsky, G.I. Sivashinsky, On hydrodynamic instability of stretched flames, *Combust. Sci. Technol.* 123 (1–6) (1997) 207–225.
- [8] A.N. Lipatnikov, J. Chomiak, Molecular transport effects on turbulent flame propagation and structure, *Prog. Energy Combust. Sci.* 31 (1) (2005) 1–73.
- [9] J. Chomiak, A.N. Lipatnikov, Simple criterion of importance of laminar flame instabilities in premixed turbulent combustion of mixtures characterized by low Lewis numbers, *Phys. Rev. E* 107 (1) (2023) 015102.
- [10] A. Porcarelli, P.E. Lapenna, F. Creta, I. Langella, Stability analysis of thermodynamically unstable counterflow lean premixed hydrogen flames, *Proc. Combust. Inst.* 41 (2025) 105906.
- [11] L. Esclapez, M. Day, J. Bell, A. Felden, C. Gilet, R. Grout, M. Henry de Frahan, E. Motheau, A. Nonaka, L. Owen, B. Perry, J. Rood, N. Wimer, W. Zhang, PeleLMEx: an AMR low mach number reactive flow simulation code without level sub-cycling, *J. Open Source Softw.* 8 (90) (2023) 5450.
- [12] M.T. Henry de Frahan, L. Esclapez, J. Rood, N.T. Wimer, P. Mullowney, B.A. Perry, L. Owen, H. Sitaraman, S. Yellapantula, M. Hassanaly, M.J. Rahimi, M.J. Martin, O.A. Doronina, S.N. A., M. Rieth, W. Ge, R. Sankaran, A.S. Almgren, W. Zhang, J.B. Bell, R. Grout, M.S. Day, J.H. Chen, The Pele simulation suite for reacting flows at exascale, in: *Proceedings of the 2024 SIAM Conference on Parallel Processing for Scientific Computing*, 2024, pp. 13–25.
- [13] W. Zhang, A. Almgren, V. Beckner, J. Bell, J. Blaschke, C. Chan, M. Day, B. Friesen, K. Gott, D. Graves, M. Katz, A. Myers, T. Nguyen, A. Nonaka, M. Rosso, S. Williams, M. Zingale, AMReX: a framework for block-structured adaptive mesh refinement, *J. Open Source Softw.* 4 (37) (2019) 1370.
- [14] J.B. Bell, R.K. Cheng, M.S. Day, I.G. Shepherd, Numerical simulation of Lewis number effects on lean premixed turbulent flames, *Proc. Combust. Inst.* (31) (2007) 1309–1317.
- [15] A.J. Aspdén, M.S. Day, J.B. Bell, Turbulence-flame interactions in lean premixed hydrogen: transition to the distributed burning regime, *J. Fluid Mech.* 680 (2011) 287–320.
- [16] T.L. Howarth, A.J. Aspdén, An empirical characteristic scaling model for freely-propagating lean premixed hydrogen flames, *Combust. Flame* 237 (2022) 111805.
- [17] T.L. Howarth, E.F. Hunt, A.J. Aspdén, Thermodynamically-unstable lean premixed hydrogen flames: Phenomenology, empirical modelling, and thermal leading points, *Combust. Flame* 256 (2023) 112811.
- [18] A.J. Aspdén, T.L. Howarth, E.F. Hunt, Three-dimensional phenomenology of freely-propagating thermodynamically-unstable lean premixed hydrogen flames, *Proc. Combust. Inst.* 40 (2024) 105634.
- [19] A.J. Aspdén, M.S. Day, J.B. Bell, Turbulence-chemistry interaction in lean premixed hydrogen combustion, *Proc. Combust. Inst.* 35 (2015) 1321–1329.
- [20] A.J. Aspdén, M.S. Day, J.B. Bell, Towards the distributed burning regime in turbulent premixed flames, *J. Fluid Mech.* 871 (2019) 1–21.
- [21] M.S. Day, S. Tachibana, J.B. Bell, M. Lijewski, V. Beckner, R.K. Cheng, A combined computational and experimental characterization of lean premixed turbulent low swirl laboratory flames II. Hydrogen flames, *Combust. Flame* 162 (2015) 2148–2165.
- [22] J.B. Bell, M.S. Day, M. Lijewski, Simulation of nitrogen emissions in a premixed hydrogen flame stabilized on a low swirl burner, *Proc. Combust. Inst.* 34 (2013) 1309–1317.
- [23] G.S. Russell, T.L. Howarth, A.W. Skiba, C.D. Carter, A.J. Aspdén, Turbulence-flame interactions in high-Karlovitz-number lean premixed hydrogen piloted jet flames, *Proc. Combust. Inst.* 41 (2025) 105868.
- [24] A. Moitro, E.F. Hunt, T.L. Howarth, O. Chaib, J. Bae, L. Weller, S. Hochgreb, A.J. Aspdén, Direct numerical simulations of laboratory-scale thermodynamically-unstable piloted bunsen flames: Flame surface area, turbulent flame speed, and flame height, *Combust. Flame* 288 (2026) 114916.
- [25] A. Kéromnès, W.K. Metcalfe, K.A. Heufer, N. Donohoe, A.K. Das, C.-J. Sung, J. Herzler, C. Naumann, P. Griebel, O. Mathieu, M.C. Krejci, E.L. Petersen, W.J. Pitz, H.J. Curran, An experimental and detailed chemical kinetic modeling study of hydrogen and syngas mixture oxidation at elevated pressures, *Combust. Flame* 160 (6) (2013) 995–1011.
- [26] J.F. Graciar, J.B. Bell, M.S. Day, The Soret effect in naturally propagating, premixed, lean, hydrogen-air flames, *Proc. Combust. Inst.* 32 (1) (2009) 1173–1180.

- [27] M.X. Yao, G. Blanquart, Isolating effects of large and small scale turbulence on thermodynamically unstable premixed hydrogen flames, *Combust. Flame* 269 (2024) 113657.
- [28] D.G. Goodwin, R.L. Speth, H.K. Moffat, B.W. Weber, *Cantera: An Object-Oriented Software Toolkit for Chemical Kinetics, Thermodynamics, and Transport Processes*, Zenodo, 2018.
- [29] H.C. Lee, A. Abdelsamie, P. Dai, M. Wan, A.N. Lipatnikov, Influence of equivalence ratio on turbulent burning velocity and extreme fuel consumption rate in lean hydrogen-air turbulent flames, *Fuel* 327 (2022) 124969.
- [30] H.C. Lee, B. Wu, P. Dai, M. Wan, A.N. Lipatnikov, Comparison of characteristics of unstable laminar and turbulent lean hydrogen-air flames, *Phys. Fluids* 37 (8) (2025).
- [31] X. Guan, H.C. Lee, P. Dai, M. Wan, A.N. Lipatnikov, Morphology of instantaneous flame surfaces in laminar and turbulent lean H_2 -air flames, *Int. J. Hydrogen Energy* 189 (2025) 152110.
- [32] P. Clavin, Dynamic behavior of premixed flame fronts in laminar and turbulent flows, *Prog. Energy Combust. Sci.* 11 (1) (1985) 1–59.
- [33] K. Seshadri, F.A. Williams, Laminar flow between parallel plates with injection of a reactant at high Reynolds number, *Int. J. Heat Mass Transfer* 21 (2) (1978) 251–253.
- [34] F. Wu, W. Liang, Z. Chen, Y. Ju, C.K. Law, Uncertainty in stretch extrapolation of laminar flame speed from expanding spherical flames, *Proc. Combust. Inst.* 35 (1) (2015) 663–670.
- [35] R. Addabbo, J.K. Bechtold, M. Matalon, Wrinkling of spherically expanding flames, *Proc. Combust. Inst.* 29 (2) (2002) 1527–1535.
- [36] S.M. Mousavi, A.N. Lipatnikov, Dependence of Zel'dovich number on pressure and temperature in lean hydrogen-air mixtures, *Proc. Combust. Inst.* 40 (1–4) (2024) 105501.
- [37] M. Matalon, C. Cui, J.K. Bechtold, Hydrodynamic theory of premixed flames: effects of stoichiometry, variable transport coefficients and arbitrary reaction orders, *J. Fluid Mech.* 487 (2003) 179–210.
- [38] S. Candel, T. Poinso, Flame stretch and the balance equation for the flame area, *Combust. Sci. Technol.* 170 (1990) 1–15.
- [39] L. Berger, A. Attili, H. Pitsch, Synergistic interactions of thermodynamic instabilities and turbulence in lean hydrogen flames, *Combust. Flame* 244 (2022) 112254.
- [40] L. Berger, A. Attili, M. Gauding, H. Pitsch, Effects of Karlovitz number variations on thermodynamic instabilities in lean turbulent hydrogen jet flames, *Proc. Combust. Inst.* 40 (1–4) (2024) 105219.
- [41] Z. Wang, X. Li, T. Li, A. Dreizler, S.M. Mousavi, A.N. Lipatnikov, B. Zhou, Experimental investigation of NH_3 - H_2 jet flames adopting multi-scalar imaging: Comparison of turbulent burning velocities obtained using different flame-front markers, *Combust. Flame* 275 (2025) 114054.
- [42] Y. Wang, A.N. Lipatnikov, Z. Chen, Characterizing the influence of thermodynamic effects on turbulent burning velocity of lean hydrogen/air mixtures using critically stretched laminar flames, *Combust. Flame* 279 (2025) 114306.