Confined Superadiabatic Premixed Flame-Flow Interaction

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Abstract

Laminar premixed unity-Lewis number flames are studied numerically, to examine flow-flame interaction in a two-dimensional closed domain. Two opposed planar flame fronts are perturbed sinusoidally and allowed to develop by consuming premixed reactants. Combustion heat release leads to global pressure and temperature rise in the domain, due to confinement. A superadiabatic condition, with products temperature rising with distance behind the flame front, is observed due to stagnation pressure rise. Variations in tangential strain rate behind the perturbed flame fronts, due to flame curvature and heat release, result in a modified local superadiabatic temperature gradient in the products. These variations in temperature gradients are shown to determine the net local confinement-heating rate in the products, leading to corresponding deviations in products temperature, and the local reaction rate along the flame front. These observations, which are not consistent with one-dimensional superadiabatic stagnation flame behaviour, are a direct result of the unrestrained unsteady nature of two-dimensional flame-flow interaction.

Introduction

A premixed flame burning through unsteady vortical flow is subjected to stretch and curvature effects induced by the local flow field. The response of flames to such disturbances is a key feature in premixed flamelet models that rely on a specified relationship between laminar burning speed and the stretch rate at the flame[1, 2, 3]. There has been a number of studies of premixed flame-vortex interactions in an open domain, where the stagnation pressure is held constant by allowing material to vent from the system[4, 5, 6, 7, 8]. Much less work has been done for closed systems[9], where the compression by the rising stagnation pressure (due to confinement) leads to an associated heating of both reactants and products, and results in a superadiabatic condition behind the flame whereby the products temperature rises with distance away from the flame.

In an open system, for a one-dimensional (1D) adiabatic unity Lewis number (Le) flame, it has been established[4] that a positive tangential strain rate does not affect the peak of the reaction rate profile, while it does lead to a thinner reaction zone. Consequently, a positive tangential strain rate is expected to reduce the local flame consumption speed, which is an integral measure of the reaction rate across the flame. The experimental results of Lee *et al.*[10] reveal no significant effect of curvature on the peak OH LIF signal, which they use as a measure of reaction rate, in a unity Lewis number two-dimensional (2D) premixed flame, in agreement with the strain-related 1D results in [4]. Two-dimensional numerical simulations[6] of premixed flames in a turbulent flowfield lead to the following observations at unity Lewis number: (1) Tangential strain rate varies inversely with curvature; (2) There is at most a weak correlation between curvature and flame consumption speed; and, (3) Flame consumption speed varies inversely with tangential strain rate. In [7] no correlation was observed between consumption speed and curvature for unity Le .

The study of 1D superadiabatic premixed unity- Le stagnation flames in [9] suggests that the reaction rate is expected to increase with tangential strain rate. This is primarily due to the 1D stagnation/opposed jet geometry, where increasing the tangential strain rate leads to the displacement of the flame closer to the stagnation plane and the hotter products.

The focus of the present work is on premixed superadiabatic unity- Le flames, in unsteady 2D flow, in a closed domain. As indicated above, the stagnation pressure rise leads to a superadiabatic condition in the products. It is of interest to investigate the response of temperature and reaction rate profiles at the flame to tangential strain rate, under these conditions.

The numerical solution uses the low Mach number approximation and is based on a predictor-corrector formulation of the finite difference projection method[11, 12]. The low Mach number approximation[13] is justified in many combustion applications due to the small operating Mach numbers and the negligible acoustic time scales relative to those of the flow and flame propagation.

The projection method was first introduced by Chorin[11], and is discussed more recently by Kim&Moin[12]. McMurtry[14] presented a projection scheme for reacting flow, using the continuity equation to update the density field. The present method follows more closely that of Mahalingam[15] and Rutland [16], in using the non-conservative energy equation, but differs in the particular implementation to arrive at a conservative density update for a closed domain. In [15, 16] an open domain was used, where mass conservation was satisfied

by the exit velocity boundary condition. In a closed domain, as the one considered here, this approach is not applicable. A conservative density update is achieved by an appropriate choice of the integral constraint for evaluating the pressure rise term in the energy equation.

A closed doubly-periodic reacting flow system, involving the time development of sinusoidally perturbed premixed flame fronts, is studied. The effect of pressure rise on the flame response to flow-induced strain rate is investigated. It is found that, in a flame-frame of reference, and at a given distance behind the flame, the net rate of temperature rise due to confinement is higher in the compressed versus stretched products. This result is shown to be consistent with the energy equation. Starting from the same initial thermal condition, and given a rising stagnation pressure, flow-compressed and stretched superadiabatic flame regions are exposed to deviating temperatures in the products, leading to deviations in the local reaction rates. Consequently, higher reaction rates are observed in flame regions with compressed versus stretched products at later time. Comparisons with superadiabatic 1D stagnation flame results[9] reveal disagreements related to the unrestrained and unsteady nature of the 2D flow.

In earlier work[17] this negative correlation between reaction rate amplitude and tangential strain rate was noted, for a flame interaction with a counter-rotating vortex pair. The present work, by focusing on relatively smaller flame perturbations without significant wrinkling, provides a more convenient flow to allow detailed study of this observation over a significant time span, and to explain its occurrence based on balances among the various contributions to the energy conservation equation.

Formulation

The set of governing equations are presented in their non-dimensional form in the low Mach number limit. Reference dimensional quantities are denoted by the subscript "ref". Aside from the low Mach number assumption, we assume zero bulk viscosity[18], and neglect body forces, giving the conservative continuity and momentum equations as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (1)$$

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{1}{Re} \Phi_x \quad (2)$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho vu)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} = -\frac{\partial p}{\partial y} + \frac{1}{Re} \Phi_y \quad (3)$$

where, ρ is the density, $\mathbf{v} = (u, v)$ is the velocity vector, p is the pressure,

$$\Phi_x = \frac{\partial}{\partial x} \left[\mu \left(2 \frac{\partial u}{\partial x} - \frac{2}{3} \sigma \right) \right] + \frac{\partial}{\partial y} \left[\mu \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right] \quad (4)$$

$$\Phi_y = \frac{\partial}{\partial y} \left[\mu \left(2 \frac{\partial v}{\partial y} - \frac{2}{3} \sigma \right) \right] + \frac{\partial}{\partial x} \left[\mu \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right], \quad (5)$$

$\sigma = \nabla \cdot \mathbf{v}$, μ is the dynamic viscosity, and $Re = \rho_{ref} U_{ref} L_{ref} / \mu_{ref}$ is the Reynolds number.

The Low Mach number energy and species equations are developed assuming a single step, first-order, irreversible chemical reaction mechanism, with premixed reactants (R) going to products (P) as in:

We neglect Soret and Dufour effects[9] and radiant heat transfer, and, assume R and P to be perfect gases with the same molecular weights, specific heats, and mass diffusion coefficients. Written in terms of temperature, the low Mach number energy equation is given by:

$$\rho c_p \frac{DT}{Dt} = \frac{(\gamma - 1)}{\gamma} \frac{dp_o}{dt} + \frac{1}{Re Pr} \nabla \cdot (\lambda \nabla T) + Da w_T \quad (7)$$

where, c_p is the specific heat at constant pressure, T is the temperature, $\gamma = c_p / c_v$, c_v is the specific heat at constant volume, $p_o = p_o(t)$ is the stagnation pressure, λ is the thermal conductivity, w_T is the chemical heat release source term, $Pr = \mu_{ref} c_{p,ref} / \lambda_{ref}$ is the Prandtl number, and $Da = (L_{ref} / U_{ref}) / (\rho_{ref} / w_{ref})$ is the global Damköhler number. The perfect gas state equation is given by:

$$p_o = \rho T. \quad (8)$$

The species conservation equation for reactants, R , is :

$$\frac{\partial(\rho Y_R)}{\partial t} + \nabla \cdot (\rho \mathbf{v} Y_R) = w_R Da + \frac{1}{Re Sc} \nabla \cdot (\rho \mathcal{D} \nabla Y_R). \quad (9)$$

where, Y_R is the local reactants mass fraction, $\mathcal{D}$ is the mass diffusion coefficient, and $Sc = \mu_{ref} / \rho_{ref} \mathcal{D}_{ref}$ is the Schmidt number. The reaction rate, w_R , is given by an Arrhenius rate expression:

$$w_R = -\rho Y_R B e^{-E/T} \quad (10)$$

where, B is a constant pre-exponential factor[9], and E is the activation energy.

The chemical heat source term in the energy equation is given by:

$$w_T = w_R \Delta h^\circ \quad (11)$$

where, $\Delta h^\circ = h_P^\circ - h_R^\circ = -\int_{T_u^a}^{T_b^a} c_p dT$ is the heat of reaction, and (T_u^a, T_b^a) are the unburnt and burnt gas temperatures for an adiabatic flame in an open system, respectively.

Finally, the time rate of change of stagnation pressure, dp_o/dt , is found by explicitly enforcing global mass conservation, consistent with the discrete update of density utilized in the scheme. Thus, using the constraint,

$$\frac{\partial}{\partial t} \int_D \rho dV = \int_D \frac{\partial \rho}{\partial t} dV = 0 \quad (12)$$

and, from the state equation,

$$\frac{\partial \rho}{\partial t} = \frac{1}{T} \left(\frac{dp_o}{dt} - \rho \frac{\partial T}{\partial t} \right) \quad (13)$$

and, substituting for $\partial T/\partial t$ from the energy equation,

$$\frac{\partial T}{\partial t} = -\mathbf{v} \cdot \nabla T + \frac{(\gamma - 1)}{\gamma} \frac{1}{\rho c_p} \frac{dp_o}{dt} + \frac{1}{RePr} \frac{\nabla \cdot (\lambda \nabla T)}{\rho c_p} + Da \frac{w_T}{\rho c_p} \quad (14)$$

gives:

$$\frac{dp_o}{dt} = \left[\int_D \frac{1}{T} \left(-\rho \mathbf{v} \cdot \nabla T + \frac{1}{RePr} \frac{\nabla \cdot (\lambda \nabla T)}{c_p} + Da \frac{w_T}{c_p} \right) dV \right] / \left[\int_D \frac{1}{T} \left(1 - \frac{\gamma - 1}{\gamma c_p} \right) dV \right] \quad (15)$$

This is in contrast with the commonly used constraint based on the velocity field divergence, presented by Majda and Sethian[13]: $\int \nabla \cdot \mathbf{v} dV = 0$, which does not ensure discrete global mass conservation in the present context.

The above equations are solved using a 2nd-order predictor-corrector finite difference projection method on a uniform mesh. The method has been discussed and validated in [17, 19]. It has been demonstrated to be convergent and accurate relative to linear stability results in wake flow, and to be globally mass conservative.

Flame Diagnostics

The flame location is identified by a specified constant level surface of the reactants mass fraction[6]. This is set at $Y_R = 0.25$, which agrees reasonably with the peak reaction rate location. The flame normal, $\mathbf{n}$, and tangential, $\mathbf{t}$, unit vectors are determined relative to the local gradient direction of the Y_R surface. Thus, $\mathbf{n} = \nabla Y_R / |\nabla Y_R|$, and $\mathbf{t} \cdot \mathbf{n} = 0$. The tangential strain rate, τ_t , is evaluated from the strain rate tensor $\mathbf{e}$ [9]: $\tau_t = \mathbf{t} \cdot \mathbf{e} \cdot \mathbf{t}$. The curvature[20], K , is defined positive when the flame is convex to the reactants, in 2D: $K = 1/\mathcal{R} = \nabla \cdot \mathbf{n}$, where $\mathcal{R}$ is the radius of curvature.

Two premixed flame speeds have been identified in the literature[21]. The flame "displacement" speed is the speed at which the flame "surface" moves relative to the local flow velocity. Thus, with the flame at a constant $Y_R = Y_f$, the displacement speed, S_d , is defined by:

$$S_d = \left[-\left(\frac{\partial Y_R}{\partial t} + \mathbf{v} \cdot \nabla Y_R \right) / |\nabla Y_R| \right]_{Y_R=Y_f} \quad (16)$$

The flame "consumption" speed, S_c , on the other hand, is an integral measure of the local consumption rate of reactants across the flame front scaled by the density and reactants mass fraction in the reactants, and is equal to S_d only for a 1D adiabatic unstrained flame in an open domain. S_c is defined here by:

$$S_c = \frac{Da}{\bar{\rho}_u \bar{Y}_{Ru}} \int_u^b w_R dn \quad (17)$$

where, $\bar{\rho}_u$ and $\bar{Y}_{Ru}$ are the mean density and mass fraction in the reactants, and the integral is evaluated along the flame normal direction. Overall flame stretch, ϕ_s , is evaluated from τ_t and K by[20]:

$$\phi_s = \tau_t + S_d K \quad (18)$$

The flame "thermal thickness", δ_f , is determined from the peak temperature gradient in the flame by:

$$\delta_f = \frac{T_b^a - T_u^a}{|\partial T / \partial n|_{max}} \quad (19)$$

Results

Consider a 2D reacting flow involving the propagation of two opposed laminar premixed flame fronts in a doubly periodic domain. The flow is initialized by the temperature, density, and species fields computed from a 1D flame calculation, with a small sinusoidal perturbation introduced to generate a flame interface with alternating positive and negative curvature regions. Since the domain is effectively closed, the stagnation pressure, p_o , is expected to rise in time as the flames consume the reactants. Relevant parameter values are: $Re = 1000$, $Da = 1.0$, $Sc = Pr = 1.0$ ($Le = 1.0$), $T_b^a/T_u^a = 6$, $Ze = \alpha E/T_b^a = 5.6$ (Zeldovich number), where $\alpha = (T_b^a - T_u^a)/T_b^a = 0.83$, $T_u^a = 1.0$. Constant transport properties are used, with $\mu = \lambda = c_p = \mathcal{D} = 1.0$, and $\gamma = 1.4$. A pre-exponential factor $B = 6.6 \times 10^4$ is assumed.

The initial condition is presented on the computational domain in Figure 1. The Figure shows two horizontal sinusoidally perturbed flame fronts, delineated by the reaction rate contours. The perturbation amplitude is 0.02, which is 4% of the domain size, and the initial flame thickness is $\delta_f^o = 0.018$. The two flame fronts burn towards the domain center, with unburnt reactants in-between them. Initial flame displacement speed is $v_f^o = S_d^o = 0.18$. Due to the combustion-related pressure rise, and the dp_o/dt term in the energy equation (14), a superadiabatic thermal condition develops behind the flame. The associated 1D initial temperature profile in the y -direction is shown in Figure 2, along with the reactants mass fraction and reaction rate amplitude profiles. This initial condition is arrived at using a 1D flame calculation, starting with two opposed flames some distance apart, and allowing them to develop by consuming premixed reactants. Because of pressure rise, no steady state is achievable. The 1D solution is allowed to develop for sufficient time to eliminate any residual convective-diffusive oscillations, remnants of its own analytical initial condition.

The time development of the flow involves the consumption of the reactants at the flame fronts, which proceeds until the the two fronts meet and the burning rate decays due to depletion of reactants. This process is accompanied by heat release leading to a rise in stagnation pressure in the domain. The time evolution of the maximum reaction rate amplitude, w_{Rmx} , the stagnation pressure, p_o , and the total mass of reactants is shown in Figure 3. Due to compression by the rising p_o , the density and temperature of both reactants and products increase, leading to the observed 4-fold increase in w_{Rmx} . The reaction ceases, the reactants are consumed, and the pressure reaches its final value, by time 2.5.

Flame Structure:

The flame structure is analyzed at a representative time instant, $t = 1.0$. The flame fronts are shown on the computational domain in Figure 4, using reaction rate contours. The two flames have moved closer together, as compared to the initial condition in Figure 1, but have maintained the same overall sinusoidal shape. Also shown are iso-contours of the tangential strain rate, τ_t , evaluated from the velocity field at each point using the local normal vector $\mathbf{n}$, as indicated above. Solid/dashed contour lines indicate positive/negative τ_t . In the absence of another imposed velocity field, the tangential strain rate field reflects clearly the influence of expansion due to heat release at the flame. The tangential strain rate in the products behind positively curved flame regions ($K > 0$, convex towards the reactants) is negative, indicating a compression effect due to the focusing of expansion velocity from the flame. On the other hand, positive strain rate (tension) is observed behind negatively curved

flame segments ($K < 0$), again due to the associated expansion velocity field. A consistent situation is observed in the reactants in front of each positively or negatively curved flame segment.

Figure 5 shows the variation of curvature K , tangential strain rate τ_t , total rate of stretch ϕ_s , and consumption speed S_c , with the x -coordinate, evaluated at the $Y_R = 0.25$ contour, for the lower flame in Figure 4. As expected from the flame shape, positive curvature is observed for $x \in [0, 0.25]$, while negative curvature is evident for $x \in [0.25, 0.5]$. The variation of strain rate along the flame, reflecting that in the products in Figure 4, is opposite to that of curvature; negative strain rate is observed at the positively curved flame and vice versa. This negative correlation between strain rate and curvature is in agreement with earlier work [6, 17].

On the other hand, the total stretch rate, ϕ_s , at the flame surface, involves also the expansion or contraction of the propagating curved flame, which, in this case, acts opposite to the local flow-induced tangential strain rate, as shown also for the lower flame in the Figure. The positively curved region ($x = [0, 0.25]$), with negative tangential strain rate, exhibits a positive net stretch rate of the flame surface. The inverse situation is observed for the negatively curved flame.

The consumption speed, S_c , is observed to exhibit inverse correlation with τ_t , in agreement with [4, 6, 17], and a positive correlation with curvature, K , as found in [17]. A similar variation is observed for the displacement speed, S_d , and for the maximum local reaction rate amplitude, w_{Rmx} . The thermal flame thickness, δ_f , which, according to the definition above, Eq. (19), is inversely proportional to the maximum temperature gradient in the flame, is found to exhibit inverse correlation with w_{Rmx} . This is consistent with analytical arguments that δ_f^2 varies inversely with the reaction rate [9].

The variation of w_{Rmx} along the flame is of particular interest, since it is not expected in a similar adiabatic flame in an open system [4, 9]. The negative correlation between w_{Rmx} and τ_t is indicated in Figure 6 for a time range 0.6–1.2. The overall trend toward higher reaction rate is evident, along with the persistent negative correlation with τ_t . Evidently, w_{Rmx} is higher at flame locations with compressed products $\tau_t < 0$, and positive curvature $K > 0$. This observation is also supported by observing a cut along the y -direction at $x = 0.125$, shown in Figure 7, which reveals the reaction rate profiles in the positively and negatively curved flames. Again, the reaction rate is higher for the lower flame at $x = 0.125$, with $\tau_t < 0$ in the products. In the following, this correlation, which was noted in [17], is discussed in detail with reference to the energy equation.

Peak Reaction Rate - Superadiabatic Flame:

The negative correlation between w_{Rmx} and τ_t is not consistent with 1D results for adiabatic flames [4], where the peak reaction rate is found to be unaffected by τ_t . It is also inconsistent with superadiabatic 1D stagnation flame results [9], where increased strain is expected to increase w_{Rmx} by driving the stagnation flame towards the hot gases.

In order to explain this correlation, we examine the energy equation, rewritten in a coordinate frame travelling at the overall flame propagation velocity, v_f , given by:

$$v_f = v_f^c + S_d n_f \quad (20)$$

where, v_f^c is the convective flow velocity at the flame location ($Y_R = Y_f$), S_d is the flame displacement speed, and n_f is the flame normal at this location. Thus, the total time rate

of change of temperature at a point in this reference frame is :

$$\frac{D_f T}{Dt} = \frac{\partial T}{\partial t} + \mathbf{v}_f \cdot \nabla T \quad (21)$$

$$= (\mathbf{v}_f - \mathbf{v}) \cdot \nabla T + \frac{\gamma - 1}{\gamma} \frac{1}{\rho c_p} \frac{dp_o}{dt} + \frac{1}{RePr} \frac{\nabla \cdot (\lambda \nabla T)}{\rho c_p} + Da \frac{w_T}{\rho c_p} \quad (22)$$

Evaluation of the various terms on the right-hand side of this equation, in the products behind the flame, reveals that both the conduction and reaction terms are negligible compared to the convective and pressure (dp_o/dt) terms. In particular, the pressure term is a distributed heat source term, with a strength proportional to temperature ($1/\rho = T/p_o$). The convective term is, to first order, in the vicinity of the flame, given by: $S_d \mathbf{n}_f \cdot \nabla T$, since $\mathbf{v} \approx \mathbf{v}_f^c$ near the flame. Given that $\mathbf{n}_f$ is in the direction of decreasing temperature, this product is negative in general, and the convective term is a heat sink that acts to reduce the temperature in the products. Further, the strength of this sink is proportional to $\partial T / \partial n = \mathbf{n}_f \cdot \nabla T$. The net rate of rise of temperature in the products is a result of balance between the pressure source and the convective sink terms.

When flow-induced strain rate stretches the products tangentially behind the flame, the temperature gradient normal to the flame, $\partial T / \partial n$, is enhanced, along with the associated convective heat sink strength. Consequently, the net heating effect is lower in the stretched products, leading to lower T_b behind the stretched flame, and therefore a lower reaction rate profile. Hence the resulting difference in maximum reaction rate between the stretched ($\tau_t > 0, K < 0$) and compressed ($\tau_t < 0, K > 0$) flames in Figure 7.

The associated temperature profiles behind each flame cut at $x = 0.125$ are shown versus distance behind the flame, at two time instants, in Figure 8. The relatively lower temperature gradient in the compressed products ($\tau_t < 0$, behind the $K > 0$ flame), and the higher temperature in the flame vicinity, are observed at both times. The temperature differential is also observed to increase in time. The associated maximum reaction rate amplitude in the flame zone is plotted versus time for both curved flame cuts in Figure 9. Starting from the same initial condition, a period of time elapses (0–0.6), before a significant differential is observed between the two cases. The differential is then observed to grow until time 1.6, after which the two flames approach each other and the reaction rate drops because of depletion of reactants.

The relative significance of the convective heat sink can be observed in Figure 10, where the various terms of the energy equation (22) are plotted versus distance behind the flame. The conduction and reaction terms are evidently negligible. The pressure term is roughly the same for both positively and negatively curved flames. On the other hand, the convective heat sink is stronger in the stretched products, leading to a lower $D_f T / Dt$ net result in these regions.

Similarly, the energy equation components are plotted versus time for the flame cuts at $x = 0.125$, and at a distance of 0.04 behind the flame, in Figure 11. Starting from the same initial condition, the convective terms of the compressed and stretched products are seen to diverge, with the stronger sink developing in the stretched products. The net result in terms of $D_f T / Dt$ is observed to exhibit a similar deviation in time, with lower $D_f T / Dt$ in the stretched products.

Conclusions

A premixed superadiabatic reacting flow involving 2D unity- Le flame propagation in a closed domain was studied with emphasis on the confined superadiabatic flame response to the flow-induced tangential strain rate.

Results show clearly the significance of local flow-induced strain rate on the temperature profile in the products, the products temperature, and the time development of the maximum reaction rate amplitude in the flame. The components of the energy equation were evaluated behind the flame, providing quantitative evidence of the dominance of the pressure heat source and the convective heat sink, and the relationship of heat sink strength to the local tangential strain rate, leading to a like relationship in the rate of temperature rise in the products, in a flame-based reference frame.

The negative correlation observed between peak reaction rate and tangential strain rate is inconsistent with 1D superadiabatic steady stagnation flame results[9]. The 1D results, on the other hand, are specific to the stagnation flame geometry in an open domain. The stagnation geometry leads to *hotter* products behind the stretched flame because the reaction zone moves closer to the hot products, due to the enhanced incoming flow velocity. Flow induced stretch in an unrestrained 2D flow, on the other hand, does not lead to normal flame displacement towards the products. The negative correlation in the present results is due to the cooling effect of enhanced convective heat losses due to steeper temperature gradients in the stretched products, leading to a lower associated flame temperature and reaction rate. The convective heat sink is due primarily to the displacement speed of the flame moving away from the products. Because of the temperature profile in the products, this motion leads to a cooling effect proportional to the temperature gradient, in a frame moving with the flame.

These results point to the importance of flow geometry and time-history in determining the response of flames to disturbances by flow structures.

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Figure Captions

- Figure 1. Initial condition, showing reaction rate contours at $t = 0$. The flame fronts are initialized with a sinusoidal perturbation of amplitude 0.02 and spatial wavelength 0.5.
- Figure 2. Initial condition, showing the one-dimensional temperature T , reactants mass fraction Y_R , and reaction rate amplitude $|w_R|$ distribution in the y -direction.
- Figure 3. Maximum reaction rate amplitude, w_{Rmx} , stagnation pressure, p_o , and total mass of reactants, versus time. Reaction ceases, the stagnation pressure reaches a level value, and reactants are depleted by time 2.5.
- Figure 4. Sinusoidally perturbed flame, shown using reaction rate contours, superposed on tangential strain rate contours, $t = 1.0$. Positive and negative strain rates are denoted by solid and dashed contours respectively. The flames burn towards the domain center, consuming the cold reactants in-between them.
- Figure 5. Normalized curvature $K\delta_f^o$, strain rate $\tau_t t_f^o$, stretch $\phi_s t_f^o$, and consumption speed S_c/v_f^o , along the lower flame, $t = 1.0$. δ_f^o and v_f^o are the flame thickness and displacement speed at time 0, $t_f^o = \delta_f^o/v_f^o$.
- Figure 6. Normalized maximum reaction rate amplitude ($w_{Rmx} t_f^o / \rho_u^o$) exhibits a negative correlation with normalized tangential strain rate ($\tau_t t_f^o$). ρ_u^o is the density of the reactants at time 0.
- Figure 7. Reaction rate profile plotted versus y , at $x = 0.125$, $t = 1.4$. The reaction rate is higher at the flame with compressed products (negative strain rate).
- Figure 8. Temperature profiles in the products at $x = 0.125$, $t = (1.0, 1.6)$, for the compressed and stretched product zones, plotted versus normal distance from the flame.
- Figure 9. Evolution of normalized maximum reaction rate amplitude, $w_{Rmx} t_f^o / \rho_u^o$, at the two flame intersections with $x = 0.125$. Starting from the same initial condition for both flames, it is evident that higher reaction rates are attained in the flame with compressed products ($\tau_t < 0$), versus that with stretched products ($\tau_t > 0$).
- Figure 10. Comparison of the various terms of the energy equation written in a coordinate frame moving with the flame velocity at $x = 0.125$, $t = 1.4$. The conduction and reaction terms are negligible compared to the main heat source due to dp_o/dt and the dominant convective heat sink. The stronger convective heat sink in the stretched products ($\tau+$) leads to a lower heating rate $D_f T/Dt$ than that in the compressed products ($\tau-$).

Figure 11. Comparison of the various terms of the energy equation written in a coordinate frame moving with the flame velocity at $x = 0.125$, and at a distance of 0.04 behind the flame. The conduction and reaction terms are negligible compared to the main heat source due to dp_o/dt and the dominant convective heat sink. The stronger convective heat sink in the stretched products ($\tau+$) leads to a lower heating rate $D_f T/Dt$ than that in the compressed products ($\tau-$).

Figure 1. Initial condition, showing reaction rate contours at $t = 0$. The flame fronts are initialized with a sinusoidal perturbation of amplitude 0.02 and spatial wavelength 0.5.

Figure 2. Initial condition, showing the one-dimensional temperature T , reactants mass fraction Y_R , and reaction rate amplitude $|w_R|$ distribution in the y -direction.

Figure 3. Maximum reaction rate amplitude, w_{Rmx} , stagnation pressure, p_o , and total mass of reactants, versus time. Reaction ceases, the stagnation pressure reaches a level value, and reactants are depleted by time 2.5.

Figure 4. Sinusoidally perturbed flame, shown using reaction rate contours, superposed on tangential strain rate contours, $t = 1.0$. Positive and negative strain rates are denoted by solid and dashed contours respectively. The flames burn towards the domain center, consuming the cold reactants in-between them.

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