SELF-SUSTAINED ACOUSTIC RESPONSE OF COUNTERFLOW METHANE-AIR PREMIXED FLAMES

A.C. Zambon
Advisor: Dr. H.K. Chelliah
Department of Mechanical and Aerospace Engineering
University of Virginia, Charlottesville, VA 22904-4746, USA

Abstract

Thermo-acoustic instabilities represent a major technical problem in many combustion applications and are generally manifested as large-amplitude pressure oscillations coupled with unsteadiness in the combustion processes. In the present analysis, the interaction of acoustic waves with planar counterflow methane-air premixed flames is investigated numerically for a range of flow strain rates and flame locations, and employing a detailed and one-step global finite-rate kinetic models. It is found that one-step global models with large activation energy always promote the amplification of acoustic pressure fluctuations in counterflow premixed flames, whereas the detailed kinetic model exhibits thermo-acoustic instabilities for specific locations of the flame. While previous unsteady counterflow work required external perturbations, the resonant unsteady phenomena predicted in this study are self-sustained under favorable boundary conditions. A detailed analysis of the characteristic time-scales associated with convection, diffusion, chemistry and acoustics is accompanied by an analysis of the heat release rate and of the effects of flame location in order to provide a better understanding of the fundamental coupling mechanisms driving the instability, namely chemical kinetic-acoustic coupling and acoustically-induced fluctuations in the mass flux of reactants into the flame.

INTRODUCTION

Under certain operating conditions, many combustion systems exhibit large-amplitude pressure oscillations coupled with unsteadiness in the combustion processes. The origin of such unsteady phenomenon, generally referred to as thermo-acoustic instability, can be related to the resonant interaction of acoustic waves with a flame front in an enclosed volume, such as a combustion chamber, which acts as a host for the amplification of pressure fluctuations. In general, the flame is very sensitive to disturbances in the flow field, and unsteadiness in the heat release rate can act as a source of acoustic perturbations. Through a feedback mechanism provided by the acoustics of the system, coupling of the oscillating heat release rate with the natural acoustic modes of the combustor can reinforce acoustic pressure oscillations and lead to acoustic resonance.

A wide range of combustion applications is affected by thermo-acoustic instabilities, both in aerospace propulsion and land-based power generation. In particular, with stringent environmental regulations, gas turbine engines are required to operate in lean-premixed mode in order to reduce pollutant formation such as NO\textsubscript{x} emissions. However, operation near the lean flammability limit increases the likelihood of heat release fluctuations and hence the occurrence of thermo-acoustic instabilities.

Recently, model-based active control approaches are being pursued, where the suppression of the undesirable pressure oscillations is accomplished by dynamic hardware components such as loudspeakers, moving airfoils or modulations in the secondary fuel supply. However, in order to develop active control schemes for these actuators, detailed information about the physics of coupling mechanisms between flame and acoustics is required with an accurate modeling of the unsteady combustion processes involved. In particular, a fundamental understanding of the flame dynamics contributing to the unsteady heat release rate is essential.

In the context of thermo-acoustic instabilities, the flame dynamics of practical combustion systems is affected by a variety of complex physical and chemical phenomena, that may occur simultaneously on multiple characteristic time-scales as well as length scales, leading to unsteadiness in the heat release rate, e.g. flow compressibility effects, thermal-diffusive instabilities and cellular flames, flame
surface area fluctuations due to hydrodynamic effects\textsuperscript{11,12}, equivalence ratio fluctuations in premixed systems (near lean flammability limit)\textsuperscript{3}, heat losses to the walls or flame holders\textsuperscript{13,14}, finite-rate chemistry effects\textsuperscript{15}. As a result of the complexities of the phenomena involved, their interactions and their inherent non-linearities, the modeling of flame-acoustics coupling is a difficult and challenging task.

In the present investigation, a numerical model is developed to study the fundamental mechanisms leading to the occurrence of thermo-acoustic instabilities in planar counterflow flames. Specifically, the counterflow flame configuration has been selected being a scaled-down chemically reacting flow field that is computable with accurate resolution of the complex multi-scale combustion phenomena involved, including detailed transport properties and finite-rate chemistry. In this configuration, a planar axisymmetric flame is established in the mixing layer of two opposed jets of combustible mixtures, as shown in figure 1. In particular, here identical conditions for composition, temperature and the magnitude of the axial velocity are employed at the exits of the opposed jets, resulting in the establishment of two twin premixed flames, one on either side of the stagnation plane, located at the mid-point of the domain, \(x = 0\), for this specific case. All thermo-dynamic and fluid-dynamic variables are symmetric with respect to the stagnation plane, with the only exception of the axial velocity component, which is symmetric with respect to the point \(x = 0\) and \(v = 0\), where \(v\) is the axial velocity. Exploiting the symmetry of the twin flames with respect to \(x = 0\), the flow field and the structure of stoichiometric methane-air twin flames are shown in figure 2.

Each counterflow flame is characterized by the strain rate, \(a\), defined for a premixed flame as the gradient of the axial velocity in correspondence of the edge of the mixing layer on the side of the reactant stream. The investigation is carried out for a separation distance between the nozzles, \(l\), of 1 cm and a stoichiometric mixture of methane and air \((X_{CH_4} = 0.095, X_{O_2} = 0.190\) and \(X_{N_2} = 0.715\)).

In the analysis of counterflow methane-air premixed flames, two flame configurations can be analyzed, featuring twin and single premixed flames.

**Twin Premixed Flames**

In the twin counterflow premixed flame configuration, two planar axisymmetric flames are established in the mixing layer of two opposed jets of combustible mixtures, as shown in figure 1. In particular, here identical conditions for composition, temperature and the magnitude of the axial velocity are employed at the exits of the opposed jets, resulting in the establishment of two twin premixed flames, one on either side of the stagnation plane, located at the mid-point of the domain, \(x = 0\), for this specific case. All thermo-dynamic and fluid-dynamic variables are symmetric with respect to the stagnation plane, with the only exception of the axial velocity component, which is symmetric with respect to the point \(x = 0\) and \(v = 0\), where \(v\) is the axial velocity. Exploiting the symmetry of the twin flames with respect to \(x = 0\), the flow field and the structure of stoichiometric methane-air twin flames are shown in figure 2.

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**Single Premixed Flame**

In the alternative single flame configuration, the combustible mixture enters the physical domain from the left and the other jet consists of hot combustion products, including water vapor, carbon dioxide and nitrogen \((X_{H_2O} = 0.10, X_{CO_2} = 0.25\) and \(X_{N_2} = 0.65\)). The reaction products have been added to the aforementioned jet in order to avoid excessive diffusion of these chemical species from the reaction layer to the right.

In the discussion of the results on premixed flames, attention is focused primarily on twin flames. Single premixed flame are specifically addressed in the context of flame location effects.

Figure 1: Illustration of twin counterflow premixed flames with the fundamental half-wave acoustic pressure mode.
Effect of Chemical Kinetics

When the unsteady heat release of the flame couples with the resonant acoustic modes of the flow configuration, counterflow premixed flames can undergo self-sustained instabilities. In this case, no external flow perturbation is needed. Under perfectly reflecting boundary conditions, the resulting pressure mode shapes and the corresponding velocity oscillations are shown in figure 3, where the mode shapes are based on solutions saved every 1000 time steps, near t = 10 ms.

The dominant acoustic pressure mode, in terms of the pressure fluctuations, \( p'_0 \), features a half-wave mode shape and is consistent with the open-tube boundary conditions of the opposed nozzles, i.e., pressure nodes at the boundaries. The fluctuating component of the axial velocity features anti-nodes at the exits of the nozzles, and a node in the interior of the domain overlapping the location of the stagnation plane, due to the symmetry of the inflow conditions.

Effect of Chemical Kinetics

As discussed in Zambon and Chelliah\(^6\), the acoustic response of counterflow non-premixed flames was investigated employing both a detailed kinetic model and a one-step global kinetic model featuring an activation energy, \( E_a \), of 30 kcal/mole. With the detailed model, decay of the pressure fluctuations, \( p'_0 \), or almost no change in their amplitude was observed, whereas a one-step model always showed a positive growth of \( p'_0 \), resulting in large-amplitude pressure fluctuations.

For twin counterflow premixed flames, figure 4 shows the evolution in time of the acoustic pressure fluctuations at the mid-point of the domain for strain rates of 220 s\(^{-1}\) (top) and 1180 s\(^{-1}\) (bottom), employing a one-step model with activation energy, \( E_a \), of 30 kcal/mole (left), and the detailed model (right). Unlike counterflow non-premixed flames, the acoustic response of counterflow premixed flames always shows a positive growth, irrespective of the strain rate or mechanism employed.

The new interesting result shown in figures 4 (b) and (d) is the amplification of pressure fluctuations observed in counterflow premixed flames with the detailed model. Although the predicted growth is smaller when compared to the corresponding one-step results, this finding points out that, in premixed counterflow flames, significant coupling between acoustic waves and flame dynamics can be established and drive the instabilities.

Considering that computations are carried out employing perfectly reflecting boundary conditions and that the quasi one-dimensional formulation of unsteady counterflow flames does not account for losses in the radial direction, the aforementioned result does not imply that all real counterflow premixed flames show resonant phenomena. The conclusion that can be drawn is that, under certain conditions, actual premixed flames might show coupling mechanisms that can trigger and drive self-sustained thermo-acoustic instabilities, whereas computations with non-premixed flames do not indicate that, even under the most favorable conditions.
Figure 4: Comparison of the evolution in time of pressure fluctuations, $p'_0$, at $x = 0$ for premixed counterflow flames at strain rates of 220 s$^{-1}$ (top) and 1180 s$^{-1}$ (bottom), employing a one-step model with $E_a = 30$ kcal/mole (right), and the detailed model (left).

Chemical Kinetic Parameters

Both for non-premixed and premixed counterflow flames, the adoption of one-step models always results in positive growth rates of $p'_0$. Figures 4 (a) and (c) show this result for an activation energy of 30 kcal/mole. Similar unsteady computations have been carried out also for activation energies of 15 and 45 kcal/mole. Figure 5 compares the evolution in time of the amplitude of pressure fluctuations, $|p'_0|$, at $x = 0$ for a premixed flame at a strain rate of 220 s$^{-1}$, employing a one-step mechanism and varying activation energy. In all cases, the initial amplitude of the pressure fluctuations is approximately the same. However, the predicted final amplitudes after 10 ms are considerably different. The slope of each curve can be considered a measure of the growth rate of the instability and the present results show that this growth rate is strongly dependent on the choice of activation energy. Specifically, the growth rate is enhanced with increasing $E_a$. The final amplitudes of $|p'_0|$ differ over a range of several order of magnitudes. For the same inflow conditions, only the one-step model with $E_a = 15$ kcal/mole is able to predict pressure fluctuations of the same order of magnitude of the ones obtained with the detailed model.

The present analysis suggests that chemical kinetic parameters are important in predicting thermo-acoustic phenomena. In particular, it points out that, in a detailed model, elementary reactions with large activation energies can be sensitive to acoustically-induced pressure or velocity fluctuations.
Effect of Strain Rate

In the counterflow premixed flame configuration, the location of the flame front is strongly dependent on the flow strain rate, since the stable position of the premixed flame is determined by a dynamic balance between the local flow velocity and the laminar burning speed of the strained flame. As the flow strain rate is augmented, i.e. the inflow velocities are increased, the flame front approaches the stagnation plane.

The growth rates of premixed flames employing both detailed and one-step kinetic models are enhanced with increasing strain rates. Comparison of figures 4 (a) and (b) for \( a = 220 \) \( s^{-1} \) with figures 4 (c) and (d) for \( a = 1180 \) \( s^{-1} \) show a difference of almost one order of magnitude in the amplitude at \( t = 10 \) \( ms \) for the detailed model, whereas the one-step model is subject to a much larger difference. However, as the strain rate is further increased, the unsteady flame becomes much more sensitive to perturbations in the flow and early flame extinction can occur due to unsteady effects. Prior to the occurrence of the dynamic extinction phenomenon, the acoustic response of the system shows a rather rapid weakening as the strain rate is increased. This interesting observation is further addressed in the next section as part of the discussion on the effects of the flame location.

Effect of Flame Location

Twin Premixed Flames

The acoustic response of twin counterflow premixed flames first shows an enhancement with increasing strain rate and then a weakening, i.e. the flame features an optimum location which provides the strongest growth rate of pressure fluctuations. Figure 6 illustrates the effect of the flame location for stoichiometric twin flames employing both the detailed and a set of one-step kinetic models. The final amplitude of the pressure fluctuations at \( t = 10 \) \( ms \), evaluated at the mid-point of the physical domain, is plotted as a function of the location of the peak of the heat release rate. The positions of the flame corresponding to strain rates of 220 \( s^{-1} \) and 1180 \( s^{-1} \) are highlighted. While the one-step kinetic models show approximately the same flame location for a given strain rate, the detailed model differs slightly, especially at a low strain rate. However, in all cases, the optimum location is reported for a strain rate around 1180 \( s^{-1} \).

Single Premixed Flame

The single counterflow premixed flame is considered specifically to further address the effects of the flame location. As shown in figure 7, for a stoichiometric methane-air mixture entering a 1 cm physical domain at 160 cm/s (from the left), the flame is positioned at about \( x = -0.125 \) cm. Without affect-
as the inlet temperature is increased from 400 K to 2000 K, the velocity node moves from the right to the left of the flame front and the growth rate is clearly affected. With an initial amplitude of about 25 dynes/cm², a positive growth rate is reported when the velocity node is downstream of the flame, e.g. $T|_{x=l/2} = 400$ K, similarly to the twin flame results, whereas decay of acoustic pressure fluctuations is predicted when the node is upstream of the flame, e.g. $T|_{x=l/2} = 2000$ K. Compared to the twin premixed configuration, the acoustic response is relatively weak for the single counterflow premixed flame, because of the vicinity of the velocity node and of the single heat release source.

On the other hand, when the one-step kinetic model is employed, a positive growth rate is always reported, regardless of the relative position between flame and velocity node. Figure 8 (b) shows the acoustic response of such a flame for values of the inlet temperature of the hot gases ranging between 800 K and 2000 K.

**Analysis of Flame-Acoustics Coupling**

The propagation of sound waves in a compressible medium is accompanied by fluctuations in all fluid-dynamic and thermo-dynamic variables, including velocity, pressure and temperature. When combustion is present, the flame structure can become unsteady. Specifically, the combustion region features two distinct zones, which can respond differently to acoustic perturbations, namely (i) the transport zone, also referred to as convective-diffusive region,
where convective and diffusive processes are almost balanced, and chemical reactions are frozen, and (ii) the reaction zone, a thin layer, also referred to as diffusive-reactive region, where chemical reactions take place, and chemical processes are almost balanced by diffusive processes.

**Time-Scale Analysis**

In the literature\(^6,15,18\), most theoretical investigations on acoustic wave interaction with flames have attempted to characterize the flame response in terms of characteristic time-scales. Considering the flame structure and the physical and chemical processes involved, three time-scales are usually employed:

- \(\tau_{\text{acou}}\), the characteristic time scale of the acoustic perturbation due to the propagation of acoustic waves or the establishment of natural acoustic modes;
- \(\tau_{\text{diff}}\), the characteristic response time of the transport zone, since in this region diffusion processes balance convection processes;
- \(\tau_{\text{chem}}\), the characteristic response time of the reaction zone.

In terms of the scaling of \(\tau_{\text{diff}}\) and \(\tau_{\text{chem}}\) with respect to \(\tau_{\text{acou}}\), several cases have been addressed theoretically with a one-step global irreversible reaction, the most relevant to the counterflow configuration being:

1. \(\frac{\tau_{\text{diff}}}{\tau_{\text{acou}}} \sim 1\), intermediate frequency acoustic waves, resulting in an unsteady response of the transport zone;
2. \(\frac{\tau_{\text{chem}}}{\tau_{\text{acou}}} \sim 1\), high frequency acoustic waves, resulting in an unsteady response of the reaction zone.

Based on the analysis of the local time-scales defined across the flame structure\(^6\), table 1 summarizes the ratios of the relevant characteristic time-scales for the premixed configuration with twin flames for the one-step and the detailed kinetic models.

**Transport Zone**

With respect to the ratio of the diffusive time-scale over the acoustic time-scale, even at a strain rate of 220 \(s^{-1}\), the estimated values are not too large, ranging from 5 to 20, suggesting the acoustic response of the transport zone. As the strain rate is increased to 1180 \(s^{-1}\), the ratio \(\tau_{\text{diff}} / \tau_{\text{acou}}\) for the reactants decreases slightly. Specifically, for the detailed kinetic model, \(\tau_{\text{diff}}/ CH_4 / \tau_{\text{acou}}\) decreases from a value of 5.7, which is already relatively small, to a value of 3. Consequently, it is not surprising that counterflow premixed flames with the detailed chemical kinetic model exhibit an acoustic response to perturbations in the flow field.

**Reaction Zone**

For the one-step kinetic model, at both strain rates, chemical time-scales are relatively close to the acoustic time-scale. Based on the understanding of the sensitivity of reaction rates due to acoustic perturbations, the ratio of \(\tau_{\text{chem}} / \tau_{\text{acou}}\) of \(O(1)\) suggests the interaction between chemistry and acoustics. In fact, the strong positive growth rate observed with one-step kinetic models with large activation energy is consistent with the natural combustion resonance reported by McIntosh\(^19\).

On the other hand, the characteristic chemical time-scales for the elementary reactions of the detailed kinetic model vary over a wide range. Based on the analysis of the heat release rate contributions discussed next, it is very unlikely to observe chemical kinetic-acoustic coupling with the detailed mechanism. Therefore, these time-scales are not reported.

**Analysis of Heat Release Rate**

In general, the rate of heat release of a reaction, \(\dot{q}\), is controlled by the corresponding rate of reaction, \(\omega\), since \(\dot{q} = (-\Delta H^0)\omega\), where \(-\Delta H^0\) is the heat release associated with the reaction.

For a reaction rate with the rate constant expressed in the Arrhenius form, the sensitivity on temperature is dominant and is a function of the activation energy, \(E_a\). Due to the characteristic exponential temperature dependence, \(\omega \sim \exp(-\frac{E_a}{RT})\), with \(T\) the temperature and \(R\) the universal gas constant, the thickness of the reaction zone decreases as the activation energy increases. Consequently, the heat release takes place in a thinner region characterized by a higher temperature, and the sensitivity to temperature fluctuations also increases.

Depending on the net exothermicity or endothermicity of a reaction, fluctuations in temperature can accelerate or decelerate the reaction rate. For an exothermic reaction with large values of activation energy, heat release oscillations can be significantly enhanced.

**One-Step Kinetic Models**

In one-step global kinetic models a single irreversible exothermic reaction is employed, generally

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Table 1: Summary of characteristic time-scale ratios for counterflow twin premixed flames at $a = 220 \text{ s}^{-1}$ and $a = 1180 \text{ s}^{-1}$ employing the one-step and the detailed kinetic models.

<table>
<thead>
<tr>
<th>$E_a$ *</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>Strain rate $\tau_{\text{diff}, CH_4} / \tau_{\text{acou}}$</th>
<th>Strain rate $\tau_{\text{diff}, O_2} / \tau_{\text{acou}}$</th>
<th>Strain rate $\tau_{\text{chem}} / \tau_{\text{acou}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>220 $\text{ s}^{-1}$</td>
<td>1180 $\text{ s}^{-1}$</td>
<td>220 $\text{ s}^{-1}$</td>
</tr>
<tr>
<td>15</td>
<td>1.0</td>
<td>1.0</td>
<td>20</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>30</td>
<td>1.0</td>
<td>1.0</td>
<td>8.6</td>
<td>6</td>
<td>8.6</td>
</tr>
<tr>
<td>45</td>
<td>1.0</td>
<td>1.0</td>
<td>5.7</td>
<td>4</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DETAILED</td>
<td></td>
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</tr>
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<td></td>
<td></td>
<td></td>
<td>5.7</td>
<td>3</td>
<td>6.6</td>
</tr>
</tbody>
</table>

* Units are $\text{kcal/mole}$.  

featuring values of activation energy ranging from 15 $\text{kcal/mole}$ to more than 45 $\text{kcal/mole}$. Under such conditions, the rate of reaction and consequently the rate of heat release can become very sensitive to perturbation in the flow field. In particular, whenever the reaction region of the flame responds unsteadily with fluctuations in the reaction rate, the associated heat release rate oscillates in-phase with pressure since the reaction is exothermic. Therefore, it is not surprising to observe the self-sustained amplification of acoustic pressure fluctuations for almost all one-step kinetic models.

Clearly, such coupling between acoustics and chemical kinetics is greatly enhanced as activation energy is increased. However, for the chemical kinetics-acoustics interaction to take place, it is necessary that the acoustic time scale is close to the chemical time scales, i.e. the diffusive-reaction region is modified by the fluctuating acoustic field.

**Detailed Kinetic Model**

A detailed kinetic model features a large number of reversible and irreversible elementary reactions, which can be exothermic and endothermic. Unlike the global reaction in a one-step kinetic model, elementary reactions feature values of activation energy that can vary considerably, ranging from zero for three-body reaction or even negative values to very large positive values. However, the activation energy of the majority of elementary reactions does not exceed 5 $\text{kcal/mole}$.

In order to account for the sensitivity of each elementary reaction to perturbations in the flow field, both the forward and backward steps need to be analyzed separately, since a change in the reaction rate in only one direction can affect the net reaction rate. In light of the previous discussion on the sensitivity of reaction rates, those reaction steps with large activation energy and associated with a large heat release are most important in assessing the unsteady response of the reaction region to acoustic perturbations. It is found that the majority of these reaction steps are endothermic. Therefore, with respect to a potential chemical kinetic-acoustic coupling, the detailed kinetic model provides an intrinsic damping mechanism for fluctuations in temperature or pressure due to the endothermicity of the most sensitive reaction steps.

**Analysis of Flame Location**

Assuming $\tau_{\text{diff}} / \tau_{\text{acou}}$ of $O(1)$, the relative position of the flame with respect to the dominant velocity node plays a major role in the potential coupling mechanism that relates acoustically-induced velocity fluctuations to the unsteadiness in the heat release rate.

**Twin Premixed Flames**

For identical twin flames, the plane of the dominant velocity nodes coincides with the stagnation plane, located at $x = 0$. Consequently, the velocity node is always located downstream of the flame front. Since the reactants are delivered to the flame front from the same direction, any oscillation in the convective flux affects the transport of the reactants into the flame front in the same degree. Specifically, a positive $v'$ induces an increase in the heat release rate ($\dot{q'} > 0$). According to Rayleigh criterion, if $q'$ and $p_0'$ give rise to a positive correlation, then the acoustically-induced fluctuations in velocity provide the driving mechanism for the instability. Intuitively, as the flame approaches the location of the velocity node, oscillations in $v'$ become smaller. In particular, beyond the location of maximum growth rate at about $a = 1180 \text{ s}^{-1}$, as shown in figure 6, a weaker positive growth rate is observed.
and the detailed kinetic model eventually shows decay of acoustic pressure fluctuations.

**Single Premixed Flame**

In the single counterflow premixed flame, the systematic variation of the inlet temperature of the stream of hot combustion products (on the right) allows the modification of the acoustics of the system, i.e. the local speed of sound and consequently the location of the dominant velocity node in the interior of the domain, without affecting the position and the structure of the flame.

As illustrated in figure 9 (a), the velocity node is usually located downstream of the premixed flame front for low temperature values at \( x = \frac{1}{2} \), similarly to the twin flame configuration, whereas figure 9 (b) shows the velocity node positioned upstream of the flame for higher values of temperature. The relative position between flame front and velocity node affects the phasing between velocity and pressure fluctuations, i.e. \( \nu' \) and \( p_0' \), in particular in the region where heat release fluctuations, \( q' \), take place. If the acoustically-induced fluctuation of convective flux of reactants to the flame front is the dominant driving mechanism for the unsteadiness in the heat release rate, as with the detailed kinetic model, the shift in location of the velocity node, going from case (a) to case (b) in figure 9, introduces a phase shift of \( \pi \) between \( \nu' \) and \( p_0' \) in the flame region. This change also implies a phase shift between \( p_0' \) and \( q' \). In light of Rayleigh criterion, if in case (a) \( p_0' \) and \( q' \) have a positive correlation due to the positive contribution of the convective flux of reactants, this correlation becomes negative in case (b) due to the negative contribution of the oscillations in the convective flux of reactants.

Figure 8 (a) shows a positive growth rate of acoustic pressure fluctuations when the flame is downstream of the velocity node (case a) and decay when the flame is upstream (case b) for the detailed kinetic model, whereas figure 8 (b) always indicates amplification of \( p_0' \) for the one-step kinetic model. In light of the discussion on time-scales and sensitivity of heat release rate, although acoustic fluctuations occur on the fast time-scale, chemical kinetic-acoustic coupling is not important when employing the detailed kinetic model. The result for the detailed model indicate that the dominant driving mechanism of the instability is due to the unsteadiness in the transport of reactants to the flame front.

On the other hand, the use of one-step kinetic models with large values of activation energy can lead to the interaction of acoustic waves with the reaction zone. Although the modulation in the transport of reactants is present, the coupling between finite-rate chemistry and acoustics is the dominant driving mechanism and is independent of the phasing between \( \nu' \) and \( p_0' \).

**Conclusions**

The fundamental coupling mechanisms driving self-sustained thermo-acoustic instabilities were investigated in twin and single counterflow premixed flames. It was found that use of one-step kinetic models featuring large values of activation energy on the fast time-scale leads to chemical kinetic-acoustic coupling. Premixed flames are also likely to respond unsteadily to acoustically-induced fluctuations of the mass flux of reactants into the flame, provided that the velocity fluctuation at the flame precedes the pressure fluctuation. A detailed analysis of characteristic time-scales, heat release rate and flame location was conducted to gain a better understanding of these coupling mechanisms responsible for triggering and driving the amplification of pressure fluctuations.
Acknowledgements
This work was supported by the Virginia Space Grant Consortium and the University of Virginia.

References


