Characterizing the fluctuations in gaseous detonation fronts

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The intrinsic instability of unsupported detonation waves results in three-dimensional spatial and temporal oscillations in the lead shock strength and consequent temperature and velocity fluctuations in the flow behind the lead shock. Inhomogeneous temperature and velocity fields have a significant effect on the reaction rate and in regular mixtures the spatial oscillation in the lead shock clearly results in keystone structures in the reaction zone front with shear layers separating gas with different degree of reaction.

As many researchers (1, 2, 3) have observed from soot foils and schlieren images and also predicted from stability analysis (4), the spectrum of length scales present in the front increases with increasing reduced activation energy. Hydrocarbon systems with reduced activation energies on the order of 12 are highly unstable, exhibiting a very disorganized structure with features over an extremely large range of length scales. Many studies (5, 6, 7) have also shown that the dynamic behavior of the detonation depends on the reduced activation energy with different scaling of macroscopic parameters such as critical initiation energy and diffraction diameter. Substantially different features have been observed in highly unstable detonations, including localized explosions, the potential for local decoupling, and mixing of reaction and unreacted gas across unstable shear layers. More work is needed to understand the nature of the highly unstable detonations.

The unstable, fluctuating nature of detonations has been motivated some researchers to make an analogy with premixed turbulent combustion (8, 9, 10). In turbulent combustion, the reaction front is affected by the incoming eddies of the external flow which stretch the flame front, increasing the surface area and burning velocity. If strain rates are high enough (on the order of $10^2 - 10^3$ s^{-1}, depending on the chemistry) local extinction of the reaction may occur. In detonation, the reaction is affected by the oscillation in the lead shock strength that results in changes in the reaction rate through the Arrhenius kinetics. If the lead shock fluctuation rate exceeds the critical decay rate, local decoupling, or quenching of the detonation may occur.

In turbulent combustion, the effects of turbulence can be summarized in a map of combustion regimes, commonly called the Borghi diagram, Fig. 1, based on the work of numerous researchers (11). We propose that a similar diagram may be constructed for detonation. As the axes of the diagram, we choose the magnitude of the lead shock oscillation normalized by the local average U'/U_{CJ}, and the magnitude of the fluctuation in the reaction time normalized by the local average τ'/τ_{CJ}. The induction time for a detonation propagating at U_{CJ} is τ_{CJ}. These quantities are analogous to the axes defined in Fig. 1 since the fluctuation (due to the cellular instability) is about the stable or “laminar” CJ solution.

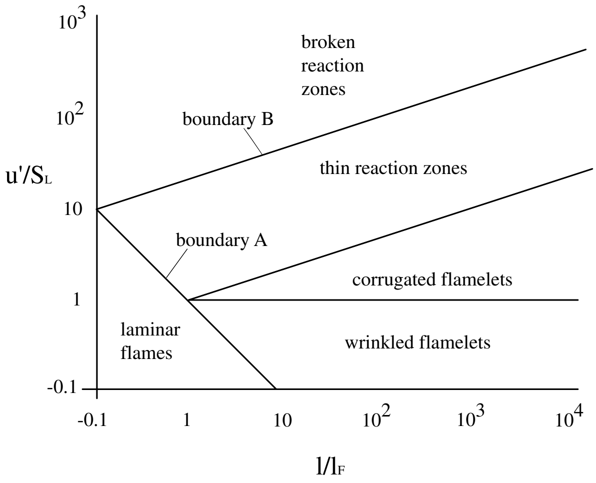

Figure 1: Premixed combustion regimes after Peters (11). u' is the rms velocity fluctuation, S_L is the laminar flame speed, l is the integral length scale, and l_F is the flame thickness

Two boundaries from the Borghi diagram are considered in particular: boundary A between laminar and turbulent flames, and boundary B between distributed, or broken, reaction zones and continuous reaction zones.

To construct the analog of Boundary A for the detonation, we draw the analogy between the Reynolds number in turbulent flames and the activation energy in detonation. These quantities each play the role of control parameters for the instability. Induction time fluctuations are related to lead shock velocity fluctuations through the activation energy. The induction time may be approximated as

$$\tau = A \exp\left(\frac{E_a}{RT_{vN}}\right) \tag{1}$$

where T_{vN} is the post-shock temperature. Using the strong shock relations, we derive

$$\frac{\delta\tau}{\tau} \sim -2\theta\frac{\delta U}{U} \tag{2}$$

The negative sign occurs because an increase in the lead shock strength decreases the induction time. For the present analysis, we are interested in the magnitude of the fluctuation, so we define

$$\tau' = |\delta\tau| \tag{3}$$
$$U' = |\delta U| \tag{4}$$

and relate the lead shock velocity fluctuation to the induction time fluctuation

$$\frac{U'}{U_{CJ}} \sim \frac{1}{2\theta} \frac{\tau'}{\tau_{CJ}} \tag{5}$$

A critical value of the activation energy for the onset of instability may be taken as the asymptote of the neutral stability curve from Lee and Stewart (12), $\theta \sim 4.5$, forming a boundary for the transition between stable (or "laminar") detonations, which are only observed in numerical studies, and unstable detonations.

An analogy to the second boundary B between distributed and wrinkled reaction fronts is derived from the critical decay rate (CDR) model of Eckett et al. (13). This model was applied previously (14, 15) as a criterion for local decoupling, or quenching, of the detonation through a cell cycle. We recast the model in terms of the current variables to form a boundary between coupled and locally decoupled fronts.

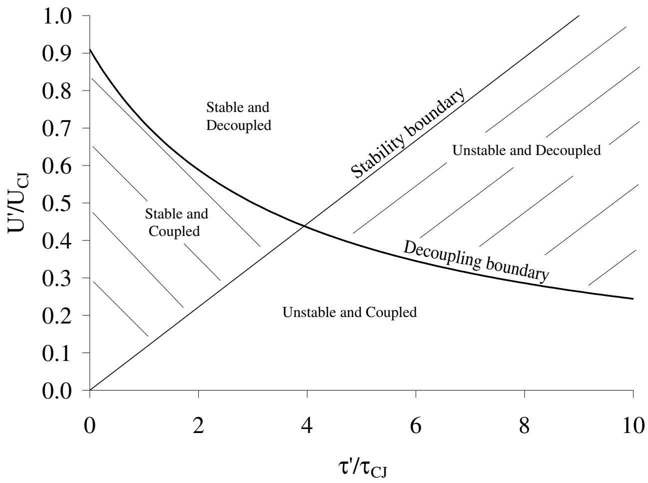

Figure 2: Proposed map of combustion regime boundaries for detonation. The axes are the magnitude of the lead shock oscillation normalized by the local average U'/U_{CJ} and the magnitude of the fluctuation in the reaction time normalized by the local average τ'/τ_{CJ}. These quantities are analogous to the axes defined in Fig. 1 since the fluctuation (due to the cellular instability) is about the stable or "laminar" CJ solution. Four regimes have been identified. The boundary (Eqn. 5) between unstable and stable detonation refers to the presence or absence of cellular instability. (Stable fronts are only observed in numerical simulations.) The boundary between coupled and decoupled is found by reformulating the criticla decay rate model of Eckett et al. (13).

The results of the stability and decoupling analyses presented above are combined in Fig. 2 to delineate four regions of detonation behavior for θ= 4.5. The decoupling boundary for θ=4.5 is shown. Consider a fixed perturbation in the lead shock velocity of about 30%, corresponding to U'/U_{CJ} = 0.3 in Fig. 2. If the activation energy of the mixture is such that this perturbation in the lead shock strength results in a fluctuation in the induction time of less than 2.5 times the CJ induction time, $\tau' \leq 2.5\tau_{CJ}$, the detonation is stable with no cellular structure. This case is not physically realistic since all laboratory experiments result in unstable fronts and stable fronts are only observed in numerical simulations. If the response in the induction time is $2.5 \leq \tau'/\tau_{CJ} \leq 8$, a coupled detonation with cellular instability results. This is the case in marginally unstable detonation. If the normalized fluctuation in the induction time is larger, $\tau' \geq 8\tau_{CJ}$, local decoupling, or quenching, of the front, may occur. This appears to be the case for highly unstable detonation. We make comparisons with available experimental and numerical data.

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