Indirect detonation initiation using acoustic timescale thermal power deposition

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Abstract

A fluid dynamics video is presented that demonstrates an indirect detonation initiation process. In this process, a transient power deposition adds heat to a spatially resolved volume of fluid in an amount of time that is similar to the acoustic timescale of the fluid volume. A highly resolved two-dimensional simulation shows the events that unfold after the heat is added.

Traditionally, combustion modelers have concluded that detonations form either by direct initiation or by Deflagration-to-Detonation Transition (DDT). Direct initiation is accomplished by depositing a large amount of energy deposited in a short time period such that a blast wave is created inside the reactive gas mixture. In DDT, diffusion, viscosity, and turbulence play a major role in preheating the reactive mixture to facilitate detonation formation [1, 4, 5, 6, 8]. These transport processes have little or no effect in direct initiation.

Direct initiation and DDT can be seen as two limiting extremes on a continuum scale using the acoustic timescale theory of Kassoy [2]. Consider a fluid volume of length scale $l$ and sound speed $a$ such that the acoustic timescale of the fluid volume can be defined $t_a = l/a$. If heat is added to the fluid volume on a timescale $t_h$ that is short compared to the acoustic timescale $t_h \ll t_a$ then the fluid experiences nearly constant volume heat addition. The amount of energy added to the volume determines whether it will form acoustic, shock, or blast waves.

The numerical simulation presented in this video focuses on acoustic timescale detonation initiation, where heat is deposited on a timescale simil-
ilar to the acoustic timescale $t_h \sim t_a$. The two-dimensional simulation presented in this video begins with a reactive mixture initially at rest and heat is added to a circular volume on the acoustic timescale $t_h \sim t_a$.

The simulation begins with the reactive gas at rest with the initial condition $\rho_0 = p_0 = Y_0 = 1$ and $v_0 = 0$. The domain lies in $x \in [-3, 57]$ and $y \in [-3, 12]$ and reflecting slip walls are present on all walls except the exit $x = 57$. The heat addition is limited to a circle of radius $R = 2$ centered at the origin. The simulation uses a heat of reaction $q = 15$, specific heat ratio $\gamma = 1.4$, activation energy $E = 13.8$, and pre-exponential factor $B = 35$. Heat is added between $t_a = 0.5$ and $t_b = 5.25$.

The Parallel Adaptive Wavelet-Collocation Method (PAWCM) is used to capture the wide range of scales that are present [3, 9]. The PAWCM combines second generation wavelets with a prescribed error threshold parameter $\epsilon$ to determine which grid points are necessary in order to achieve a prescribed level of accuracy. The hyperbolic solver developed for the PAWCM is used to maintain numerical stability and reduce spurious oscillations across jump discontinuities [7]. The effective grid resolution for the simulation is $15360 \times 3072$.

Figure 1 demonstrates the indirect detonation initiation process by presenting a series of snapshots of temperature contours corresponding to the same events shown in the video. Heat is deposited in a circle in the bottom left hand corner from $0.5 \leq t \leq 5.25$. The rapid deposition of heat creates compression waves that propagate away from the initially heated region. Before $t = 2$, the reactants inside the deposition region are consumed in a chemical explosion, which adds additional heat to the deposition region. It is difficult to discern from the contour at $t = 2$, but the interface between the burning and reactive gas forms a rippled surface. It is thought that this is a result of the Darrieus-Landau instability at the burning gas interface because once the reactants are consumed the growth of surface fluctuations ceases.

At some point shortly after $t = 2$ when the compression waves first reflect off the left and bottom walls the compression waves become fully discontinuous shock waves. The reflected and transmitted shocks form Mach stems that propagate in the positive $x$- and $y$-directions. The reflected waves impinge on the burnt-unburnt gas interface and induce Richtmyer-Meshkov instabilities, which then increase the fluctuation magnitude at the material interface. This can be initially observed in the $t = 3.5$ contour.

At about $t = 2.5$, a second explosion occurs in the lower left corner when the shock waves reflect off the bottom and left walls and raise the pressure in that region in a duration short enough that the temperature
Figure 1: Sequence of temperature contours demonstrate the multidimensional indirect detonation formation process for times $2 \leq t \leq 24$.

rises with pressure. The reactive gas explodes once it has reached a sufficient temperature.

In the $t = 5$ frame, the original outward propagating shock wave has reflected off the left and bottom walls and the Mach stems are clearly visible in the temperature contour. On the left wall, the leading edge of the shock wave is just about to reflect off the upper wall, starting in the upper left corner. When reflection occurs on the upper boundary, a hot spot appears in the upper left-hand corner of the channel, characterized by substantial local inertial confinement. This hot spot releases heat and generates compression waves that propagate away from the hot spot location.

At $t = 7$, Fig. 1 shows the reflected wave re-enters the reacted region and is refracted, which induces an additional longitudinal component to the wave direction. The transverse waves compress and heat previously unreacted fuel.
pockets, which ignite and help produce additional longitudinal waves, as well as sustaining the transverse waves the reverberate off the top and bottom walls.

Kelvin-Helmholtz roll-up instabilities are clearly visible in frames \( t = [10, 12, 14] \) at the burnt-unburnt gas interface with a fairly high level of detail. The existence of such a detailed interface serves as an indicator that any numerical diffusion present in the algorithm has been minimized to the point that these features are possible to capture.

At about \( t = 14 \) the heat release rate by the preheated gas begins to escalate. This acceleration in heat release can be observed in the temperature contour sequence as the rapid consumption of fuel starting at \( t = 14 \) and ending at \( t = 24 \) with the formation of the over-driven detonation wave emerging from the lead shock front.

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