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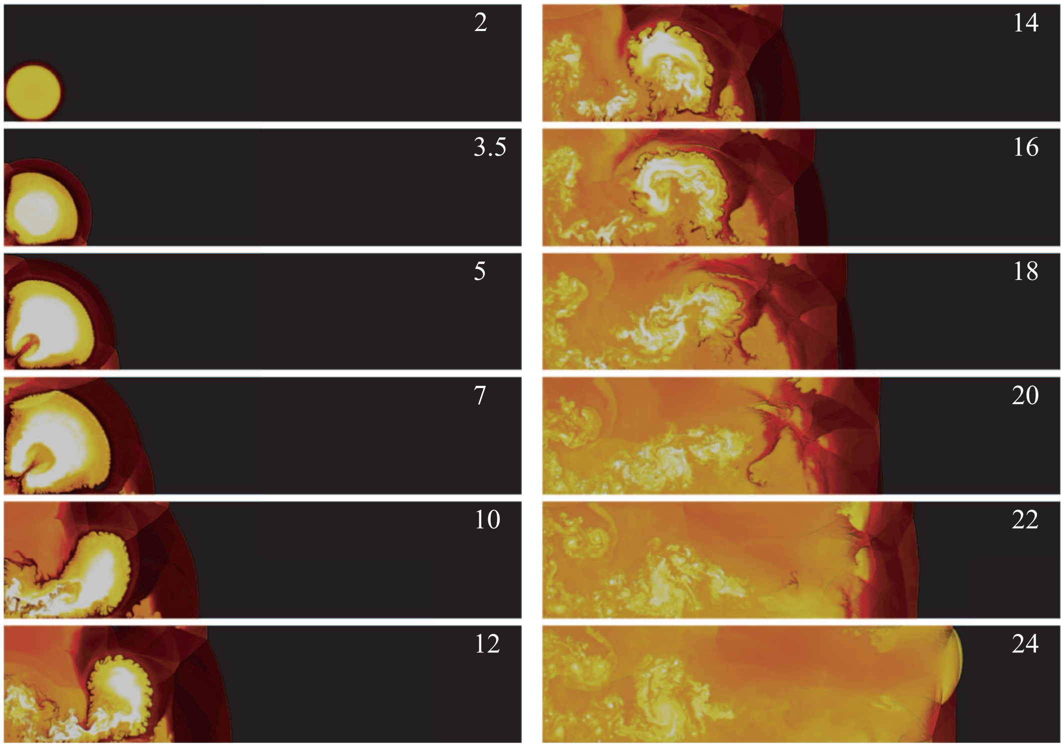

FIG. 1. Sequence of temperature contours demonstrate the multidimensional indirect detonation formation process for times $2 \leq t \leq 24$ (enhanced online) [URL: http://dx.doi.org/10.1063/1.4820130.1].

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Detonations can form through deflagration to detonation transition (DDT) from a laminar flame or through direct initiation from a blast wave. Only a small amount of energy deposition is needed to ignite a flame deflagration. An enormous amount of energy is required to create a blast wave. If the heat addition timescale and size of the region where energy deposition occurs are taken into account using the thermomechanical theory of Kassoy,[1] these two mechanisms can be seen as two limiting extremes on a continuous scale of physical phenomena. This is demonstrated by considering 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 energy is added to the fluid volume on a timescale t_h that is short compared to the acoustic timescale, $t_h \ll t_a$, the fluid experiences nearly constant volume heat addition as long as the energy deposited during the heat addition timescale is less than a specifically defined limit.[1] The

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amount of energy added to the volume determines whether it will be the source of acoustic, shock, or blast waves. Beyond the aforementioned limit the energy addition process is fully compressible, characterized by sonic or greater internal expansion Mach numbers.

The numerical simulation presented in this video depicts the consequences of energy deposition into a circular volume of a reactive mixture initially at rest to produce what can be considered an indirect detonation initiation process. The reactive Euler equations with one-step chemistry are solved using the Parallel Adaptive Wavelet-Collocation Method (PAWCM).[2] The hyperbolic solver developed for the PAWCM is used to maintain numerical stability and reduce spurious oscillations across jump discontinuities.[3] The effective grid resolution for the simulation is $15\,360 \times 3072$.

Both Fig. 1 and the video demonstrate the indirect detonation initiation process with a series of temperature contours. The thermal power deposition heats the gas and reacts on the acoustic timescale, $t_h \sim t_a$, leading to $O(1)$ Mach numbers inside the heated region. The internal gas expansion acts as the source of compression waves in the neighboring gas. The compression waves become shock waves and reflect off the walls to form Mach stems that propagate in the positive x- and y-directions. The reflected shock waves impinge on the burnt-unburnt gas interface and induce Richtmyer-Meshkov instabilities, which then increase the fluctuation magnitude at the material interface.

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. The pressure in that region rises similarly with temperature, indicating a hot spot explosion occurs with little change in density. This two-dimensional event is very similar to the one-dimensional hot spot explosions observed in Regele *et al.*[4]

In the upper left corner of the $t = 5$ frame, the leading edge of the shock wave is just about to reflect off the upper wall. When reflection occurs, a hot spot forms and reacts fast enough to produce a local pressure rise with temperature. The internal gas expansion is the source of a shock wave in the neighboring gas. At $t = 7$, 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 compression waves.

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. At about $t = 14$ the heat release rate by the preheated gas begins to escalate. The acceleration from $t = 14$ to $t = 24$ results in an over-driven detonation wave emerging from the lead shock front. Thus, indirect detonation initiation is achieved. This process is distinctly different from DDT and direct initiation in that there is no transport phenomena involved and no blast wave is created.

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