EXTENDED ABSTRACT
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"FIREBALLS: VERY RAPID DETONATION INITIATION BY TRANSIENT, SPATIALLY RESOLVED POWER DEPOSITION"

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Rationale:

Pulsed Detonation Engines (PDE) employ a cyclic detonation process, ideally at about 100 Hz, to generate thrust. If the fuel/oxidizer mixture is added at an average speed of about 100 m/s to an engine 1 meter in length, the filling time alone requires ten milliseconds. The detonation initiation and evolution process must occur on a much shorter time scale, preferably a millisecond or less.

Conventional wisdom suggests that practical igniters in PDE's will generate turbulent flames that ultimately evolve into a detonation. The evolution process includes rapid acceleration of a turbulent flame front, burning increasingly large amount of reactive mixture per unit time. The enhanced rate of heat release is associated with the spontaneous appearance of tiny hot spots, also known as reaction centers. These tiny regions of locally high pressure (typical length scale about a micron) explode, creating strong blast waves that heat neighboring unburned material as they propagate. Compression wave coalescence leads eventually to the formation of a nearly planar detonation. The millisecond time scale of this evolution implies that the detonation may appear only far downstream in a chamber one meter in length.

Needless to say, the elapsed time for this complex evolutionary DDT is long compared to that for a direct initiation (blast wave initiation of reaction) that might follow a very significant deposition of thermal energy into a tiny volume of reactive mixture on a sufficiently small length scale. Unfortunately, the energy deposition requirements for direct initiation are thought to be incompatible with the PDE mission.

It would be desirable to reduce the detonation initiation time-scale (and the DDT distance) as much as possible in a practical PDE operating in the range 100 Hz. Perhaps the turbulent flame process can be accelerated through the use of tubularizing hardware and perhaps by inducing the needed hot spot distributions as quickly as possible. A second option, perhaps more difficult

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to achieve, is to develop an advanced igniter that can create a critical localized, reactive, high pressure hot spot. In either case, it will be useful to understand how localized hot spots are generated and how they act as both ignition and compression wave sources to facilitate the formation of detonation waves.

Most models of detonation phenomena in PDE's and detonation tubes are designed to predict chamber travel times and pressure-time histories. Typically, the combustion process begins with a plausible, but unrealistic, initiator, because the early time details are not of interest. The primary goal is to produce a sustained detonation as quickly as possible and follow its evolution through the unburned mixture in the chamber. This approach anticipates that the detonation formation process is relatively independent of the igniter characteristics However, it is likely that the early time history of a combustion wave initiated by an imposed blast wave will differ considerably from that following spark ignition or a related form of thermal excitation. This difference can be important in PDE applications where the DDT length needs to be minimized.

Related Studies

Mathematical models of *thermally initiated* planar detonations have been developed to study the earliest phases of combustion wave formation. Numerical solutions to the complete, reactive Navier-Stokes equations are used to show that a significant heat transfer rate from a hot boundary to a colder reactive gas, initially at rest, can be the source of a complex initiation process on the microsecond time-scale (Refs. 1,2,).

References 3 and 4 describe a more physically versatile model of detonation initiation and evolution following thermal power deposition (e.g., a spark) directly into a specified volume of reactive gas at rest adjacent to an insulated boundary. Reactive Euler equations are solved computationally to describe the birth of an overdriven detonation and its evolution to a C. J. wave. The time scale for thermal power deposition is similar to the acoustic time scale of the heated region. A complex series of reactive gasdynamic events characterizes a DDT process leading to an overdriven detonation.

Current Work

The current modeling effort focuses on the formation and evolution of a reactive hot spot initiated by transient spatially distributed thermal power deposition from an external source. A high activation energy, one step reaction is used to model the chemistry. A novel type of asymptotic analysis is used to resolve important time and length scales.

A high pressure hot spot of dimension D' is created by a sufficiently large thermal power deposition on a heating time scale t_H', much less than the local acoustic time scale $t_A = D'/a_o'$, where a_o' is the ambient speed of sound (Ref. 5.). The initial, inert heating process occurs during a brief period of nearly complete inertial confinement. The pressure gradient, compatible with the spatially distributed temperature in this constant volume process, causes the spot to expand.

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Initially, a low Mach number expansion occurs and only weak, linear acoustic waves are generated in the external cold gas. Continued source heating on a defined longer time scale causes the temperature (and pressure) increase in the nearly constant volume process to be asymptotically large relative to the initial values. A high activation energy reaction is initiated in the spot and the external source is extinguished. Chemical heat release causes further large temperature and pressure increases along with a rapid acceleration of the expansion speed to a substantial subsonic value, and the appearance of shock waves in the cold external environment. The latter are not sufficiently strong to initiate a high activation energy reaction.

A locally supersonic, but decelerating reaction wave sweeps across the spot from the superheated center toward the cooler outer region. Near the edge one finds that asymptotically large gradients in temperature and pressure exist in a narrow region separating burned gas from that which has not yet been ignited. The gradients are associated with evolving large temperature and pressure discontinuities that describe dramatic decreases to the relatively cold values at the spot edge. There is an equally large gradient in the concentration of reactant. This reaction front is accompanied by a growing localized velocity maximum, arising from the large local pressure gradient. Asymptotic analysis of the describing equations shows that the accelerating local gas speed and the decelerating reaction wave speed become commensurate at a well defined time and place. The nonuniformly valid solutions for the temperature and pressure gradients, as well as for the growing gas velocity show there is a narrow zone near the spot edge where local Mach number is becoming sonic and where fully compressible reactive gasdynamics must be modeled. These transient solutions describe the evolution of a very high temperature fireball created during a period of near inertial confinement.

The bizarre behavior of the solutions near edge of the fireball describe the emergence of a strong detonation characterized by a strongly supersonic shock across which there are extreme increases in pressure, temperature and velocity. The reaction zone exists adjacent to back of the shock. This coupling is made possible by the asymptotically large temperature rise across the shock causing a very rapid reaction initiation process.

This present analysis describes a “direct” detonation initiation in that the detonation appears at the edge of the fireball. The results are quite different from traditional direct initiation analyses, where an inert blast wave is imposed on a reactive system in order to create the detonation. The energy deposition level need to create the appropriate blast wave appears to be far larger than that predicted for detonation initiation from the current analysis.

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