Numerical Simulations of Multiphase Detonations in Pulse Detonation Engines

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Introduction:

There are many applications that involve multiphase detonations. The motivation for our work is the current interest in Pulse Detonation Engines (PDEs). Most of the PDE related work to date has focused on gaseous mixtures [1]. However, for many practical applications that are volume and weight-limited, the air-breathing PDE will require the use of a liquid fuel. Although significant work has been accomplished in multiphase detonations [for example, 2-6], the field is not as developed as gaseous detonations. For example, different detonation velocities have been observed for a fuel-air mixture of specified stoichiometry depending on parameters such as droplet size and tube diameter [3-6]. While different explanations have been made for the above observation, their effect on the performance of a system such as the PDE has not been ascertained. Recently, some progress has been reported on laboratory PDEs operating on liquid fuels [7, 8]. In this paper, we report on a basic computational study of multiphase detonations in a single tube, idealized PDE.

Liquid fuels in PDEs introduce additional complications such as atomization, droplet breakup, partial vaporization and incomplete fuel-air mixing. Parameters such as droplet size and distribution will play a major role. The sensitivity of the detonation velocity and structure to the fuel droplet size distribution and the axial and radial variations in equivalence ratio are not known. What effects any such variations will have on the head-end pressure necessary for producing thrust of the PDE need to be ascertained. In addition, radial and/or axial injection of the fuel sprays will usually result in considerable wall deposition. A numerical model that can capture radial and axial variations in fuel distributions and the effects of droplet size will be a valuable tool in further investigations of liquid fuelled PDEs. In this paper, we report on the current status of the development of such a computational tool, presenting results on multiphase detonations and comparisons with the limited experimental data that is currently available.

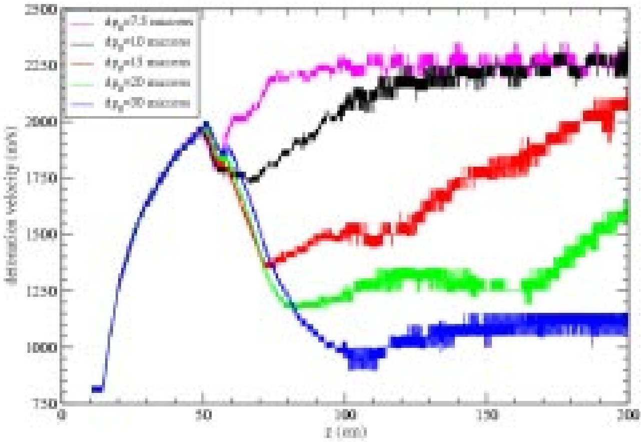
The Numerical Model:

We use a Eulerian-Lagrangian formulation, which includes 2-way coupling between the gas and droplet phases to numerically simulate multiphase detonations. The equations governing the gas-phase flow are solved using the FCT algorithm. Lagrangian particle tracking is used in calculating the position and velocity of the droplets. Effects of the dispersed droplets on the gas phase are accounted for through source terms in the gas phase governing equations. In our simulations of a JP-10-O_2 system, the evaporation rate is modeled through an equilibrium formulation and the induction time is calculated using a temperature and mixture dependent expression.

Results and Discussion:

The geometry simulated is that of a straight tube PDE, closed at one end and open at the other. The pressure profiles from the simulation of a JP10-O_2 detonation show the formation of a detonation wave and a constant plateau pressure region behind the front.

The effect of droplet size on the computed detonation velocity is shown in the figure. Here one sees that for small droplet sizes (less than 10 μm), the detonation after initiation is asymptoting to an equilibrium detonation velocity of approximately 2250 m/s. The computed detonation velocity agrees quite reasonably with experimental measurements at NPS [8]. In their experiments with virtually all JP-10 fuel in droplet form with a mean diameter of 11 μm (+/- 1.5 μm) and with a targeted equivalence ratio of ϕ =1, they observed detonation velocities at the end of their tube near 2250 m/s (+/- 240m/s). Thus the results of our simulations are consistent with their experimental data. In the figure, we also see that for the largest droplet size simulated (30 μm), the detonation velocity settles down to a much smaller value of 1100 m/s. For droplets of intermediate size, the final equilibrium detonation velocity that will be attained is not clear from the simulations. Longer tubes may allow us to ascertain this final detonation velocity. However for practical PDE applications, the length of the tube is limited and such studies will have little value. The performance impact of the observed deficit in the detonation velocities in tubes of finite length is currently being investigated.



Summary:

We have developed a numerical model to simulate multiphase detonations in an idealized PDE. Using an equilibrium vaporization model and temperature-dependent induction time, our numerical simulations of a JP-10-O_2 system give results in agreement with experimental data. Our studies of the effects of droplet sizes indicate that, at least for tubes on the order of 1.5m, droplet sizes larger than about 15 μm result in detonation velocities significantly less than the maximum equilibrium value. More generally, as droplet size increases, detonations asymptote more slowly to an equilibrium velocity. We therefore see the experimentally observed trend that in short tubes, larger fuel droplets result in a smaller detonation velocity. Since our numerical model does not currently allow for heat losses to the tube wall, we conclude that droplet size effects on detonation velocity are not primarily ascribable to such losses. The impact of the above observations on the performance of the PDE is currently under investigation and will be reported at the meeting.

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