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Experimental and numerical investigation of propagation mechanism of gaseous detonations in channels with porous walls

Kiumars Mazaheri [a,*], Yasser Mahmoudi [b], Majid Sabzpooshani [a,1], Matei I. Radulescu [c]

[a] Department of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran
[b] Department of Engineering, University of Cambridge, Cambridge, United Kingdom
[c] Department of Mechanical Engineering, University of Ottawa, Ottawa K1N6N5, Canada

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ABSTRACT

In the present work the propagation of gaseous detonations in a channel with porous walls is investigated experimentally and numerically. The main goal of the study is to determine the role of diffusive turbulent mixing and transverse waves in controlling the detonation limits in channels with porous walls. Detonations in propane–oxygen and hydrogen–oxygen–argon mixtures, which are characterized by their irregular and regular cellular structures, are considered in the experimental and numerical investigations. Euler simulations are performed for parameters corresponding to both regular and irregular detonations. In the smooth wall region Schlieren photographs of hydrogen–oxygen–argon detonation show laminar reaction zones behind the main front. In addition, as the detonation propagates over the porous wall, due to the mass divergence into the damping section, the frontal wave curvature increases. The number of transverse waves decreases in the porous section which is caused by the attenuation of the detonation wave. In comparison to the stable argon diluted detonations, experiments for unstable propane–oxygen detonations illustrate lower wave curvature and high turbulence in the reaction zone in the porous section. The numerically obtained results for both regular and irregular detonations show that close to the porous wall the front curvature increases, a finding that is also observed in experiments. If the curvature extends to the whole channel width the detonation wave fails to propagate. Nevertheless, the numerical critical limit of W/λ for unstable detonations is found to be higher than that of stable detonations, which is in contradiction with the experimental results. This discrepancy can be explained by the effect of turbulent diffusive mixing in controlling the reaction rate in highly unstable detonations, which is not taken into account in the current numerical simulations.

1. Introduction

Recently, increasing attention has been focused on gaseous detonation and the need to study explosion hazards in pipeline transportation systems of gas hydrocarbon fuels. The propagation of a detonation wave through a channel with porous walls is a fundamental detonation problem. The effects of pores on the wave dynamics influence the global propagation characteristics of the detonations [1]. Experiments have revealed that detonation fronts exhibit complicated three-dimensional time-dependent cellular structures consisting of an ensemble of interacting triple points, turbulent shear layers and transverse shocks [2–4]. While the conventional ignition mechanism of the gases in the detonation wave structure is via adiabatic shock compression, there is growing evidence that the turbulent mixing of species and energy can also be responsible for controlling the reaction rates in gaseous detonations [5–10]. In regular structure detonations, intense chemical activity is observed behind the leading shocks, where very few signs of unreacted pockets are found behind the lead shock [11–13]. Conversely, it has been shown numerically [7,14,15] and experimentally [9,16–18] that in irregular structure detonations, hydrodynamic instabilities generate a turbulent mixing zone of hot reacted and cold unreacted gases. These instabilities are of the Richtmyer–Meshkov (RM) and Kelvin–Helmholtz (KH) types [9,15,19]. From a practical perspective, the rate of decomposition of the gases in the detonation wave structure is expected to control the detonability limits of a given gaseous mixture. For example, the rate of energy release within the detonation structure controls the ability of detonations to propagate in tubes with lateral losses.

* Corresponding author. Fax: +98 21 82883962.
E-mail address: kiumars@modares.ac.ir (K. Mazaheri).
[1] Current address: Department of Mechanical Engineering, University of Kashan, Kashan, Iran.

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Global hydrodynamic models pioneered by Zeldovich and Kompaneets [20] can be constructed to determine how the detonation wave propagates (or not) in the presence of frictional and heat losses [21] and mass divergence into the boundary layers at the walls [22,23]. The experiment configuration proposed to capture the dependence of detonability limits on the physical processes controlling the reaction rate in the detonation structure itself is the detonation propagation in tubes with porous walls [24–30]. When detonations propagate through porous-walled tubes, the permeability of the walls leads to gas leakage into the walls. Figure 1 shows a schematic of the resulting reaction zone structure. The divergence of the flow in the reaction zone is analogous to the detonation structure with yielding confinement in condensed phase detonations [2], i.e. the rate stick experiment. On smaller scales, the porous walls also act as a damper of transverse pressure waves, which attenuate upon reflection [24]. Indeed, most investigations of detonations in porous walls attribute the detonation failure solely to the attenuation of transverse pressure waves [25,29,31]. In reality, the porous wall acts as an ideal boundary loss that simultaneously renders the wave one-dimensional by suppressing the multi-dimensional transverse wave structure. This introduces the lateral mass divergence mechanism of failure, which can be simply modeled and permits meaningful comparison between experiment and predictions. Such a comparison was conducted by Radulescu [27] and Radulescu and Lee [26].

Figure 2 shows the experimentally [27] obtained dependence of the detonation wave speed on the porous tube diameter for two detonable mixtures with significantly different reaction zone structures. This figure illustrates the quenching of the detonation wave below a certain critical value of the tube diameter. The detonation in the acetylene–oxygen–argon mixture has a laminar reaction zone structure, while methane–oxygen detonations have a very turbulent reaction zone structure [9]. The experimental results (symbols) are compared with predictions made from a quasi-one-dimensional model (lines) obtained with realistic chemistry and accounting for the lateral mass divergence in the reaction zone without any empirical parameters [27]. For the regular detonation, the model effectively captures the experimentally determined limit and velocity deficit. For the highly irregular structure detonation, the model predicts the detonation failure limit at an order of magnitude larger than obtained experimentally. Likewise, the detonation is able to propagate at lower velocities in the experiments (i.e. 65% of the CJ velocity), but the model predicts extinction at speeds below ~95% of the CJ velocity. Moreover, while the model predicts the limits to be narrower in the more irregular mixture (i.e. a larger critical diameter), the experiments show the opposite trend. Previous investigations [26,27] have speculated that this inconsistency is due to the role of transverse waves, which is not taken into account in the 1D model. These very large departures obtained for the highly irregular detonations were interpreted as indicative of multi-dimensional effects on the global reaction zone structure of highly unstable detonations and the potential role of transverse waves and turbulent mixing in suppressing the thermal character of the ignition process in the detonation structure [9].

Very recently Mehrjoo et al. [32] conducted a series of experiments to investigate the failure mechanisms of detonations in a porous-walled tube. They confirmed the previous failure mechanism of stable and unstable detonations and concluded that for unstable turbulent detonations, the successful transmission relies heavily on the frontal instability to generate local explosion centers, while, for stable laminar cases the failure is caused by the excessive global curvature.

The current paper presents a series of experiments and numerical results aimed at clarifying the detonation propagation and failure mechanism in porous wall tubes. This is to determine the role of detonation instability and multi-dimensional effects in controlling the reaction rates in detonation waves. The experiments are conducted with detailed flow visualization of the wave structure in the porous wall section. Due to the failure of quasi 1D model in predicting the detonability limit in unstable detonations, we then utilized the porous wall model developed by Reddy et al. [28] and performed 2D unsteady inviscid Euler simulations to explore the role of transverse waves and hydrodynamic instabilities in the propagation mechanism of gaseous detonations in leaky channels. The computations were performed for low, moderate and high activation energy mixtures to study how the change in activation energy affects the detonability limits in permeable channels. The detailed simulations offer more insight into the accuracy of quasi-one-dimensional models, and aim at clarifying the mechanism of wave curvature following the detonation interaction with porous walls. The results are then interpreted in terms of the flow divergence model introduced by Radulescu [27]. The plan of the paper is as follows. The details of the experimental set-up are presented in Section 2. The mathematical model formulated to capture the detonation interaction with a porous wall is given in Section 3. Section 4 discusses the numerical method used to solve the mathematical model. The boundary and initial conditions are defined in Section 5. The numerical results relevant to the attenuation of detonation in low activation energy mixtures are discussed in Section 6.1. Section 6.2 presents the numerical results for attenuation of detonation in moderate activation energy mixtures. To compare with the experiments the results for highly unstable detonations are presented in Section 6.3. To confirm that the wave curvature and detonations structure is well captured by the resolution employed, the effect of grid resolution is presented in Section 6.4. The 1D numerical simulation of the effect of area divergence on the reaction zone structure is presented in Section 7. The experimental results are presented in Section 8. Section 9 gives the comparison between numerical results and experimental observations and finally Section 10 concludes the paper.

2. Experimental details

To study the reaction zone structure of detonations propagating in a porous wall tube, a series of experiments were performed for both stable and unstable detonations. The experiments were performed at the Shock Wave Physics Group Laboratory at McGill University. The details of the experimental set-up are presented in Radulescu [27] and Radulescu and Lee [26]. The experiments were performed in thin rectangular channels, 1 m long, 10 cm in height and 2.5 cm in width. The porous wall section was 46 cm long. The porous walls were obtained by lining the top and bottom walls of the channel with 14 layers of wire mesh. The steel mesh had four wires per millimeter, each wire of a diameter of 0.114 mm. The resulting open area ratio of each wall was 30%. A schematic of experimental setup is shown in Fig. 3.

Two opposing walls of the channel were made of glass, which permitted flow visualization. The propagating detonations were visualized using a Schlieren Z-set-up using a 1-μs duration light source (Palflash) and a regular 35 mm camera for recoding images. A neutral density filter was used to attenuate the light signal and hence eliminate any self-emission. The mixtures investigated were stoichiometric oxy-hydrogen diluted with argon and oxy-propane. Detonation in propane mixture displays a very irregular cellular structure [33] while, the argon-diluted hydrogen detonation exhibits a very good cellular regularity [33]. The mixtures were prepared before an experiment in a separate vessel by the method of partial pressures and allowed to mix for at least 24 h. The detonation tube was evacuated before an experiment to pressures less than 0.07 kPa. The mixture sensitivity was controlled by the initial