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Understanding flame trapping in detonation combustion via vacuum chambers

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ABSTRACT

It is of great interest for the engineering community to understand effective mechanisms to inhibit transition from deflagration to detonation (DDT). Recent experimental studies indicate that suppression of DDT is possible by incorporating a vacuum chamber adjacent to the propagation tunnel. In the present study computational fluid dynamic simulations are used to evaluate the influence of such a low pressure chamber on the propagation of deflagration and detonation waves. This study focuses on understanding the mechanisms by which such suppression is possible. It is demonstrated via numerical experiments that the success depends strongly on the location of the chamber w.r.t propagation of detonation pressure waves.

1. Introduction

Explosions in industrial and mining setting remain a major cause of economical and human losses despite increase in safety regulations. Approximately 200 fatalities have been reported in the USA between 1970 and 2010 as a result of explosions caused by natural gas and coal dust (United States Department of Labor; Zipf et al., 2014). Recent research on the mechanism of flame acceleration and transition from deflagration to detonation (DDT) has provided a better understanding on factors that enhance flame acceleration and that may lead to detonation events (Ciccarelli and Dorofeev, 2008; Gamezo et al., 2008, 2007; Kessler et al., 2010; Oran and Gamezo, 2007; Oran et al., 2011; Peraldi et al., 1988; Smirnov et al., 2014; Zipf et al., 2014). In addition to the experimental, numerical, and analytical research on DDT, significant efforts to design efficient flame arresters, and detonation suppression mechanism have been reported (Jiang et al., 2008; Shao et al., 2014; Wu et al., 2009). The commonly used method for suppression of explosive flames is to spray or mix some materials into the region which is susceptible to explosion, or to extinguish the flame after the ignition took place. Commonly used suppression materials are, water mist, inert gases, inert dust or powders. A review of these methods can be found in (Shao et al., 2014). The current paper focuses on the recently proposed methodology for the suppression of flame and explosion propagation based on the incorporation of a low pressure chamber on the path of the propagating detonation wave (Jiang et al., 2008; Shao et al., 2014; Wu et al., 2009).

The experimental study performed in (Jiang et al., 2008; Shao et al., 2014; Wu et al., 2009) demonstrated that a low pressure chamber placed perpendicular to a rectangular tube in which a Methane Air flame propagates, decelerates and ultimately avoids DDT. In these experiments, the low pressure region was separated from the detonation channel by a thin glass layer that breaks under the pressure disturbances ahead of the flame. No active control of the diaphragm activation was reported. In addition, it was concluded that the overpressure produced inside the detonation channel is reduced from 1.4 MPa to 0.16 MPa once the low pressure chamber was activated. Wu et al. (Wu et al., 2009) extended the study reported in Jiang et al. (Jiang et al., 2008) to investigate the effects of shape and size of the vacuum chamber on explosion suppression. This experimental study indicated that the cross-sectional area of the connected chamber should be in the same order of magnitude as the tunnel itself and the length of the chamber should be greater than 5% of the tunnel length. In these studies (Jiang et al., 2008; Wu et al., 2009), it is also suggested that the chamber should be located closer to the ignition source, however the question of how close is not quantified. Moreover, at what time relative to the detonation wave, the barriers should be broken is not known. In a similar study, Shao et al. evaluated the propagation of a reaction front in Methane air mixture inside an L-shaped duct (Shao et al., 2014). The vacuum

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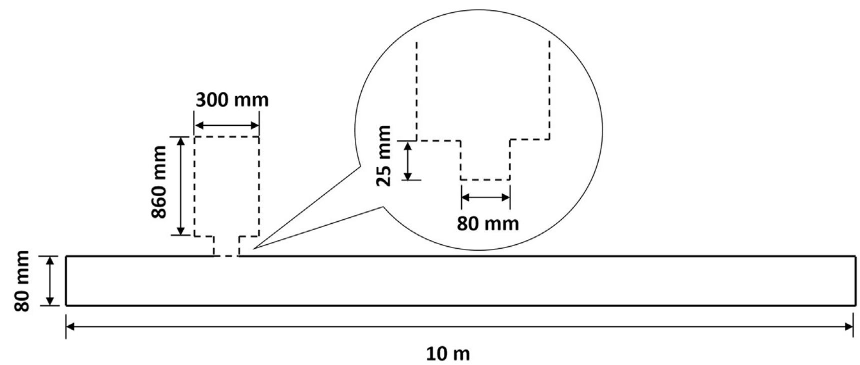

Fig. 1. Sketch of the geometry used in numerical simulations.

chamber was placed at the turning point of the L-shaped duct. A firing pin extending from the vacuum chamber into the detonation channel was used as activation mechanism to break the diaphragm separating the low pressure region. Different lengths of the firing pin were implemented in order to establish the influence of the time delay and the suppression effectiveness of the mechanism. It was concluded that suppression of the flame and explosion-over pressure is possible for conditions under which the diaphragm is broken in coordination with the presence of the detonation front.

Despite much experimental research on the suppression of deflagration and detonation propagation by the means of low pressure chamber, little numerical or theoretical research has been reported on this subject. The current paper presents numerical simulations performed towards a better understanding of the suppression mechanism by which vacuum chambers are effective in preventing deflagration to detonation transition (DDT). Some preliminary results relevant to the current study can be found in (Escobar et al., 2015). In order to control DDT, predictive models are needed. The prediction of DDT is not a trivial matter while it is function of many parameters and their interaction there of; such as geometrical details, fuel type, stoichiometry, turbulence-chemistry/flame interaction, and last but not the least important, the nature of inherent numerical errors, e.g. artificial viscosity. A more detailed discussion of DDT can be found in the recent studies (Kessler et al., 2010; Rosas et al., 2014; Smirnov et al., 2014; Zipf et al., 2014). As far as the present study is concerned the relevant issues are (i) to have a scheme with which a transition from deflagration to detonation is possible, (ii) to have a method whereby a rough approximation of the location of DDT can be made. The first is accomplished by way of using a quasi-laminar fluid model as explained later, and the second is done by using the criteria cited by (Rosas et al., 2014) and suggested by (Peraldi et al., 1988). According to (Peraldi et al., 1988), DDT is most likely when the flame speed approaches the local speed of sound for the combustion products. The numerical study presented here explores some of these concepts and their viability with regards to suppression of DDT.

In the current paper, we first elaborate on the numerical scheme and parameters used in the simulations. Then we perform the numerical study of transition from deflagration to detonation (DDT) in a straight channel without the presence of the chamber. The results show the detailed processes of DDT. Finally, we investigate the DDT within a channel fitted with a low pressure chamber to illustrate the suppression effects of such a chamber. Furthermore, we also propose a criterion for the best location of the chamber to suppress the DDT, which will yield positive consequences in the development of explosion prevention technique relevant to mining industries.

2. Methodology

Computational Fluid Dynamics (CFD) is used to evaluate the flow characteristics of a low pressure chamber for the suppression

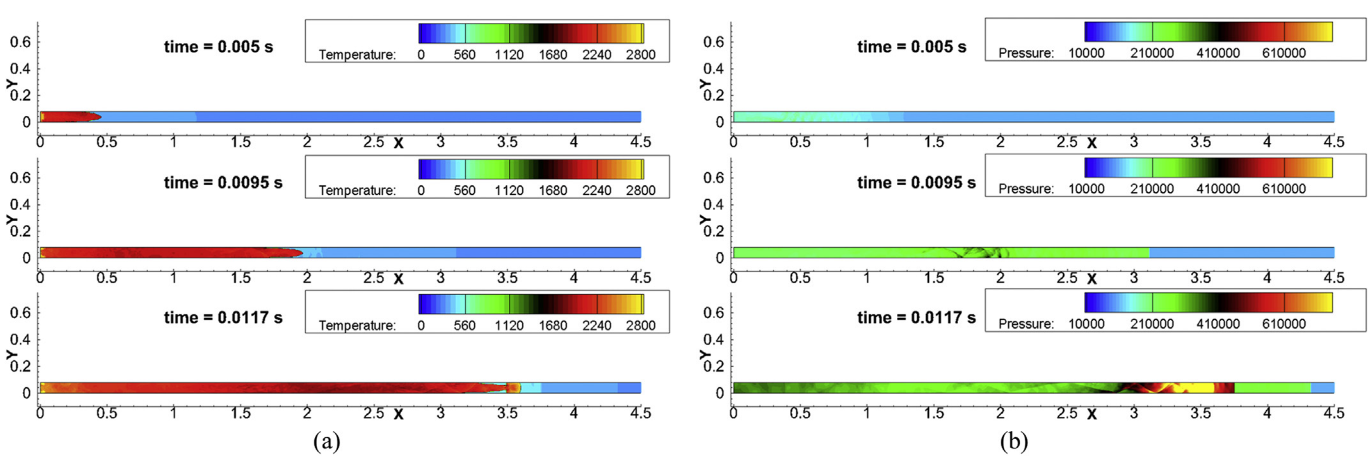

Fig. 2. Temperature (a) and pressure (b) plots for transition from deflagration to detonation (DDT) within a straight tunnel. Three stages of DDT are shown from top to bottom, Including deflagration propagation, localized high pressure-high temperature locus, and detonation stages.