Journal of Loss Prevention in the Process Industries 39 (2016) 24–29

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Detonation wave attenuation in dust-free and dusty air

A. M. Tahsini

Aerospace Research Institute, Tehran, IRAN

ARTICLE INFO

Article history:
Received 13 July 2015
Received in revised form
12 September 2015
Accepted 8 November 2015
Available online 12 November 2015

Keywords:
Attenuation
Detonation
Hydrogen
Numerical simulation
Particle cloud
Two-phase flow

ABSTRACT

The aim of the present study is to analyze the attenuation of detonation waves in dust-free and dusty air. The two-phase model for compressible reacting flow including chemically inert solid particles is used. Hydrogen–oxygen detonation is simulated using detail chemical kinetics. Finite volume method is utilized in this numerical procedure where the AUSM$^+$ scheme and the method of Saurel are used to calculate the gas-phase and particle-phase fluxes, respectively. The cloud density, material density, and particle radius are the parameters considered in this analysis. The propagation of wave in pure air is investigated, and the effect of particle cloud on suppression augmentation is studied. The results demonstrate that beside the values of particle cloud density, particle material density, and particle size, the action time is an important parameter in wave's suppression process, too. In addition, it is illustrated that the maximum speed time-history of both gas and particle phases tend the same trend for small particle sizes.

1. Introduction

Gaseous detonations are the self-sustaining shock waves propagating in combustible mixtures and are coupled to and are sustained by the exothermic chemical reactions. They are fast supersonic regimes of burning where the chemical reactions are initiated by the shock waves. In principle, detonations are an extremely efficient means of combustion and releasing the chemical energy content. They create less entropy than the conventional constant pressure processes such as those used in conventional propulsion systems (Li et al., 2010).

The high propagation speed of the detonation wave yields a large increase in reaction rates relative to the deflagration mode, and the chemical energy is completely released within a narrow region behind the leading shock wave. Some aspects of detonation development, structure, stability, chemical kinetics, and multidimensional dynamics remain poorly understood, and numerous efforts have been done recently to investigate these features (Ferrero et al., 2013; Fan et al., 2012; Finigan et al., 2012; Kudo et al., 2011; Kawane et al., 2011; Yan et al., 2011; Levin et al., 2010).

On the other hand, in different branches of industry such as mining, grain handling, processing facilities, and in powder technologies, serious explosion hazards exist. Thus an understanding of all aspects of detonation in two-phase mixtures is very essential for the control of initiation, propagation, and suppression of detonations in dusty flow fields.

Detonation suppression by inert particles is one of the useful techniques for avoiding dangerous incidents. The basic principle of this technique is the dispersal of the chemically inert particles in the path of detonation wave to quench the fire and attenuate the wave. The two-phase suspension absorbs a large amount of momentum and heat which may result in the control of detonation.

Many studies have been carried out on two-phase detonations. Gavrilenko et al. (1986) performed experimental analysis on particles acceleration due to detonation waves. The effect of initial position and fragmentation of particles on their maximum velocity is studied in their experiments. Khasainov and Veyssiere (1996) studied numerically the formation of detonation in hybrid two-phase mixtures and showed that there are three different propagation regimes in such systems.

Kutashev and Pichugin (1996) numerically investigated the effect of spatial non-uniformities in the distribution of inert particles on the combustion wave extinction. Fedorov and Fomin (1997) computed the effect of particle concentration on the detonation velocity and its decrement. Carvel et al. (2003) experimentally studied the influence of particle concentration on detonation propagation in combustible mixtures. They found that, under certain particle size and loading conditions, a second pressure discontinuity is formed behind the initial detonation front, for both inert and combustible particles.

Papalexandris (2004, 2005) examined the structure and stability

E-mail address: a_m_tahsini@yahoo.com.

http://dx.doi.org/10.1016/j.jlp.2015.11.006

Nomenclature

C_d	Drag coefficient
D_g	Mass diffusion coefficient
e_g	Gas phase total specific energy
F_p	Force between gas and particles per unit volume
h	Heat transfer coefficient
h_g	Gas phase total specific enthalpy
h_p	Particle phase total specific enthalpy
m_j	Mass fraction of species j
n_p	Particle numbers per unit volume
Nu	Nusselt number
p	Pressure
Pr	Prandtl number
Q_p	Heat transfer rate between gas and particle per unit volume
Re	Reynolds number
r_p	Particle radius
t	Time
u_g	Gas phase velocity
u_p	Particle phase velocity
ρ_g	Gas phase density
ρ_p	Particle phase density
τ_{xx}	Shear stress
$\dot{\omega}_j$	Mass rate of production of species j

of detonations in mixtures of gases and solid particles via direct numerical simulations by employing a simple one-step reaction mechanism. Dong et al. (2005) and Chen et al. (2006) performed experimental investigations on the effect of particle cloud density and size on the explosion suppression for methane-air and oxygen-hydrogen mixtures, respectively. Their results showed that increasing inert particle cloud density enhances the ability to attenuate the explosion processes.

Kosinsky (2008) numerically studied the mitigation of explosion by means of inert dust cloud. He considered the non-reacting flow field which the strong pressure wave propagates after rupture of the diaphragm between high pressure and high temperature section and a low pressure section, as a shock tube problem. Fomin and Chen (2009) analytically investigated the effect of thermodynamic properties of particles on detonation suppression. It is found that particles with higher specific heats exert most effective features.

Fedorov et al. (Fedorov et al., 2010, 2012a, 2012b; Fedorov and Kratova, 2013; Tropin and Fedorov, 2014) numerically analyzed the explosion and detonation attenuation by means of inert particles, and studied the effect of different particle materials. Gottiparthi and Menon (2012) numerically simulated the effect of inert particle clouds on detonations using a simplified chemical model with Arrhenius kinetics, in two and three dimensions. Fomin et al. (2013) investigated the detonation wave reflection from a rigid wall in gas-particle mixtures. Vasilev et al. (2014) experimentally studied the damping of a detonation wave in dusty methane–oxygen–nitrogen mixture, and analyzed the critical parameters of the heterogeneous medium that provide complete suppression of the detonation wave's propagation.

Although there are many studies on the detonation suppression with the help of particle cloud, they have been performed by adding the particle suspension to the main reacting gas mixtures, and detonation attenuation in the dusty air is poorly investigated. What usually happens in reality is that detonation may occur in potentially explosive restricted area, and must be controlled and suppressed downstream where there is no explosive mixture. In the present study, the attenuation of already-generated detonation wave by the pure dust-free or dusty air is numerically studied and the effects of particles' characteristics are investigated.

2. Governing equations and numerical procedure

In the present study, the one-dimensional equations governing the continuum, compressible, chemically reacting two-phase flow representing the conservation of mass, momentum, energy, and species for the gas phase, and the conservation of mass, momentum, and energy for the particle phase are used. It is assumed that particles are spherical and do not collide each other, volume occupied by particles and gravity effect are omitted, internal temperature of particles is uniform, and particle phase does not have contribution for pressure. The conservation form of equations is:

$$\frac{\partial U}{\partial t}+\frac{\partial (F+F_v)}{\partial x}=ST \tag{1}$$

where

$$U=\begin{bmatrix}\rho_g\\ \rho_g u_g\\ \rho_g e_g\\ \rho_g m_j\\ \rho_p\\ \rho_p u_p\\ \rho_p h_p\end{bmatrix} F=\begin{bmatrix}\rho_g u_g\\ \rho_g u_g u_g+p\\ \rho_g u_g h_g\\ \rho_g u_g m_j\\ \rho_p u_p\\ \rho_p u_p u_p\\ \rho_p u_p h_p\end{bmatrix} F_v=\begin{bmatrix}0\\ -\tau_{xx}\\ q_x-u_g\tau_{xx}\\ \rho_g D_g m_{j_x}\\ 0\\ 0\\ 0\end{bmatrix} ST=\begin{bmatrix}0\\ F_p\\ Q_p+u_pF_p\\ \dot{\omega}_j\\ 0\\ -F_p\\ -Q_p-u_pF_p\end{bmatrix} \tag{2}$$

The force and heat transfer between two phases which appear in the source term of equations are computed using eq. (3) (Thevand et al., 1999).

$$\begin{aligned}
F_p &= n_p\frac{1}{2}\rho_g\pi\, r_p^2\, C_d(u_p-u_g)|u_p-u_g|\\
Q_p &= n_p 4\pi\, r_p^2\, h(T_p-T_g)\\
C_d &= 0.48+28\mathrm{Re}^{-0.85}\\
Nu &= 2+0.6\mathrm{Pr}^{0.33}\mathrm{Re}^{0.5}
\end{aligned} \tag{3}$$

The finite-rate chemical kinetics which was proposed by Stahl and Warnatz (1991) is employed here as a full chemistry model for hydrogen–oxygen combustion. So, nine chemical species exist within the reaction mechanism, and eight conservation equations for species should be considered beside one equation for overall mass fraction. Finally, there are fourteen coupled equations to be solved simultaneously and numerically in this flow field.

To develop a numerical program, the cell-centered finite-volume method is used to discretize the governing equations. The gas phase inviscid terms are treated using an AUSM$^+$ method to express the numerical flux at the cell faces (Liou, 1996), and the particle phase are treated using the method described in Saurel et al. (1994). The present simulation procedure has been validated using variety of benchmark problems, and also utilized