International Journal of Multiphase Flow 99 (2018) 467–473

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Numerical study on the mitigation effect of water in the immediate vicinity of a high explosive on the blast wave

Yuta Sugiyama[a,*], Tomotaka Homae[b], Kunihiko Wakabayashi[a], Tomoharu Matsumura[a], Yoshio Nakayama[a]

[a] *National Institute of Advanced Industrial Science and Technology (AIST), Central 5, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8565, Japan*
[b] *National Institute of Technology, Toyama College, 1-2 Ebie-neriya, Imizu, Toyama 933-0293, Japan*

ARTICLE INFO

Article history:
Received 4 September 2017
Revised 12 November 2017
Accepted 22 November 2017
Available online 23 November 2017

Keywords:
Mitigation
Blast wave
Water
Energy transfer
CFD

ABSTRACT

This paper investigates explosions in a straight square tube in order to understand the mitigation effect of water on blast waves that emerge outside. Numerical simulations are used to assess the effect of water that is filled inside the tube. The water reduces the peak overpressure at the tube exit and outside, which agrees well with the experimental data. The increases in the kinetic and internal energies of the water are estimated, and the internal energy transfer at the air/water interface is shown to be an important factor in mitigating the blast wave on the ground in the present numerical method. Two mechanisms of the energy transfer are proposed in the present study. Initially, the strong shock wave reflects off and transmits water. A high-energy transfer into the water from air is promoted by the shock compression of water. Subsequently, as the shock wave propagates along the water surface, the air is adiabatically compressed continuously, and the pressure and temperature differences between the shocked-air and water induce a more gradual transfer of internal energy into the water.

1. Introduction

High explosives release a high-pressure and high-temperature gas after detonation and are widely used in industrial technologies (e.g., mining and explosive working) and in the medical field (e.g., extracorporeal shock-wave lithotripsy). However, when an accidental explosion occurs, the process of gas expansion generates a blast wave, which is a hazard to people and can cause extensive damage to property. The extent of the physical hazard caused by a blast wave can be estimated by its peak overpressure, which is dependent on the distance between the ignition point and the adjacent residential area.

In order to reduce the physical hazard, means of minimizing the effects of an explosion using water have been investigated for many years as shown in Fig. 1. Surrounding a high explosive with water mist (Adiga et al., 2009; Borisov et al., 1983; Campbell and Pitcher, 1958; Pierce, 1978; Thomas et al., 2000; Willauer et al., 2009) as shown in Fig. 1(a) or encircling it with a water barrier (Cheng et al., 2005; Chong et al., 1999; Homae et al., 2006; Keenan and Wager, 1992; Sugiyama et al., 2014) as shown in Fig. 1(b) are effective methods for attenuating the blast wave.

When the blast wave collides with water mist, larger droplets break up into a finer mist and evaporate, which extracts energy from the blast wave (Adiga et al., 2009; Thomas et al., 2000; Willauer et al., 2009). Willauer et al., (2009) investigated the mitigation effect of water mist on the overpressures of the blast wave generated by the detonations of TNT in a confined space, and found that overpressure reduced by about 35% after spraying water mist. They supported the mitigation mechanism (Ananth et al., 2008; Thomas et al. 2000) that heat absorption by evaporation behind the shock wave front is a primary mechanism in a confined space.

A water barrier in contact with and encircling a high explosive also mitigates the blast wave. The acoustic impedance mismatch between water and air drastically mitigates the transmitted blast wave from water to air. The interaction of the blast wave and the water barrier causes the redistribution of internal and kinetic energies over the detonation gas, the barrier material, and air, thus directly attenuating the blast wave (Cheng et al., 2005; Chong et al., 1999; Homae et al., 2006; Keenan and Wager, 1992; Sugiyama et al., 2014). The increment of volume of the water gives the greater reduction of the blast wave. Water absorbs several tens of percent of the released energy by a high explosive and disturbs the propagation of the blast wave, which directly gives the attenuation of the blast wave.

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[*] Corresponding author.
E-mail address: yuta.sugiyama@aist.go.jp (Y. Sugiyama).

https://doi.org/10.1016/j.ijmultiphaseflow.2017.11.014

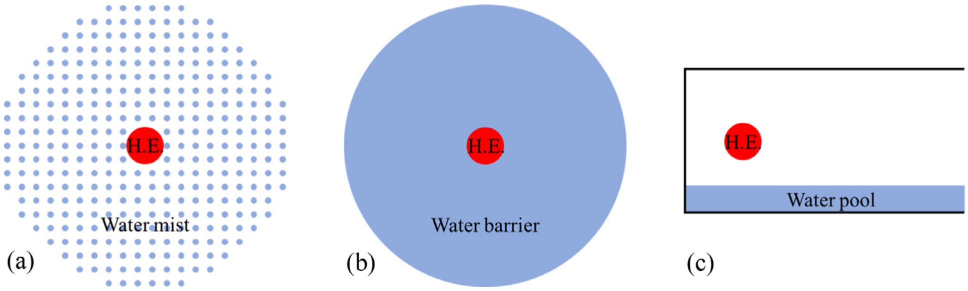

Fig. 1. Schematics of means of minimizing the effects of an explosion using water.

Homae et al. (2016) conducted experiments involving an explosion inside a subsurface ammunition magazine model (an L-shaped cylindrical tunnel). In that study, mist was not generated and water was not in contact with the high explosive before the experiment (see Fig. 1(c)). The shock wave propagated along the water surface, whose presence inside the horizontal chamber might have further mitigated the peak overpressure outside. Hence, their study implied different mitigation mechanisms from those by mist and a water barrier. Because detailed data on the explosion phenomenon are required to clarify the mitigation mechanism, a numerical simulation would be a useful tool. In our previous studies, we numerically modeled the previous experiment (Homae et al., 2016) and confirmed that water mitigated the blast wave from the subsurface magazine model (Sugiyama et al., 2015a, 2016).

Homae et al. (2018) used high-speed photography of explosion phenomena using a straight square tube of 30 mm on each side and measured the pressure inside and outside it in order to understand when and how water affects the blast wave. Their study showed that water clearly reduced the peak overpressure at a distance of 80 mm from the ignition point. They changed the water filled region and denoted that the water filled region inside a tube strongly affects the blast wave mitigation. This indicates that the initial stage after detonation, during which the high-pressure and high-temperature gas interacts with the water, weakens the shock wave substantially. Sugiyama et al. (2018) numerically investigated a part of the experiments in which water is filled between the end wall and the exit of the square tube, and water depth is 5 mm (Homae et al., 2018) in order to understand the mitigation effect of water on the blast wave. They confirmed that water would be useful for the blast wave mitigation. In the present study, we discuss the effective method for the blast wave mitigation using water and quantitatively understand the mitigation mechanism of the blast wave inside the tube, considering multiphase compressible flows of air and water. The numerical simulation separately estimates the kinetic energy and internal energy transfers between air and water.

2. Numerical methods

2.1. Six-equation model

We apply the six-equation model by Zein et al. (2010). The governing equations are the three-dimensional compressible Euler equations (1), the advection equation of volume fraction (2), and internal energy equations with source terms for equilibrium pressure and temperature conditions (3) and (4).

$$\frac{\partial \mathbf{Q}}{\partial t}+\frac{\partial \mathbf{E}}{\partial x}+\frac{\partial \mathbf{F}}{\partial y}+\frac{\partial \mathbf{G}}{\partial z}=0, \tag{1}$$

where

$$\mathbf{Q}=\begin{bmatrix}\alpha_1\rho_1\\ \alpha_2\rho_2\\ \rho u\\ \rho v\\ \rho w\\ \rho e\end{bmatrix},\quad \mathbf{E}=\begin{bmatrix}\alpha_1\rho_1 u\\ \alpha_2\rho_2 u\\ \rho u^2+p\\ \rho vu\\ \rho wu\\ (\rho e+p)u\end{bmatrix},\quad \mathbf{F}=\begin{bmatrix}\alpha_1\rho_1 v\\ \alpha_2\rho_2 v\\ \rho uv\\ \rho v^2+p\\ \rho wv\\ (\rho e+p)v\end{bmatrix},$$

$$\mathbf{G}=\begin{bmatrix}\alpha_1\rho_1 w\\ \alpha_2\rho_2 w\\ \rho uw\\ \rho vw\\ \rho w^2+p\\ (\rho e+p)w\end{bmatrix}$$

$$\frac{\partial \alpha_1}{\partial t}+u\frac{\partial \alpha_1}{\partial x}+v\frac{\partial \alpha_1}{\partial y}+w\frac{\partial \alpha_1}{\partial z}=\mu(p_1-p_2)+\frac{1}{\kappa}H \tag{2}$$

$$\frac{\partial(\alpha_1\rho_1\varepsilon_1)}{\partial t}+\frac{\partial(\alpha_1\rho_1\varepsilon_1 u)}{\partial x}+\frac{\partial(\alpha_1\rho_1\varepsilon_1 v)}{\partial y}+\frac{\partial(\alpha_1\rho_1\varepsilon_1 w)}{\partial z}+\alpha_1 p_1\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)=\mu p_I(p_1-p_2)+H \tag{3}$$

$$\frac{\partial(\alpha_2\rho_2\varepsilon_2)}{\partial t}+\frac{\partial(\alpha_2\rho_2\varepsilon_2 u)}{\partial x}+\frac{\partial(\alpha_2\rho_2\varepsilon_2 v)}{\partial y}+\frac{\partial(\alpha_2\rho_2\varepsilon_2 w)}{\partial z}+\alpha_2 p_2\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)=-\mu p_I(p_1-p_2)-H \tag{4}$$

$$\rho_i\varepsilon_i=\frac{p_i}{\gamma_i-1}+\frac{\gamma_i\pi_i}{\gamma_i-1}+\rho_i q_i \tag{5}$$

$$T_i=\frac{p_i+\pi_i}{C_{vi}\rho_i(\gamma_i-1)} \tag{6}$$

$$\kappa=\frac{\frac{p_1+\gamma_1\pi_1}{\alpha_1}+\frac{p_2+\gamma_2\pi_2}{\alpha_2}}{\frac{\gamma_1-1}{\alpha_1}+\frac{\gamma_2-1}{\alpha_2}} \tag{7}$$

$$H=\theta(T_2-T_1) \tag{8}$$

$$p_I=\alpha_1 p_1+\alpha_2 p_2 \tag{9}$$

Here, α_i and ρ_i indicate the volume fraction and density, respectively, of the ith fluid ($i=1$ for air and 2 for water). u, v, w, p, H, and e are the velocities in the x, y, and z directions, the pressure, the amount of internal energy transfer between fluids at the relaxation step, and the total energy per unit mass, respectively. ε_i, T_i, and p_i denote the internal energy per unit mass, temperature, and pressure, respectively, of the ith fluid. A stiffened gas equation of state is used to model air and water, as shown in Eqs. (5) and (6). γ_i, π_i, and q_i are thermal parameters: $\gamma_1=1.4$, $\pi_1=0$ Pa, $C_{v1}=717$ J/kg/K, and $q_1=0$ J/kg for air, and $\gamma_2=2.65$, $\pi_2=8.81\times10^8$ Pa, $C_{v2}=1816$ J/kg/K, and $q_2=-1167\times10^3$ J/kg for