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Implications of droplet breakup and formation of ultra fine mist in blast mitigation

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ABSTRACT

Blast-induced droplet breakup producing ultra fine water mist process was examined in view of assessing its implications on blast mitigation. An earlier review proposed that droplet breakup process, amongst other implications, may weaken the shock due to breakup energy absorption. In this work, droplet breakup energies for water droplets have been determined from the surface energies of both parent and child droplets. A breakup energy of 18 J/kg was required to fragment a 0.5 mm parent droplet into 10,000 mono-dispersed child droplets. Compared to the vaporization energy of 2.25 MJ/kg, the droplet breakup energy was found not significant in weakening the shock. While the droplet deformation energy and curvature effects could increase the breakup energy, its overall contribution to the total energy extraction was not as significant as the latent heat of vaporization. Further, the analysis shows about 22-fold increase in surface area of the child droplets. The study revealed the surface-to-volume ratio of the ultra fine droplets and their vaporization timescale should be well positioned for shock energy extraction.

1. Introduction

The US Navy has recognized the benefits of water mist for fire suppression [1,2], and as a result these systems have been installed in the Navy's latest class of amphibious ships, the *San Antonio* class (LPD-17). As these systems are being included in more ship designs, there is a desire to investigate their potential use in limiting the primary damage area (PDA) caused by an explosion from a weapon or terrorist attack [3–5]. Many reports have cited mitigation of condensed-phase explosions and vapor cloud explosions using water mist, and a few have addressed some of the plausible mechanisms by which mitigation was achieved [3,5]. These include the extraction of energy from both the shock front and the chemical reaction zone when water droplets fragment and evaporate [3,5]. The water mist droplet size and concentration, the chemical composition of the explosive (missile, TNT, dust cloud), and the geometric complexity of the area being mitigated determine how well the water droplet interaction promotes energy absorption and thus mitigation.

Ideally, a shipboard water mist system would mitigate the initial blast overpressures and any quasi-static overpressures and secondary effects caused by a blast. Shipboard environments are geometrically complex, consisting of multiple compartments ranging in size and containing varying degrees of congestion. A few reports suggest that a blast in this type of environment could actually enhance the overpressures due to the reflection of shock waves [3]. The other issues are the time, the amount of water, and water droplet size needed to achieve mitigation in the event of an incident.

The Naval Research Laboratory (NRL) was sponsored by the Office of Naval Research (ONR) to study these issues by conducting a series of small-scale blast mitigation tests in the summer of 2005 [6]. The tests were carried out in a bombproof shelter at the Naval Surface Warfare Center (NSWC), Indian Head, Maryland using TNT. In the TNT blast experiments, the quasi-static pressure produced by the detonation of a 5 lb (2.2 kg TNT) charge of TNT was reduced by as much as 47%. Approximately 27 liters of water was injected into a compartment whose inside dimensions were $4.6\,\mathrm{m} \times 4.6\,\mathrm{m} \times 3.1\,\mathrm{m}$ ($15.1\,\mathrm{ft} \times 15.1\,\mathrm{ft} \times 10.1\,\mathrm{ft}$). The water mist characterization studies indicated that mitigation was achieved with droplet sizes ranging from 35 to 550 μm with a Sauter mean diameter (SMD) $>50\,\mu\mathrm{m}$ and a mass loading of 76–87 $\mathrm{g/m^3}$ [7]. Thus, only about 18–21% of the 412 $\mathrm{g/m^3}$ was suspended at any given time in the test series. This is likely the result of droplets settling to the floor and along the chamber walls. SMD is the diameter of the droplet whose surface to volume ratio is equal to that of the entire spray [8].

The results of the blast mitigation studies suggest that there are other mechanisms, in addition to water droplet fragmentation and evaporation [3,5], by which water mist mitigates the blasts.

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Nomenclature

d	diameter
d_c	maximum diameter
d_{initial}	initial diameter of the droplet (m)
D	diffusion coefficient ($\mathrm{m^2/s}$)
E_p or e_p	surface energy of parent droplet (J)
E_c or e_c	surface energy of child droplets (J)
$m_{\mathrm{vap},o}$	mass fraction of water vapor in the mixture.
$m_{\mathrm{vap},\infty}$	mass fraction of water vapor away from surface
Oh	Ohnesorge number $= \mu/(\rho d\sigma)^{0.5}$
S_p	surface area of a parent droplet ($\mathrm{m^2}$)
S_c	surface area of child droplet ($\mathrm{m^2}$)
t_{vap}	evaporation time (s)
U	velocity (m/s)
V	relative velocity (m/s)
We	Weber number $= \rho V/d\sigma$
σ	surface tension, water 7.2×10^{-2} N/m
ρ	density of fluid ($\mathrm{kg/m^3}$)
ρ_l	liquid water density $= 1000\,\mathrm{kg/m^3}$
Γ	exchange coefficient $= D\rho$ (kg/m s)
Γ_{vap}	water vapor exchange coefficient (kg/m s) $= 2.6\times10^5$ kg/m s

We propose a comprehensive set of mechanism of interactions. Fig. 1 shows a schematic of the proposed interaction of water droplets in the detonation process. The water mist (parent droplets) is essentially unaffected by the incoming shock wave. Once the front has passed, the droplets enter an environment where the air is moving at supersonic velocities. These forces shear the coarse parent droplets into smaller droplets (child droplets) and energy is absorbed from the shock front. The child droplets produced can interact with the shock front, the reaction front, and the reaction product zone (Fig. 1) by other mechanisms in addition to evaporation to absorb energy from the blast.

Behind the shock front, the small droplets are rapidly accelerated to the shock velocity and absorb kinetic energy from the blast, as there is a transfer of momentum from the gas phase to the water phase. When the droplets penetrate the reaction front, they can absorb radiation and evaporate, causing further weakening of the blast. If the droplets reach the reaction products zone, more evaporation may occur, resulting in slowing down the expansion and absorption processes.

The chemical composition of high explosives and its amount determine the time scales for the shock and reaction front propagation. Water mist droplet size plays a key role in determining the time scales for droplet breakup, momentum transfer, evaporation, and radiation absorption. Blast-induced droplet breakup process is critical to producing child droplets capable of penetrating the different blast zones to achieve mitigation by latent heat and kinetic energy absorption. A number of recent studies are available that evaluate the effect of ultra fine mist (UFM) on cooling and suppression of fires [15–19].

An earlier review [3] proposed that droplet breakup process, amongst other implications, may weaken the shock due to the breakup energy absorption. The objective of this work was to assess the implication of droplet breakup process, first by estimating the magnitudes of breakup energy. The breakup energies for various schemes of droplet size and number of droplets are compared with the droplet vaporization energies and their timescales using analytical tools. The overall emphasis is to identify and understand the factors affecting the blast mitigation process using water mist. This knowledge can be used to optimize and engineer future Navy ship-wide water mist systems having the capability of acting as both a fire suppression system and a blast mitigation system.

2. Background

The aerodynamic droplet breakup process in water spray blast mitigation is an attractive beneficial feature for technology development. This blast-induced droplet breakup occurs due to local acceleration of the gas and the coarse water droplet acceleration. The droplet breakup dominates when the relative velocity between the gas and droplet develops, so that the droplet Weber number is more than 12 for a sufficient time [3,9–14]. The process has been demonstrated in reduced scale experiments as well as in limited large-scale tests.

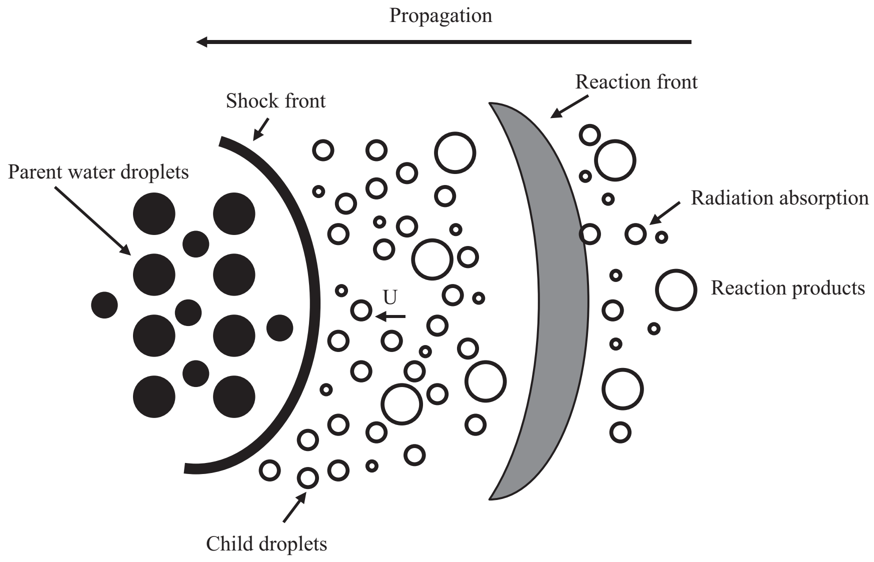

Fig. 1. Interaction of water droplets in detonation process.