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Implications of fine water mist environment on the post-detonation processes of a PE4 explosive charge in a semi-confined blast chamber

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A B S T R A C T

The effects of a fine water mist environment in a semi-confined blast chamber on the chemical and thermodynamic processes following detonation of a 20 g PE4 explosive charge have been investigated. The effects were quantified by the analysis of pressure profiles recorded where several parameters including arrival time of the shock at the sensors, peak overpressures, specific impulse of the positive phase, period of the negative phase and the specific impulse of the multiple reflections were quantified. The effect of the fine water mist on the arrival time, peak pressures and the specific impulse of the positive phase agrees with previous findings in literature. In this paper, the focus is on the implications of the fine water mist on the negative phase and the impulse of multiple pressure reflections. The period of the negative phase was found to have increased by 40% and with higher negative peak pressure in the mist condition compared to the atmospheric condition. The activities of the multiple pressure reflections were found to have decreased considerably, both in number and in amplitude leading to lower impulses (by about 60%) for the water mist conditions.

1. Introduction

Explosion blast mitigation methodologies are being investigated in the protection realm and two of the popular approaches are the use of water and water mist [1–4]. Water mitigation effects are complex and a fundamental research approach is needed to fully understand the exact nature of the physical and or chemical attenuation mechanisms, as well as which parameters play a major role in the process. The dependence of these parameters on the interaction of the water with both the shock-front and the reaction-front is of interest. Additionally, environmental constraints such as confinement, may introduce conditions whereby the use of this attenuating mechanism against blast can actually have the opposite effect [2,3]. A typical example is the case where momentum enhancement is obtained from acceleration of water particles onto a surface.

Water has blast suppression capabilities in three different forms, i.e. bulk water, sprays and fine mist. Whilst water has been traditionally studied for fire suppression, numerous reports have described mitigation of condensed-phase explosions and vapour cloud explosions using water mist, water-walls and active and passive water deluge systems [2–5]. The results of several research studies have indicated that explosion effects can be reduced by adding water mist in the vicinity of a detonating charge [3,4]. The water mist has the potential to attenuate shock pressure as well as reducing pressure loading in confinement through the interaction of the water mist with the reactive detonation gaseous products. As the shock front travels, some of the water droplets are swept behind it, and are subjected to supersonic air velocities and higher temperatures than the ambient. Extremely high shear forces on the droplet surface can cause fragmentation and the formation of very small sized droplets (child drops). These droplets evaporate, absorbing latent heat whilst also exchanging momentum with the surrounding air [5]. Fine water mist is defined within NFPA 750 as a water spray where 99% of the water produced is distributed by droplets that are smaller than 100 μm in diameter at the required design pressure at the water mist discharge nozzle [6,7].

There are several mechanisms in which the water mist can be used to mitigate the effects of an explosion. The blast wave resulting from the explosion can break up larger water droplets into smaller ones, more particularly at the shock front, which can directly lead to an attenuation of the shock wave. The attenuation of peak pressure of the wave can reduce the initial loading on

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container walls and other objects. Water molecules can slow down or quench the chemical reactions taking place behind the shock front, and dilute the concentration of the explosive gases in the enclosure and hence prevent a secondary gas explosion or fire [8–11]. Thus, adding water mist in a reactive mixture can cause significant changes on the characteristics of an explosion via the thermal effect due to the absorption of heat, the dilution effect caused by the reduction in the reactants concentration and chemical effects owing to the activity of water vapour that may alter some reaction paths. Besides the cooling of the detonation products, the increased surface area of the water droplets interact with the gas stream through drag and could reduce the kinetic energy of the flow [7]. The effect of water mist on blast shock-fronts and the development of quasi-static pressure in both enclosed and unconfined spaces was also reported in the literature [8,9]. The consensus from these investigations is that the water does not directly suppress the secondary reactions in unconfined blasts but that the mitigation mechanism at the shock-front with water mist is through momentum extraction. In confined spaces multiple reflections introduce mixing which complicates clear analysis of the mechanisms.

Adiga et al. [10] proposed a mechanism by which interaction of water droplets in the post detonation environment occurs with the various physical and chemical processes. In their model, the shock wave propagation causes parent droplets to shear into smaller droplets, so-called child droplets, whereby energy is absorbed from the shock front. The child droplets produced, will then interact with the shock front itself, the reaction front (if present), and the reaction product. Energy will be absorbed from the blast due to evaporation.

Williams [11] conducted experimental and numerical studies with nano-mist technology on the effects of ultrafine water mist as a flooding agent in a 28 m^3 detonation compartment. The ultrafine water mist was found to be able to successfully extinguish all pool fires. The blast-induced droplet breakup process was also studied to assess its implications on blast mitigation and it was found that the energy extraction due to vaporization was much more significant than the effect of fragmentation in weakening the shock [9,10]. A high-speed, long-acting water mist system was used for methane explosion mitigation in underground facilities, from which the overpressures were decreased by a maximum reduction coefficient of 2.98 [12].

The current investigation utilises a 20 g RDX-based high explosive charge (PE4) in a scaled semi-confined blast chamber that can be filled with a fine water mist. The objective is to clarify the contributions of mechanisms to the mitigating effect of water-mist in the presence of RDX-based explosive events. The focus is on the effect of a water mist environment on the near field blast properties in the blast chamber, with specific emphasis on the negative phase ("vacuum" period) and the resulting impulse after multiple pressure reflections of the blast wave inside the chamber. The "Negative phase" also referred to as negative duration is to the first negative pressure area immediately after the first positive peak pressure [13]. Three tests for both the atmospheric environment (without the mist) and fine water mist environment were executed. A confined environment is preferred as it creates a controllable volume in which the required water-mist can be created. Furthermore, it allows multiple reflections of the blast wave and thermal volume enabling interferences of the threat mechanism with the mist environment. The measured reflected pressure and overpressures records are used as primary diagnostic parameters in the analysis.

2. Experimental

Fig. 1 shows the experimental setup used to investigate the implications of the fine water mist environment on the processes following the detonation of a 20 g PE4 charge in a semi-confined blast chamber. The chamber is a 1.2 m long and 1 m diameter steel vessel with wall thickness of 6 mm. One end of the chamber was unconfined (only closed with a plastic wrap to avoid the water mist escaping the chamber). Two types of pressure sensors were used, namely; reflected pressure transducers, termed Face-On (FO) hereafter, and overpressure transducers, termed Side-On (SO) hereafter. The type of FO sensors used was Kulite model ETS-IA-37-1000SG, with sensitivity 4.490 mV/PSI and 4.515 mV/PSI. The SO pair sensors used was PCB Piezo-electronic model 137A22 with sensitivity 1345 mV/MPa.

The FO sensors, FO-R (positioned on the right) and FO-L (positioned on the left), were mounted flush with the wall of blast chamber. The Helmholtz cavity was incorporated on FO-R with diameter 9.5 mm and depth 1.56 mm to filter the signal, while it was not fitted on FO-L. The pencil probes containing the SO sensors protruded through the wall with the sensor locations 55 mm from chamber inside wall for all the shots. The two pairs of sensors were placed diametrically opposite each other as illustrated in Fig. 1(a). The SO probe on the right side (seen from the chamber position and designated SO-R) was facing upwards and the other Side-on probe (SO-L) facing downwards to avoid water dripping on them during the water mist environment test. A Graphtek digital acquisition system was used to capture the signals from these sensors. The sampling frequency was set of 20 MHz which rendered 50ns sampling time resolution. A high-speed camera, Photron SA4 was positioned on the side pointing towards the open side, as shown in Fig. 1(b), to capture the explosion events inside the chamber. For the atmospheric environment, no water mist was allowed into the chamber. The partial cover in Fig. 1(b) and (c) made of thin perforated cling plastic material was used to close the open side of the chamber, to minimise the loss of water mist with minimal impaction on the blast propagation.

A 20 g PE4 cylindrical charge with length to diameter ratio (*L/D*) of 1 with length of 25 mm was placed in a polystyrene thermal insulation assembly to insulate the explosive charge from the thermal influences within the chamber, as illustrated in Fig. 1(d). The polystyrene assembly housed the M2A2 detonator in a wooden sleeve to prevent static friction and a light sensor for recording the initiation time. The explosive charge assembly was suspended centrally in the chamber and the detonator was fired in the downward direction.

Two sets of nozzles were installed symmetrically on the centre along the length of the chamber. Each set contained three nozzles of 300 μm. The nozzles were connected to a pipe system that supplied water at a constant pressure and subsequently fine water mist into the chamber. The validation of the equilibrium of the water mist inside the chamber was pre-determined using a 650 nm laser and a photodiode mounted symmetrically opposite from each other, towards the open end of the chamber. Initially in the absence of the water mist in the chamber, the photodiode measures the maximum light intensity. As the mist was introduced, the intensity reduced corresponding to the attenuation of the light signal and equivalent to saturation within the chamber. Fig. 2 shows the measured light signal captured during the tests and the filtered signal to determine saturation period. From Fig. 2, the saturation period was determined to be at least 50s.

The concentration of the fine water mist in the chamber was determined to be 1 kg/m^3 for the total six nozzles. The droplet size was derived from the equations of formation of droplet size [14] and found to be below 100 μm. The water mist environment was created by opening the water into the system and allowing a predetermined time (50s) to achieve the required saturation inside the blast chamber.

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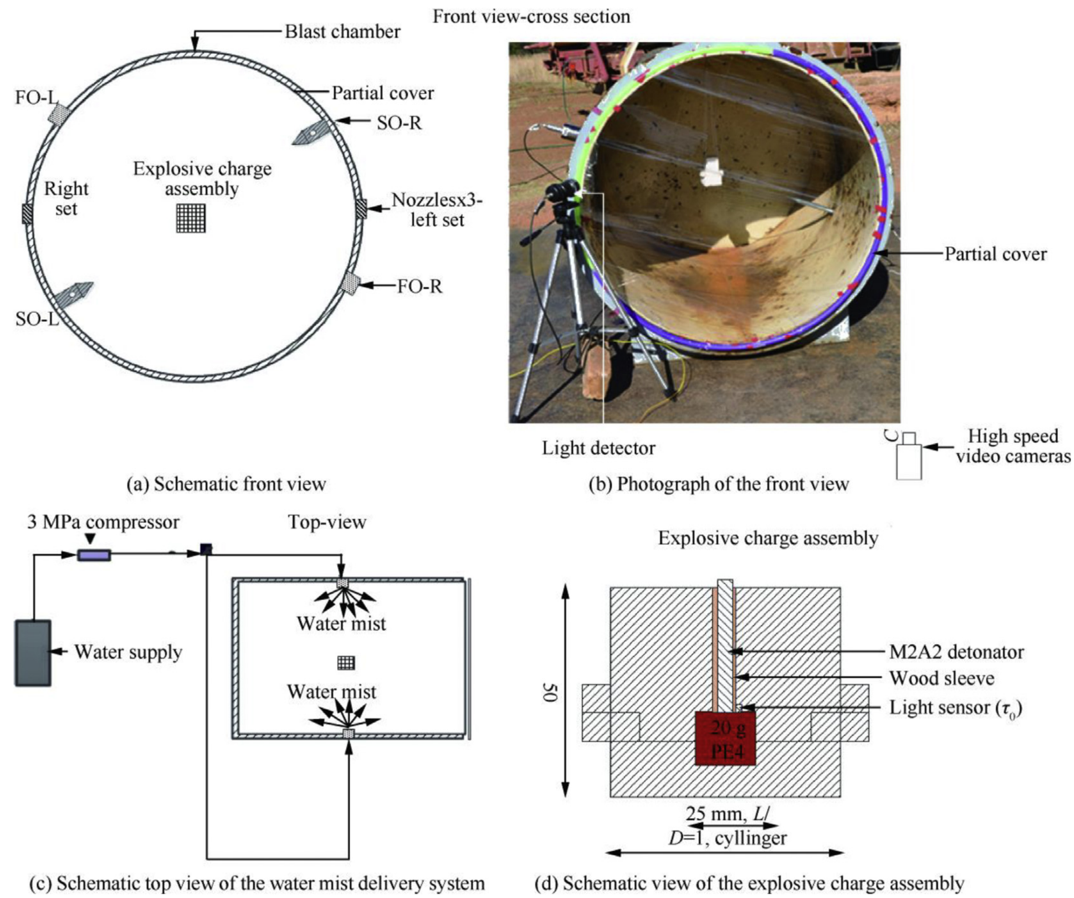

Fig. 1. The experimental setup (a) Schematic front view, (b) Photograph of the front view, (c) Schematic top view of the water mist delivery system and (d) schematic view of the explosive charge assembly.

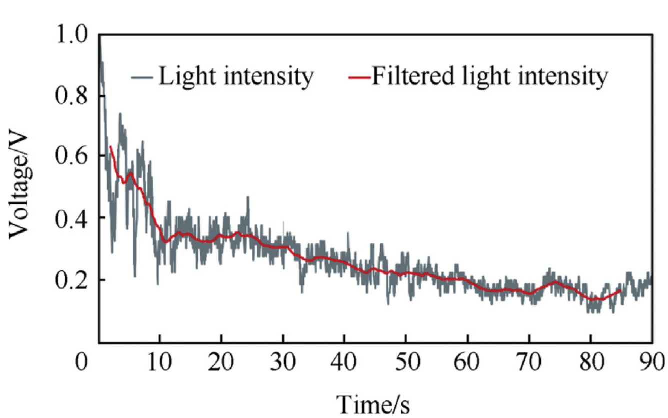

Fig. 2. Saturation as a function of time.

3. Results and discussion

To evaluate the implications of the conditions of the fine water mist environment on the post-detonation processes, the pressure-time profiles measured were analysed. The effect of the water mist can manifest itself on the initial peak pressure of the blast wave through interaction with shock front [7,8] and/or evidence of interaction with the detonation products can be expected to be observed on subsequent peaks in the pressure recordings. The observed attributes of the pressure profile are discussed below and are then summarised to enable the comparison between the two conditions.

In an attempt to investigate the differences in the pressure signature of the blast within a semi-confined blast chamber with, and without water mist, the reflected pressure records of the shots without and those with water mist were analysed and the data signal is unsmoothed. The overpressure records were only used as back-up diagnostics for arrival time and peak pressure, in order to assess anomalies that may occur in the chamber due to the firings. The FO records was analysed up to 5 ms. After 5 ms cross-reflection of the pressure pulses from opposite and lateral sides are expected to clutter the pressure signature which complicates the analysis considerably. Fig. 3(a) and (b) shows the pressure signals of all shots, the atmospheric (1–3) and water mist (4–6) environment for FO-R and FO-L. Fig. 3(c) and (d) illustrates the average pressure profile of all shots without and with mist.

There are some important observations that can be made from Fig. 3(a) and (b). Firstly, the consistency of the higher positive peak pressures for the FO-R compared to FO-L is observed as the charge was fired downward in the direction of FO-R as shown in Fig. 1 (a) and will therefore record higher peak pressures than FO-L, that actually only catches the blast wave from the rear bridge wave (rear expansion of the gases). This can be clearly seen from the explosion event photographs (Fig. 7) where the expansion of the fireball (indicative of the expected peak pressures) is much faster in the downward direction than the upward directions.

The second is the consistency of the frequency in the pulses in the positive phase. This is interpreted as the ringing in the blast chamber that is moving the embedded Helmholtz cavity on FO-R sensor and on FO-L due to the absence of the cavity and thus

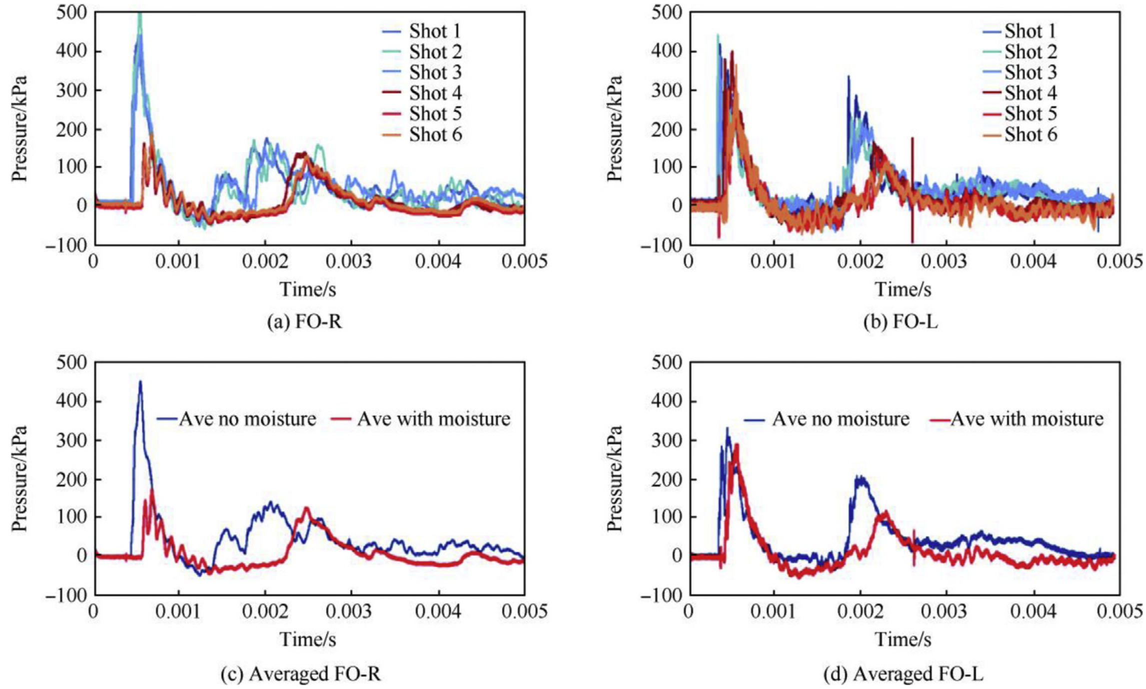

Fig. 3. Pressure signature of all 6 firings; without mist (1,2,3) and with mist (4,5,6), Reflected pressure (a) FO-R and (b) FO-L, (c) averaged FO-R and (d) averaged FO-L.

affecting the pressure measurement. The signal change is more pronounced in the water mist environment due to the increased density of the medium, but the frequency is essentially the same for both conditions. It can be clearly observed how this ringing smooths out with time as the vibration in the blast chamber settles down but the vibrations are more significant on the FO-L throughout to the end due to the unfiltered recording.

3.1. Arrival time

The first clear differentiation between the two cases is the arrival times, Fig. 3(c) and (d), of the peak pressure pulse at the sensor. With the atmospheric condition, the pulse arrives at the FO-R sensor at 0.43ms indicating an average shock velocity of 1163 m/s over the 500 mm of travel. For the case with water mist, the pulse arrives at 0.53ms which indicates an average shock velocity of 943 m/s over the same distance. The FO-L on the other hand, the results are expected to be the same but it can be observed that with the atmospheric condition, the pulse arrives at the sensor at 0.36 ms indicating an average shock velocity of 1389 m/s over the 500 mm of travel. For the case of with water mist, the pulse arrives at 0.45 ms which indicates an average shock velocity of 1111 m/s over the same distance.

It is clear that the shock velocity is attenuated by the mist content as has been reported in literature [9–12]. The arrival time on both sensors for the atmospheric condition compares well with theoretical expected values [15,16] which predicts it to be at 0.4 ms for a stand-off distance of 500 mm and net explosive content of 20 g PE4. The positive phase period for the first peak was determined to be 0.54 ms and 0.44 ms for the atmospheric and water mist conditions, respectively. This implies that work was done on the water droplets which sapped energy from the blast wave and leads to a known phenomenon of lowered positive impulse due to the water mist. An interesting feature of the recordings is the similar start of the negative phase in real time at about 1 ms for both conditions despite the difference in arrival time and positive phase period

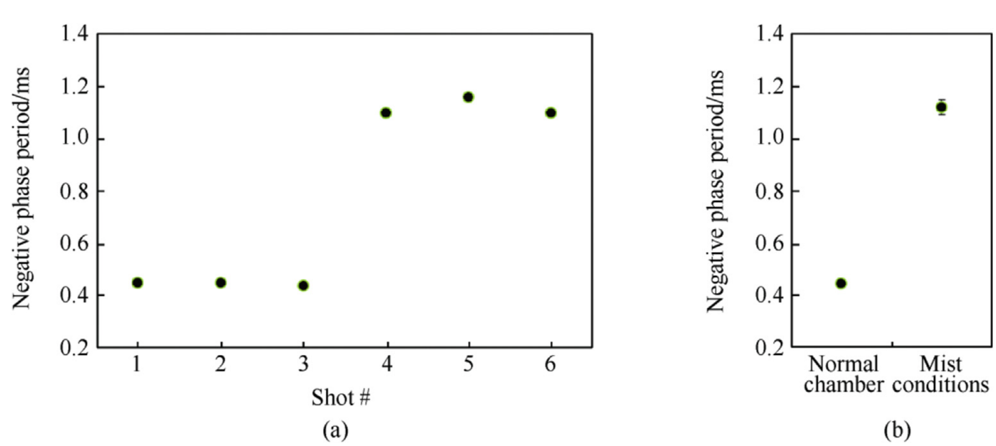

Fig. 4. a) Negative phase period for the all the shots, and b) average of the negative phase periods for the atmospheric (Normal) and mist condition.

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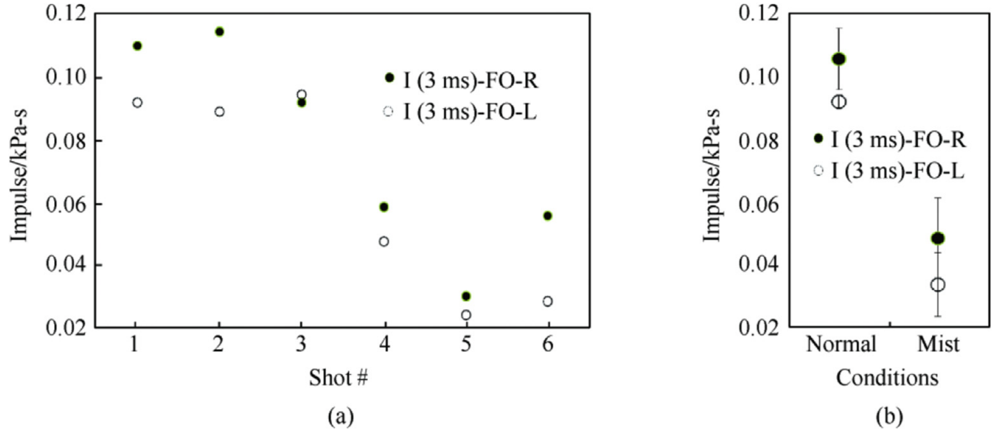

Fig. 5. a) Impulse, I (3 ms), for the multiple pressure reflections (after negative phase) for the all the shots and b) average values of the impulse for the atmospheric (Normal) and mist condition.

discussed above. It is evident from the results above that the arrival time and peak pressures are attenuated by the water mist content in the blast chamber. The percentage of increase in the arrival time is about 19% for the mist case. This effect is well known and documented.

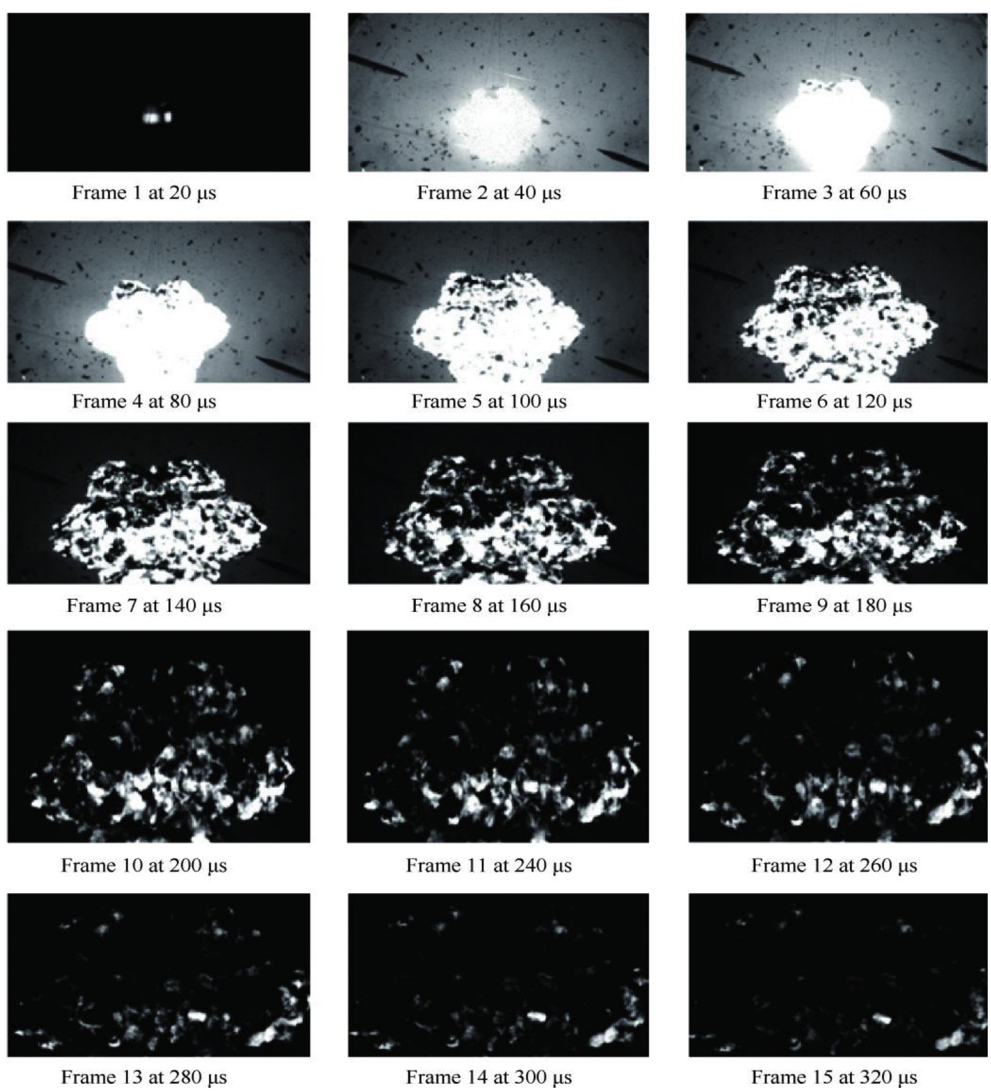

Fig. 6. Frames of the Fireball event during the blast in atmospheric environment.

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3.2. Negative phase

Fig. 4(a) shows the negative phase period values on the FO sensors for the shots conducted in the chamber with the atmospheric and fine mist conditions. Following the delayed timed of arrival, the negative phase period for the fine mist conditions appears to be prolonged as also shown in Fig. 4(b). The prolonged "vacuum" period implies that the rates at which multiples waves reflections arrives back at the chamber walls are reduced which is in line with the reduction in the velocity of the shock wave front. That is, the arrival times of the reflected waves are further reduced.

The most interesting feature however, is the massive broadening of the negative phase for the water mist compared to the atmospheric condition on both sensors. The negative duration for the atmospheric condition is only 0.44 ms while for the mist condition it is 1.25 ms and 1.00 ms for FO-R and FO-L, respectively, almost three times longer. The second reason for the increase in the negative phase is that the gas kinetics is slowed down considerably by the re-distributed fine water-particles remaining between the initial pulse and the fire-ball (i.e. in the negative phase).

There are two mechanisms that contribute to the retardation, namely atomic (molecular) collisions and thermal cooling. The hot gases move (as seen from the arrival times) initially with velocities of kilometres per second as the blast wave is forming and the temperature of these gases are in the range of 2000 °C. It is conceivable that over a few milliseconds the thermal energy is absorbed by some of the fine water particles, thus effectively cooling down the resulting mixture of water and detonation products. This slows down the expansion of the fireball and the result is two-fold, a broadening of the negative phase (increased period) and a decreased internal vacuum at the core of the fireball expansion.

3.3. Second maximum

The difference between the second maximum peak (after the negative phase) for FO-R and FO-L records, Fig. 3(c and d), in the atmospheric condition is due to cylindrical character of the charge and the direction of detonation [17]. This difference is eradicated by the presence of the water mist. The main feature of the second maximum is the recompression of the internal core of the fireball with a corresponding generation of a secondary outward moving shock. The secondary shock is delayed as well as lower in amplitude and duration in the water mist conditions. This indicates that the gases and velocities for the reflected waves are slowed down by the mist across the distances between the chamber wall and the recompression zone, as well as a loss of energy in the compression wave itself.

3.4. Multiple pressure reflections

A very interesting feature in the multiple pressure reflections observed in the water mist conditions is the presence of a second "vacuum" zone after the secondary compression of the detonation products by the reflected waves (Fig. 3). This feature is not present in the atmospheric condition profiles and indicates possible mixing of the water droplets with the products which are easily swept up by the outward moving shock. Fig. 5(a) shows the specific impulses of the multiple pressure reflections from the end of the negative phase up until 3 ms. These impulse values are reduced for the fine mist condition by about 60% as shown in Fig. 5(b). The implication of the reduction in this impulse is that the rate and the intensity of the multiple reflections are reduced for the mist environment relative to the atmospheric conditions.

Fig. 6 shows high-speed video images of the atmospheric environment (shot 1), which shows activities up until 320 μs. While Fig. 7 shows the event of the fireball during the explosion inside a water mist saturated environment (shot 3) at 20 μs intervals. The events for the mist condition are observed to be short lived and seems to have been quenched by the water mist. The short lived optical activities within the mist conditions can be compared to the pressure profile for the same condition which appear to have been quenched compared to that of the atmospheric conditions. Moreover, there is a possibility that the droplets in the water mist environment absorbed some light emissions from the blast activities during the high speed video recording. However, clear is the difference of the geometry of the gas expansion compared to that of the atmospheric condition.

The dominant end result for the negative phase and multiple pressure reflections processes is potentially the thermal cooling and energy extraction. The result implies that the thermal cooling occurred along the positive duration of the shock leading to the faster decay of the pressure from its peak values. The increased arrival times for peak pressures can be converted to an energy absorption value when evaluated together with the pressure decrease. This will be attempted in further analysis of the results. Besides the primary role of the polystyrene being the temperature insulator for the explosive charge, it might have had a slight delay

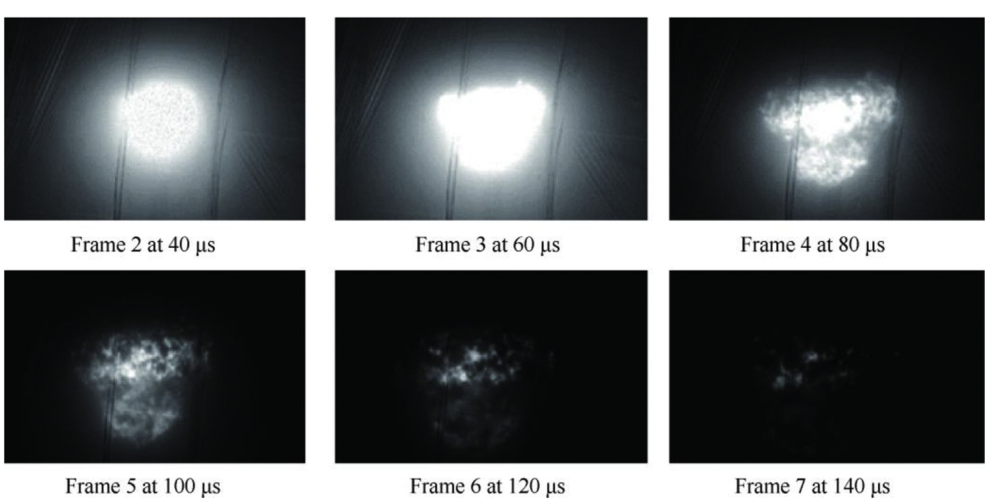

Fig. 7. Frames of Event of the Fireball during the blast in a water mist saturated environment.

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effect on the blast wave propagation and can contribute to the post-detonation gaseous products which may enhance the blast, but the material was used for all the shots. The effect however is not evaluated in this paper.

4. Conclusions

The experiment was conducted to investigate the implications of fine water mist environment on the post-detonation processes of a 20 g PE4 explosive charge in a semi-confined blast chamber. The fine mist conditions have delayed the shock arrival times and attenuated the peak overpressure, in line with result that have been reported in literature.

The contribution of this paper is the observation of a prolonged negative phase (about 40%). It is also shown that the activities of the multiple pressure reflections within the blast chamber were significantly affected. The reflected waves are delayed in the water mist environment and subsequent late time pressure peaks are quenched. The specific impulse, as integrated from reflected pressure transducers over 3 ms, decreased by about 60% for the water mist environment. Analysis of the high speed footages showed short lived light emissions of the fireball in the water mist conditions. It also shows that there is a significant difference in the geometry of the fireball in the water mist compared to the atmospheric conditions, at early times.

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