NUMERICAL STUDY ON SHOCKWAVE ATTENUATION BY WATER MIST IN CONFINED SPACES

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ABSTRACT

Hydrogen safety has become the first consideration, especially after fuel cell automobiles were pushed into commercial auto market. Tunnels are important parts of traffic infrastructure featured in confinement or semi-confinement. Hydrogen detonation is a potential accident scenario while hydrogen fuel cell vehicles are operated in a traffic tunnel with a confined space. Pressure shockwaves are mostly produced by hydrogen detonation and propagate along the tunnel. As a designed safety measure, water mist injection is hopefully to mitigate the pressure loads of such shocks. To model the interaction between shockwaves and water droplets, a droplet breakup model has been developed for the COM3D code, which is a highly validated three-dimensional hydrogen explosion simulation code. By using the model, the hydrogen detonation shockwave propagation in confined volumes is simulated in the study. The attenuation effects of water mist on the pressure shocks in the simulations are elaborated and discussed based on the simulation results.

Key Words: confined space; tunnel; hydrogen detonation; shockwave; hydrogen safety; water injection; water mist; hydrogen fuel cell vehicle (HFCV).

1 INTRODUCTION

In order to solve the problems of environmental pollution and energy consumption caused by the traditional automobile industry, great attention has been paid to the development of hydrogen energy and hydrogen fuel cell vehicle (HFCV) around the world. The recently issued report on the future trend of hydrogen energy by the Hydrogen Council shows that by 2050, the demand for hydrogen energy is going to be 10 times more of the current, and hydrogen energy to account for about 20% of the entire energy consumption. It is estimated that by 2030, the number of fuel cell passenger cars would reach 10-15 million globally.

The application scenarios of HFCVs can be anywhere of the existing conventional traffic infrastructure, such as underground carparks, traffic tunnels, underpasses, even maintenance shops. A common feature of the facilities is confined or partially confined. Hydrogen accumulation could occur in the confined spaces once hydrogen is released accidentally. Fast combustion even direct detonation of hydrogen could take place to the confined hydrogen cloud which is readily ignited spontaneously or unintentionally, if mitigation systems of the traffic infrastructure defect. A car accident involving HFCV occurring in a traffic tunnel is a typical accident scenario. Hydrogen distribution and combustion in such a scenario have been investigated in literatures [1-5], without mitigation by water injection.

The most risky combustion regime of hydrogen-air mixture is direct detonation if relevant criterion for detonation is satisfied in a confined space. It produces high pressure shockwaves and propagates supersonically e.g., faster than 2000 m/s, endangering safety of human life and properties. Water intervention is a traditional safeguard for a fire emergency. Therefore, this study is focused on the investigation of the interaction between detonation shockwaves and injected water mist in a confined space like a tunnel.

In fact, the mitigation measure by using water droplets was investigated to attenuate shockwaves in previous studies [6-25], with different droplet sizes e.g. from micron to millimetre, mist cloud dimensions ranging 10 cm up to 4 m, and variant liquid phase concentrations of 0.005 – 15 kg/m^3. A major point in summary of the studies is that the shockwaves are attenuated more effectively by larger droplet mist cloud with a higher liquid phase density distributed in a wider range of volume. One of the goals of this study is to develop concerned droplet models to simulate the interaction between shockwaves and mist cloud.

2 SHOCKWAVE ATTENUATION MECHANISMS

The attenuation of shockwave by mist is realized by exchanges of momentum, kinetic energy and heat between the very dynamic expanding hot gases and the initially still and cold droplets in normal cases.

As the first mechanism, the momentum of the fast expanding gases is transferred to the standing droplets while they are entrained to move by the gas flow. The entrainment must slow down the gas expanding velocity. So, the effect is also called momentum absorption by the droplets. No matter what it is called, the kinetic energy of gas molecules is transferred partially to the liquid particles in the entrainment process. Based on a straightforward deduction from the momentum equation, an important factor determining the momentum absorption is the liquid phase density. A higher liquid density brings a more efficient momentum absorption.

A droplet can break up into smaller parts if the shockwave is so energetic. In the phenomena, a fraction of the kinetic energy of expanding gases is converted into the surface energy of fragmented descendent droplets, because the surface area of liquid phase increases from one large droplet to small ones with an assumption of shape in sphere. Droplet breakup is the second mechanism of shockwave attenuation. A droplet breakup model consists of three key elements: breakup criterion, breakup time and determination of the descendent droplet size. The breakup criterion depends on the dimensionless Weber number *We*, which denotes the ratio of inertia force and surface tension of liquid. Droplet starts to fragment if *We* reaches a critical value. Correlations were developed and available for the breakup time and the descendent droplet size.

It is always in an emergency that cold water is injected into a hot environment for mitigation. So it is certain that heat transfer takes place from the hot gases to the cold droplets, accompanied by vaporization possibly, although it is a relative slow process comparing to direct momentum or kinetic energy transfers between the two phases. The heat absorption by droplets is the third mechanism. An assessment manifests that the slow heat absorption plays a less important role in shockwave mitigation.

The last attenuation effect of mist cloud is wave reflection. Namely, the shockwave must be partially reflected while it arrives and hits on the liquid surface of droplets. The reflection certainly decreases the shock intensity, as an attenuation effect of droplets.

The theoretical formulation about the concerned particle modelling and code implementation in COM3D code is addressed in detail in [26]. Verification cases of the models against experimental data refer to [27]. The article is focused on the numerical simulations by using the models of shockwave attenuations in a conceptual tunnel structure in a mini-scale and an experimental detonation facility with a gas volume of 220 m^3 at KIT.

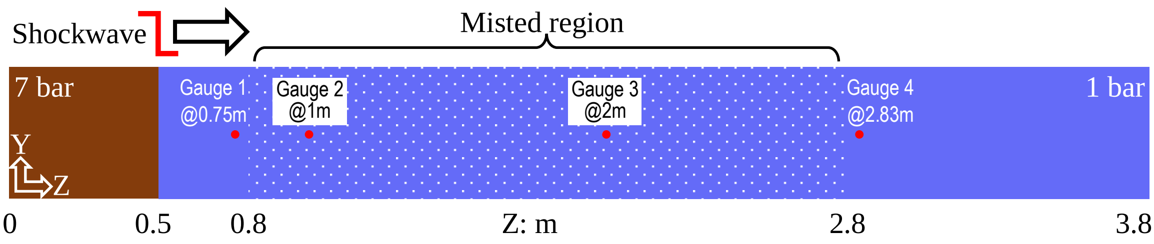
3 SIMULATION OF A SCALED TUNNEL

3.1 Geometry and boundary conditions

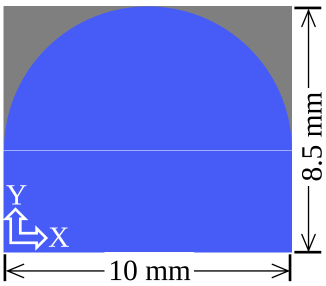
A pressure shockwave experiencing mist cloud is first simulated in a seriously downscaled tunnel or more precisely speaking, in a small tube. A fine mesh with a small cell size e.g. in millimeter facilitates to reserve the accuracy of the numerical solutions while discretizing the tube geometry. Therefore, a "tunnel" in a mini scale is simulated for a better computing time efficiency.

To further simplify the problem, an artificially initiated pressure shock by a high pressure membrane break is configured, instead of a genuine hydrogen detonation shockwave. The consideration can save the combustion simulation effort, but does not conflict to the purpose to test the validity of the developed model of particles against shockwave.

The 3.8 m long tube is schematically shown in Fig. 1(a), with the first half meter filled by air at 7 bar and the remainder at 1 bar. The break of the membrane in between the two pressure regions can bring a shockwave with a Mach number of 1.5 approximately. The 2 m long misted region is between the Z-coordinates of 0.8 m and 2.8 m. Two pressure gauges are positioned in front of and behind the mist cloud; the other two are within the misted region. The gauges record the time histories of pressure at the defined locations to represent the propagating process of shockwave.



(a)



(b)

Figure 1. A mini-scaled tunnel with misted region, (a) longitudinal cut view, (b) transverse cross section

The aspect ratio in Fig. 1(a) is not proportional. The modeled tube is much thinner. As shown in Fig. 1(b), the horse-shoe shaped cross section is 10 mm wide and 8.5 mm high. The total modeled volume is 3.23×10^{-4} m^3. A cell size of 0.5 mm is decided and in total, 2.6×10^6 uniformly sized cubic cells are used to mesh the whole domain in the tube.

Large droplet and fine droplet clouds are defined as two different kinds of mists in simulations, respectively, to investigate their shockwave attenuation capabilities. The large droplet has a diameter of 800 μm with a liquid density of 40 kg/m^3 and a droplet number of 13,280; the fine droplet has a diameter of 120 μm with a liquid density of 2 kg/m^3 and a droplet number of 197,000. The volume of the misted region stays the same as 8.9×10^{-5} m^3.

3.2 Simulation results

The overpressures in front of and behind the mist cloud are recorded by the Gauge 1 and 4, respectively in the simulations, as shown in Fig. 2, for the different scenarios with or without mist suppression. According to the dash-dotted curves in the figure, a shockwave with a front pressure of about 1.5 bar is generated by the outbreak of the high pressure region. Based on the location of the pressure gauges and the arrival times of the shock front, it is estimated that the shockwave travels at a speed of about 500 m/s, namely, a Mach number of about 1.5.

In the cases with water intervention, the pressure evolutions in front of the mist cloud (Gauge 1) and behind the cloud (Gauge 4) are shown by the curves in black and in green, respectively, in Fig. 2. The shielding effect of the mist cloud against the pressure shock is obvious. The pressure increases indicated by the black curves are due to the reflection effect of shockwave by the cloud surface. The reflected wave and the original incident shockwave superimpose to each other right in front of the cloud. The superimposing causes a higher pressure. Moreover, the large droplet cloud has a much stronger reflection effect than the fine droplet mist.

The green curves in Fig. 2 show that the large droplet cloud suppresses the peak pressure significantly, by about 55%, while the peak pressure in case of fine droplet mist keeps almost the same as that without water intervention. Nevertheless, the feature of the shockwave is transformed seriously. According to the green curves, the arrival times of the shock fronts are different at the Gauge 4. The time for the mist case is about 0.6 ms later than that without mist. It manifest that the propagating speed of the shockwave is slowed down by the mist by about 12%.

The damage potential of a shockwave depends not only on the peak pressure but also the time duration of the positive overpressure. Therefore the overpressure integration over time, called shockwave impulse, is adopted to measure the damage potential of a shock. Based on the records of the Gauge 4, the shockwave impulses behind the mist region are shown in Fig. 3 for the different scenarios. Apparently, the original shockwave impulse 525 Pa·s for the dry case is attenuated to 421 Pa·s by the fine droplets, and to 197 Pa·s by the large droplets, respectively.

The 2nd and 3rd pressure gauges are located in the mist region. Their records are shown in Fig. 4, presenting the attenuation process of the mist cloud against the shockwave.

A detailed view of the attenuation of the shock front pressures at the Gauge 2 is shown in the zoomed window in Fig. 4. It is interesting that, the shock front pressure in the fine mist case is even lower than in the large droplet case. At a later stage, the pressure increases gradually in the fine mist case, while the pressure maintains for some time then decays gradually in the large droplet case. The shape of the shockwave is roughly kept in the latter case although the peak pressure is suppressed.

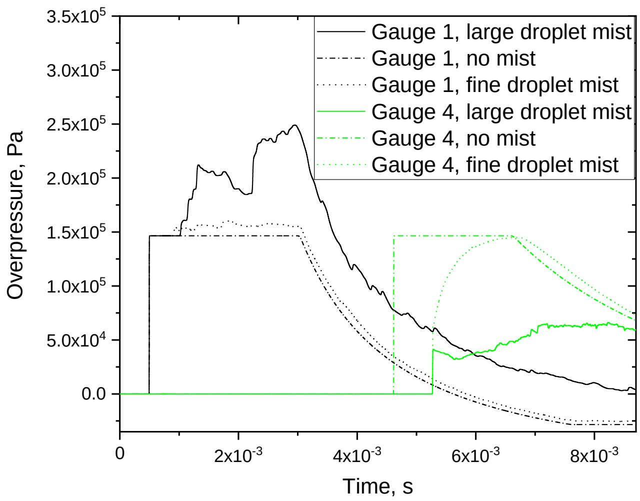


Figure 2. Overpressure time-histories at Gauge 1 in front of the mist region and at Gauge 4 behind the mist region for different cases with large/ fine droplet mist and without mist, respectively

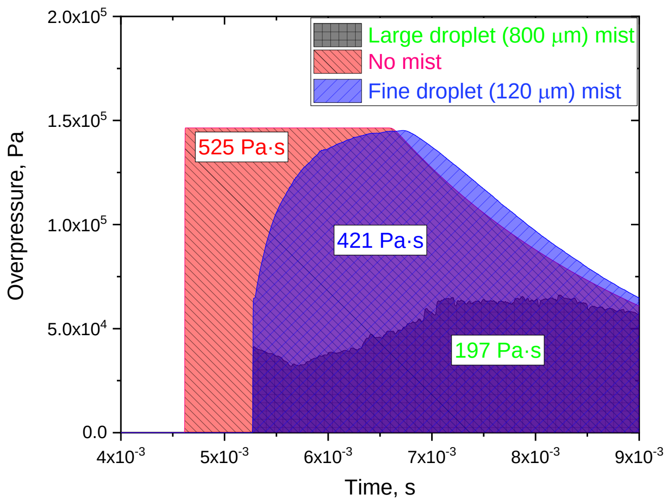


Figure 3. Shockwave impulse as pressure integration over time for different cases with large/ fine droplet mist and without mist, respectively, showing the attenuation effect of mist against shockwave

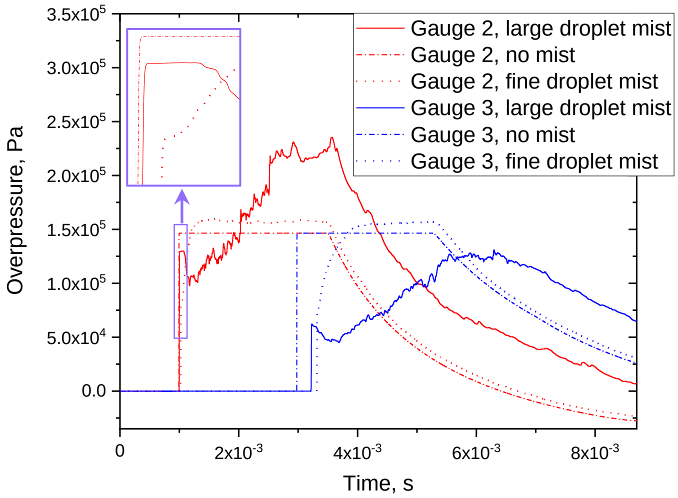


Figure 4. Overpressure time-histories at Gauge 2 and 3 within the mist region for different cases with large/ fine droplet mist and without mist, respectively

It manifests that two kinds of mists may have different attenuation mechanisms. At the earlier stage, the fine mist performs a better momentum absorption, thus the front pressure decreases quickly and significantly. At a later stage, the simulation indicates that droplet breakup barely occurs in the fine mist case. However, droplets break up much more frequently in the large droplet case, which is the primary mechanism to attenuate the shockwave for this case.

Fig. 4 also tells the truth that the shock fronts are decelerated with a slight difference between the fine mist case and the large droplet case. The figure shows that the shock front always arrives earlier in the large droplet case than the fine mist case. However, the green curves in Fig. 2 show that the both shock fronts arrive almost simultaneously at the Gauge 4. It can be explained that, in the large droplet case, the shockwave decelerates further while travelling from the Gauge 3 to 4, most likely due to the frequent breakup of droplets. By occasion, the both shockwaves arrive at the Gauge 4 at the same time in the fine mist case as in the large droplet case, respectively.

4 SIMULATION OF DETONATION FACILITY

4.1 Detonation facility with sprays

Detonation shockwaves are generated in plan by igniting 4 g hydrogen in a detonation unit positioned in a central place of the experimental facility – A2 vessel at Karlsruhe Institute of Technology with a gas volume of 220 m^3, as shown in Fig. 5(a). Symmetrically located four water spray devices are applied to make mist clouds to attenuate the shockwaves initiated by the hydrogen detonation.

A half of the facility volume is modeled due to its symmetry. A vertical and a horizontal cut views of the computational domain are shown in Fig. 5 (b) and (c), respectively.

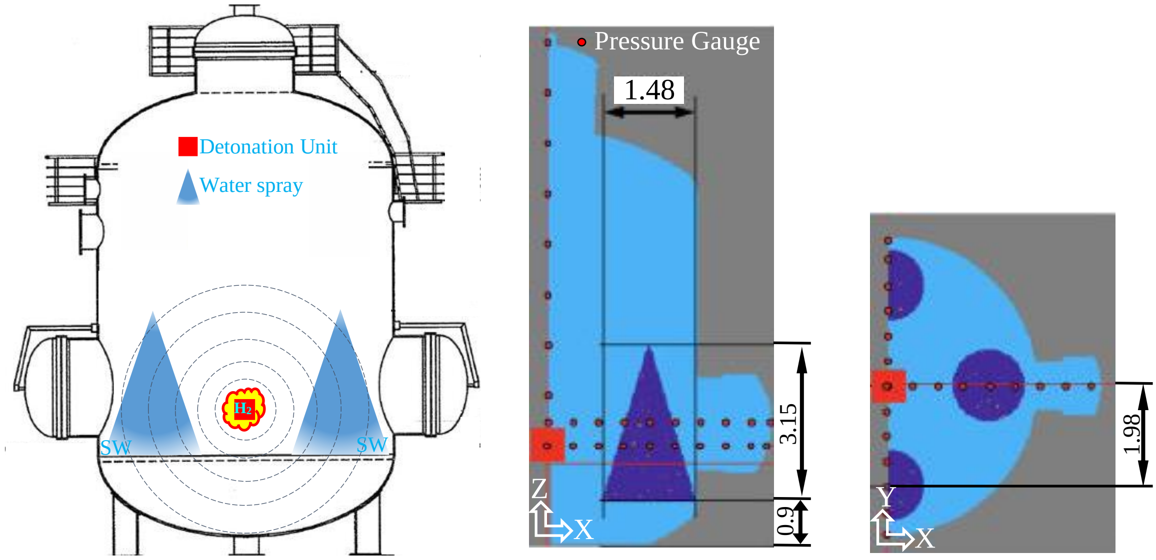


Figure 5. Geometrical models of hydrogen detonation vessel with sprays, (a) CAD drawing of the vessel, (b) vertical cut view of the computational domain showing schematically the detonation unit, droplet cloud and pressure gauges, (c) horizontal cut view of the model

Each spray device generates a mist cloud in a conical shape with a height of 3.15 m and a bottom radius of 0.74 m, a volume of 1.8 m^3. The droplet size is defined as 500 μm and the liquid phase concentration as 1 kg/m^3. In total 2.76×10^7 particles are defined. However, only 10^4 “representative” particles are computed by using a multiplication approach due to limited computing resource.

The half domain is modeled by 1.82 million cubic cells with a uniformed size of 0.0435 m.

4.2 Detonation with spray off

As a base case, hydrogen detonation is simulated without water intervention. The 4 g hydrogen is ignited at time t = 0 ms in the detonation unit put on a solid tray. A high pressure up to 8 bar and a high temperature up to 2000 K caused by the acute H_2-O_2 reactions initiates pressure shockwaves, propagating spherically from the detonation unit. The shockwave developing process is shown in Fig. 6 as pressure contour plots at different times. At t = 1.32 ms, the spherical shock front is almost formed with a slight asymmetry in the vertical axis due to the solid plate where the detonation unit stands. A low pressure region is formed at the center of the unit because of the fast expansion of the gases. At this time, the shockwave has a peak pressure of 2 bar with a Mach number of 1.41. At t = 2.63 ms, the pressure shock is quite mature presenting a decayed pressure of 1.4 bar and a Mach number of 1.16. At t = 5.17 ms, the shock front hits on the vessel bottom plate and is reflected there. The wave reflection forms a higher pressure indexed by red. At t = 7.77 ms, the shock front hits on the vessel wall, where the shockwave is reflected. At t = 11.23 ms, a complicated pressure distribution is formed owing to the superimpositions between the original incident shockwave and the reflected ones.

The pressures are recorded by the pressure gauges at the defined locations, which are compared to those attenuated by water mist in next sub-section.

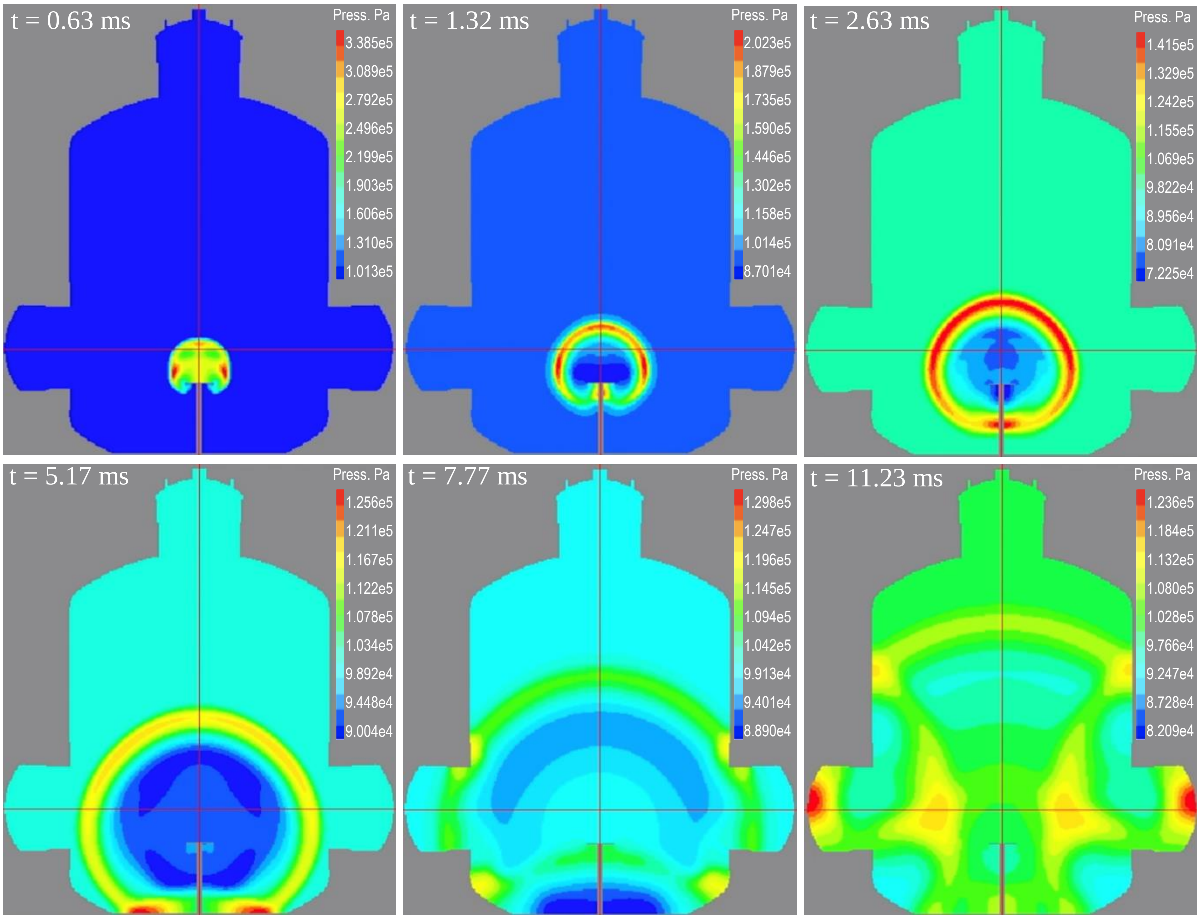


Figure 6. Detonation shockwave developing and propagating process and wave reflections on the vessel bottom plate and the wall

4.3 Shockwave attenuation by mist

A wet case is simulated by restarting the base case with the presence of the defined droplet clouds from the time t = 0 ms. The shockwave overpressures caused by hydrogen detonation are compared between the case with mist attenuation and without mist. As shown in Fig. 7, the compared shock front overpressures are the records of the column of gauges aligned horizontally in the line from the vessel centre to the conical cloud centre at the same height of Z = 1.22 m, and at a distance from the vessel centre X = 1.74 m, 2.18 m, 2.61 m, 3.05m, respectively. The Gauge 1 locates in front of, not within, the cloud; the Gauge 4 behind the cloud. The Gauge 2 and 3 are within the cloud.

As expected, the peak pressure is not affected by the presence of cloud, as shown by the curves in black in Fig. 7, where is outside of the misted region. However, the records of the other three gauges manifest that the overpressures are deducted by 15 – 20 % due to the presence of the droplet clouds. According to arrival times of the peak pressures, it seems that the mist clouds barely influence the shockwave propagating speed.

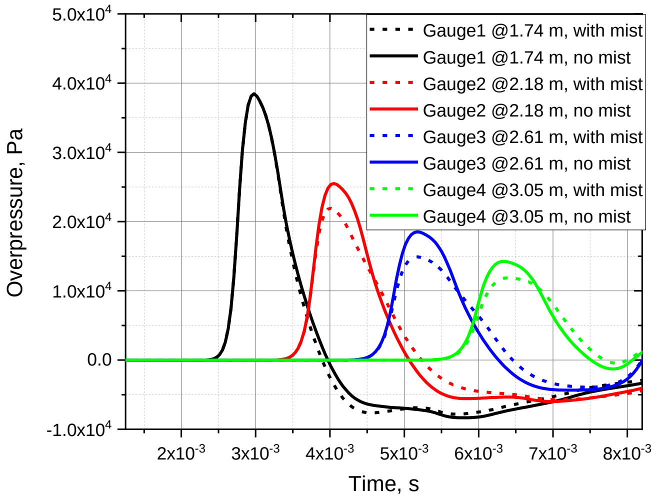


Figure 7. Overpressures in cases with/ without mist attenuation, recorded by the column of gauges aligned horizontally in the line from the vessel centre to the conical centre at same height of Z = 1.22 m, and at a distance from the vessel centre X = 1.74 m, 2.18 m, 2.61 m, 3.05m, respectively

5 CONCLUSION AND OUTLOOK

The attenuation mechanism of water droplet cloud against pressure shockwaves is elaborated. By using a turbulent combustion code with droplet models, the water mist attenuation phenomenon on shockwaves is studied by simulations in a conceptual mini-scaled tunnel and an experimental facility in a large scale. The attenuation effect of water mist on shock front pressures is observed in both cases. The simulation results of the experimental facility supplies hints to design tests in laboratory. Further validation of the developed particle models is foreseen next step.

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