Influence of Water Mist on Flame Acceleration, Transition to Detonation and Detonation Propagation in H_2-Air Mixtures

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1 Introduction

Explosion of H_2–air mixtures is an omnipresent risk in severe accident scenarios in nuclear power plants. Prediction of explosion impact on the containment of a nuclear reactor is complicated by uncertainty regarding initial conditions prior to ignition. The present study is part of a research project aiming at approaching real-world conditions during accidents in nuclear power plants. In the first part of the project, the influence of mixture inhomogeneity on flame acceleration [1], transition to detonation [2] and detonation propagation [3] has been studied. The second part, which is presented in this work, focuses on the influence of water mist on explosion processes in homogeneous H_2–air mixtures. Water loading ratios between 0.01 and 0.1 kg/m^3 are relevant for severe accident scenarios in nuclear power plants.

Significant knowledge has been accumulated on gaseous explosions with water mist or water sprays, cp. review paper by Thomas [4]. The motivation of these investigations was mainly mitigation of explosion hazards in industrial applications by water sprays. Examined water loading ratios were often higher than relevant for nuclear reactor accident scenarios. In the majority of small and large scale studies available, reduction of explosion severity by sprays has been reported. Heating and evaporation of droplets causes a decrease in combustion temperature, lowering both the mixture burning velocity and the expansion ratio. Holborn et al. [5] and Battersby et al. [6] pursued an experimental approach for generating water mist very similar to the present study, employing ultrasonic atomizers. Battersby et al. determined a reduction in maximum overpressure of about 35 % with 0.09 kg/m^3 water loading ratio in a 11.5 vol. % H_2–air mixture.

Our goal was to design an experiment with well-defined boundary conditions that allows for investigation of slow and fast deflagrations, transition to detonation and detonation propagation in H_2–air with water mist. Central requirements concerning water mist properties were: Defined droplet size distribution; Real-time measurement of water loading ratio; Homogeneous spatial droplet distribution.

2 Experimental Setup

2.1 Geometry and Measurement Techniques

Experiments were conducted in a classical explosion channel with a length of 4.2 m and a rectangular cross section (0.06 m height, 0.3 m width). The channel was equipped with flat plate obstacles with a blockage ratio of 30 % at a spacing of 0.3 m. The first obstacle position is x = 0.15 m, the last x = 4.05 m. Piezoelectric pressure transducers (type Kistler 601A) were installed in the channel top plate (No. 1–5) and in the end plate (No. 6). Transducer positions are given in Tab. 1. This facility has been used in numerous studies before. Comprehensive information can be found in respective publications [1–3, 7].

Table 1: Distance of pressure transducers from point of ignition.

No.	1	2	3	4	5	6
x [m]	0.4	1.4	2.1	2.8	3.7	4.2

2.2 Generation of H_2–Air Mixture

For mixture preparation, the channel is first flushed with air. Second, the volume is partially evacuated to a predefined value p_{vac}, so that ambient pressure is reached after H_2 injection. Third, H_2 is injected through 126 evenly distributed ports in the top plate. Recirculation of H_2 and molecular diffusion leads to a quick homogenization of the mixture. From earlier experiments with concentration gradients, where a layer of H_2 was formed at the channel top and diffusion led to defined concentration gradients, it is known that a diffusion time t_d between injection and ignition of 60 s led to a homogeneous mixture [7]. Since we now inject H_2 perpendicularly without forming a layer, a shorter diffusion time is sufficient to reach homogeneity. In preliminary experiments it could be shown that diffusion times down to 5 s yield homogeneous mixtures. Overpressures during explosion in these mixtures are equal to overpressure after 60 s diffusion time within the measurement accuracy. We conducted all experiments presented in this work at a diffusion time of t_d = 10 s.

2.3 Water Mist Generation, Injection and Characterization

The explosion channel is equipped with a water mist injection system (Fig 1). Fourteen ultrasonic atomizers (1) are installed in a volume underneath the explosion volume (2), generating quiescent water mist. They are placed in cylinders (3) which are filled with water at a defined level. Water is provided through supply pipe (4) and removed by pipe (5) between the experiments. The water mist is transported into the explosion volume by an air flow generated by an external diaphragm pump (6), circulating air in a closed loop. The air flow is distributed between the atomizer units through a pipe system and is measured with a rotameter (7). Pressure losses in each branch were adjusted such that air flows through the units differ by less than ± 5 %. This was proven by constant temperature anemometry (CTA). Flowing into the cylinders at a flow rate of 17 l/min per atomizer unit, the air transports the water mist through inclined holes above each unit (8) into the explosion volume. Recirculating inside the volume, droplets distribute homogeneously. Air is recirculated towards the diaphragm pump through orifices in the bottom plate of the explosion volume (9). Water loading ratio is controlled by setting the time for water mist injection t_m.

Droplet size distribution is measured by laser scattering (MALVERN particle sizer). Fig. 2 (a) shows the distribution with a Sauter mean diameter (SMD) of 13 μm. Measurement of light extinction has been chosen to determine the water loading ratio. A diode laser (660 nm, 77 mW) operated at 40 mW is used as a light source. A beam splitter reflects part of the beam towards a reference photodiode, which is used for correcting temporal fluctuations of laser output power. The measurement beam is guided through windows into the explosion volume at x = 2.17 m. Behind the volume, the measurement photodiode detects transmitted light intensity. Photodiodes are connected to an sglux MULTIBOARD measurement amplifier. Diode and amplifier characteristics were calibrated by means of neutral density filters of

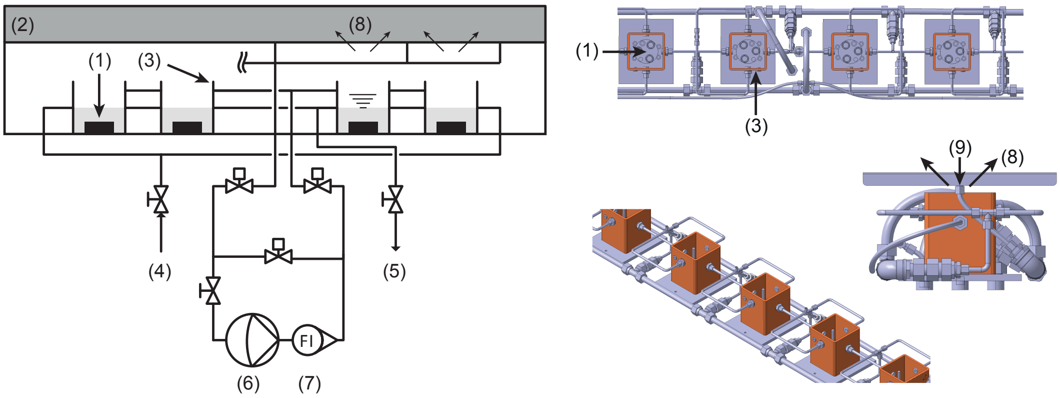
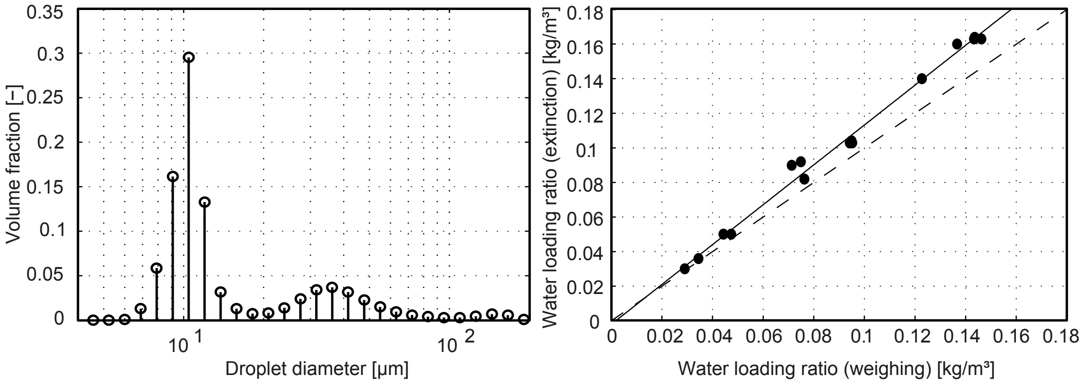


Figure 1: Water injection system. Not all fourteen atomizer units displayed.



(a) (b)

Figure 2: Droplet size distribution measured by laser scattering (a); Calibration of extinction measurement by weighing of samples (b).

known transmission at 660 nm. Employing the Beer-Lambert law, Eq. (1) [9], with the extinction coefficient σ_e according to Eq. (2), yields the particle number of concentration N as a function of intensity I measured behind and I_0 before light transmission through the water mist with the optical path length L = 0.3 m. Extinction efficiency Q_e is assumed constant, which is valid for particle sizes larger than 4 μm [9].

$$\frac{I}{I_0} = e^{-\sigma_e L} \tag{1}$$

$$\sigma_e = N Q_e A_p = \frac{N Q_e d^2 \pi}{4} \tag{2}$$

Since deviations from the Beer-Lambert law must be expected due to droplet sedimentation at the windows, and also due to multi-scattering effects at high water loading ratios, calibration of the extinction measurement technique was performed (Fig. 2 (b)). Samples with a volume of 380 ml were taken from the explosion volume and water mass weighed using a SORATORIUS MC 410 S scale. Initial conditions of the system (e.g. depositions on the windows) before water mist injection are taken into account through an automated calibration measurement before each experiment.

2.4 Experimental Procedure

The overall procedure for each experiment is as follows: Evacuation of the channel to p_{vac}; Activation and calibration of extinction measurement; Channel flushing with water mist for time t_m; Waiting time t_w = 10 s until water mist is quiescent; H_2 injection; H_2 diffusion time t_d = 10 s; Ignition - explosion (initial conditions for explosion: ambient pressure and temperature); Channel flushing with air for 180 s; Water refill for atomizers for 90 s; Water level equilibration for 150 s; Pipe system flushing with external air for 30 s. Each set of parameters (H_2 concentration X_{H2}, water mist injection time t_m) was repeated three times.

3 Results

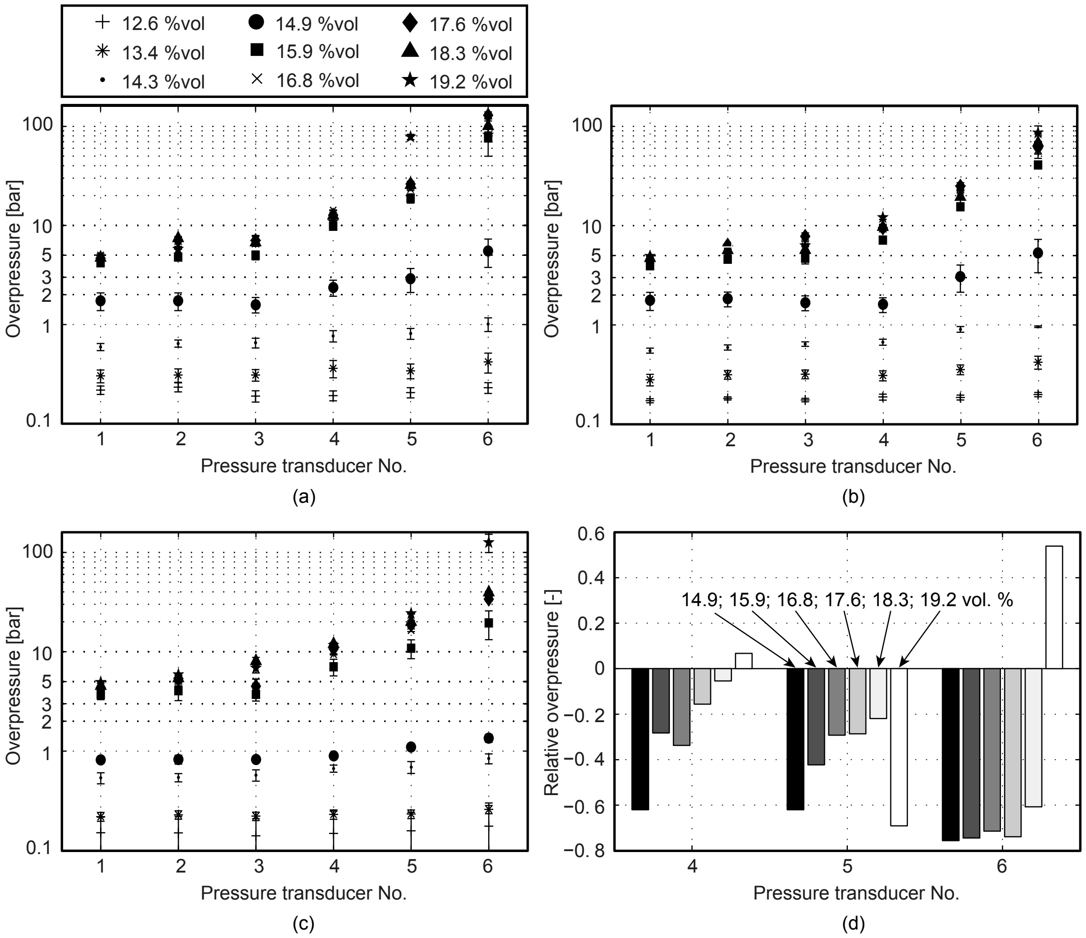
Three series of measurements were conducted: Reference experiments without water mist; Experiments with a water loading ratio of 0.06 kg/m^3; Experiments at 0.11–0.12 kg/m^3. In each of these groups, H_2 concentrations from 12.6 up to 19.2 vol. % were examined. This range covers phenomena from slow flames up to transition to detonation. Additionally, experiments in a near-stoichiometric mixture (X_{H_2} = 30 vol. %) were conducted to study detonation propagation.

3.1 Peak Overpressure

Figure 3 (a)–(c) shows peak overpressure at each pressure transducer depending on H_2 concentration in dry reference experiments (a), 0.06 kg/m^3 (b) and 0.11–0.12 kg/m^3 water loading ratio (c). From the comparison of (a) and (c), it is obvious that water mist reduces maximum overpressures and thus retards flame acceleration. Differences between (a) and (c) are well measurable, whereas differences between (a) and (b) lie within the measurement precision. At higher H_2 concentrations pressure transducers 4–6 showed tendencies of thermal shock in the measurements of (b), which may erroneously lower measured pressures at these transducers. Thus we focus on the comparison of (a) ("dry mixture") and (c) ("wet mixture").

Peak overpressures are lowered by water mist by up to 75 %, depending on pressure transducer position and H_2 concentration. Significant flame acceleration does not occur in dry and wet mixture at H_2 concentrations between 12.6 and 14.3 vol. % (overpressure remains fairly constant along the channel length). These experiments with slow flames are comparable to those presented by Battersby et al. [16], who found a reduction of peak overpressure of about 35 % between a dry mixture at X_{H2} = 11.5 vol. % and a wet mixture with a 0.09 kg/m^3 water loading ratio. Our measurements show a reduction of 23–36 % at pressure transducers 1–6 at 12.6 vol. % and 0.12 kg/m^3. The added value of our study compared to [5, 6] is particularly the extension towards faster explosion regimes. Until pressure transducer 3, flames do not significantly accelerate even at elevated H_2 concentrations. It is insightful to study phenomena at 14.9 vol. % upwards at transducers 4–6. Relative comparison of overpressures of dry and wet mixture (Fig. 3 (d)) reveals that the effect of water mist on overpressure decreases with increasing H_2 concentration in the investigated range. The concentration of 14.9 vol. % is particularly interesting since water mist hinders transition from slow to fast flames here. Peak overpressure is 1.4 bar at the end plate in the wet experiment, while 5.5 bar is measured in the dry experiment. This equals a reduction of 75 %. We find that a water loading ratio of 0.11–0.12 kg/m^3 causes a reduction of overpressure similar to a reduction of H_2 concentration by about 0.6 vol. % in the deflagration regime.

Phenomena at the end plate of the facility at pressure transducer 6 can be further evaluated. As we showed in [8], local explosions occur at the end plate as soon as deflagrations approach the end plate



(a) (b) (c) (d)

Figure 3: Peak overpressure without liquid water case 1 (a), water loading ratio 0.06 kg/m^3 case 2 (b), 0.11–0.12 kg/m^3 case 3 (c); relative difference in overpressure between wet (case 3) and dry (case 1) mixture at p_4–p_6 (d).

at a velocity close to the sound speed of the combustion products in the range of 800–1000 m/s. These explosions, initiating transition to detonation, cause overpressures of 100 bar and higher. Reflection of both slower deflagrations and detonations causes distinctly lower overpressure. In dry mixtures, such high peak pressures first occur between X_{H_2} = 15.9 and 16.8 vol. %. In the wet mixture, overpressure does not exceed 40 bar at H_2 concentrations of up to 18.3 vol. %. Only at 19.2 vol. % a high peak pressure of 125 bar is measured. In the dry mixture transition to detonation occurs close to transducer 5 at 19.2 vol. %, causing high overpressure. In the wet mixture, on the other hand, transition occurs at the end plate, yielding higher overpressure than effected by detonation reflection at the end plate in the dry mixture. This analysis clearly shows that water mist mitigates explosion hazards in the presented configuration by retarding transition from slow to fast flames and especially transition to detonation.

3.2 Detonation Velocity

Experiments in a near-stoichiometric mixture (X_{H2} = 30 vol. %) were performed in order to investigate the influence of water mist on detonation propagation. Detonation velocity was determined from detonation arrival time at pressure transducers 4, 5 and 6. A water loading ratio of 0.12 kg/m^3 was used.

In the dry reference mixture, a propagation velocity of 1984 m/s was measured, which almost equals the Chapman-Jouguet velocity for this mixture (D_{CJ} = 1987 m/s). Detonations in mixtures with water mist propagated at 1927 m/s, which equals a velocity deficit of about 3 % compared to the reference experiment. D_{CJ} of a dry mixture at 28 vol. % H_2 is 1922 m/s, so that the influence of water mist equals a reduction in X_{H2} by 1–2 vol. %.

4 Concluding Remarks

The question has been posed by what extent water mist can influence explosion of H_2–air in severe accident scenarios. Experiments showed that water loading ratios around 0.11–0.12 kg/m^3 mitigate explosion hazards through reduction of explosion overpressure. Measured reduction in overpressure equals the effect observed by reducing H_2 concentration by 0.6 vol. % in the deflagration regime and 1–2 % in the detonation regime.

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References

[1] Boeck, L.R., Hasslberger, J. and Sattelmayer, T. (2014) Flame acceleration in hydrogen/air mixtures with concentration gradients. Combustion Science and Technology, vol. 186, pp. 1650–1661.

[2] Boeck, L.R., Msalmi, S., Koehler, F., Hasslberger, J. and Sattelmayer, T. (2014) Criteria for DDT in hydrogen-air mixtures with concentration gradients. 10^{th} International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions. Bergen, Norway.

[3] Boeck, L.R., Berger, F.M., Hasslberger, J. and Sattelmayer, T. (2014) Detonation propagation in hydrogen-air mixtures with concentration gradients. Submitted to Shock Waves, 14/07/2014.

[4] Thomas, G.O. (2000) On the conditions required for explosion mitigation by water sprays. Trans IChemE, vol. 78, pp. 339–354.

[5] Holborn, P.G., Battersby, P., Ingram, J.M., Averill, A.F. and Nolan, P.F. (2012) Modelling the mitigation of lean hydrogen deflagrations in a vented cylindrical rig with water fog. Hydrogen Energy, vol. 37, pp. 15406–15422.

[6] Battersby, P.N., Averill, A.F., Ingram, J.M., Holborn, P.G. and Nolan, P.F. (2012) Suppression of hydrogen–oxygen–nitrogen explosions by fine water mist: Part 2. Mitigation of vented deflagrations. Hydrogen Energy, vol. 37, pp. 19258–19267.

[7] Vollmer, K.G., Ettner, F. and Sattelmayer, T. (2012) Deflagration–to–detonation transition in hydrogen-air mixtures with concentration gradients. Combustion Science and Technology, vol. 184, pp. 1903–1915.

[8] Boeck, L.R., Hasslberger, J., Ettner, F. and Sattelmayer, T. (2013) Investigation of peak pressures during explosive combustion of inhomogeneous hydrogen–air mixtures. Proc of the 7^{th} International Seminar on Fire and Explosion Hazards. Providence, RI, USA.

[9] Hinds, W.C. (1999) Aerosol technology: Properties, behavior, and measurement of air- borne particles. 2nd Edition, John Wiley and Sons Inc.