

MITIGATION OF HYDROGEN-AIR EXPLOSIONS USING FINE WATER MIST SPRAYS

S.J. Jones[1], A.F. Averill[1], J.M. Ingram[1], P.G. Holborn[1], P. Battersby[1], P.F. Nolan[1], I.D. Kempsell[2] and M.J. Wakem[2]
[1]Explosion and Fire Unit, London South Bank University, Borough Road, London, SE1 0AA (+44-207-815-7980)
[2]British Nuclear Group, Sellafield, Seascale, Cumbria, CA20 1PG (+44-1925-832000)

Due to the flammable nature of hydrogen in air mixtures, their presence requires elimination by ventilation or inerting. In some cases, this is difficult. Therefore, research has been conducted into developing an additional hazard management strategy. ‘Proof of principle’ physical experiments using a fine water mist, as a means of mitigation have been successfully performed and these are endorsed by the results from a series of computational fluid dynamic simulations.

KEYWORDS: impact, ignition, hydrogen in air explosion, water, mist, mitigation, inerting

INTRODUCTION

Because the flammable range of hydrogen in air is substantial (i.e. approx. 4 to 74%) the generation and use of hydrogen will always present some likelihood that a deflagration or explosion might occur. The most common techniques to prevent explosions are by ventilation or inerting with nitrogen or argon. In some cases this will be difficult to implement, either because of the nature of the plant or containment or because the inerting process itself may result in a safety hazard to operators.

The decommissioning of a nuclear waste storage plant is considered in this paper. In nuclear waste, hydrogen will be produced either electrolytically through corrosion of materials such as Magnox fuel cladding (99% Mg) or by radiolysis of aqueous solutions. It is known that significant transient releases of hydrogen could occur during decommissioning that would result in a transient flammable atmosphere. As an alternative approach to venting or inerting, the use of fine water mists to suppress ignition of hydrogen flammable atmosphere is considered here. Although water mist has been used successfully in the suppression of fires very little attention has been given elsewhere to the ignition suppression of flammable gas mixtures such as hydrogen in air. If a hydrogen in air mixture is ignited then the presence of a water mist will cool any flame that it encounters. Under the right circumstances it would be possible to use such a water mist to render a given concentration of hydrogen in air inert, thus raising the flammable limit and thereby reducing the risk of an explosion occurring.

A ‘proof of principle’ study on the effectiveness of water mists’ suppression has been completed, using the LSBU (London South Bank University) ‘exploding wire’ (i.e. a strong igniter) hydrogen in air – water mist experimental scale rig. A computational fluid dynamics simulation of this scale rig allowed the spatial and temporal distributions to be determined. Such information can be used with an inerting map criteria to predict the inerting capability of the water mist employed and hence the degree to which the lower flammable limit of a hydrogen in air mixture can be raised.

MITIGATION OF HYDROGEN-AIR IMPACT IGNITIONS USING WATER MIST SPRAYS

Existing research work has looked at the use of water mist in the suppression of fires and flammable hydrocarbon gas mixtures. In comparison, relatively little attention has been given to the suppression of flammable hydrogen in air mixtures with water mists. Hydrogen behaves differently to other hydrocarbons so hydrocarbon results cannot be extrapolated. There is therefore a clear need to investigate the potential of such water mists in raising the lower flammable limit of hydrogen in air mixtures. Success would offer a new hazard management strategy for flammable mixtures. This would be a cost-ffective alternative to the existing principal options of air dilution and inerting. The first stage of experimentation, described in this paper was to provide a 'proof of principle' of the concept.

The observations and quantifiable results of these physical experiments have been compared with predictions based on a computer simulation, incorporating a Lagrangian particle tracking model. It has been shown that the presence of the water mist increases the concentration of hydrogen at which the lower flammability limit occurs.

THE WATER MIST INERTING CONCEPT

The basic concept of water mist inerting involves introducing a water mist comprised of fine water droplets into a flammable hydrogen in air mixture. If the mixture should become ignited the water mist will cool any flame that it encounters and so inhibit flame propagation. Under the right circumstances it is possible to use such a water mist to render a given concentration of hydrogen in air inert, thus raising the flammable limit and thereby reducing the risk of an explosion occurring. The amount of heat extracted will be determined by both the size of the droplets and the volume fraction they occupy which gives a measure of their concentration.

This leads to the idea of an 'inerting map'. The inerting map sets out the droplet size and the volume fraction of water mist required to inert a given concentration of hydrogen. Such a map can be constructed by using a simplified mathematical treatment to model the effect of water mist on flame propagation behaviour [1].

Figure 1 shows an example of such an inerting map for a 15% hydrogen in air mixture at a temperature of 35°C. The map plots the mist droplet size along the horizontal axis and the volume fraction of water mist along the vertical axis. For a mist with a given drop size the minimum volume fraction of water mist is shown that is required to achieve inerting and move above the critical limit into the non-flammable zone. Thus, for a mist with a larger drop size of 100 microns a much higher volume of water mist is required

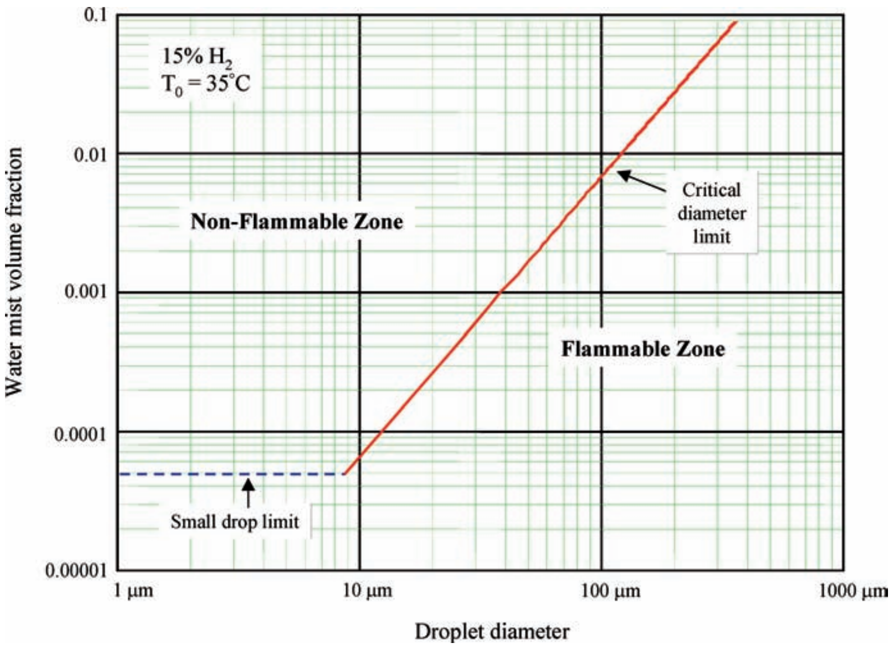

Figure 1. Example of a water mist inerting map constructed for a 15% hydrogen-air mixture at 35°C.

than for a mist made up of 10 micron droplets – that is the smaller droplets are much more efficient at suppressing the flame than larger ones. This is true up to a certain point, known as the small droplet limit located at around 10 microns. Below this point the droplets are so small that they completely evaporate before reaching the flame and so the inerting capability becomes independent of droplet size and merely depends upon the volume of water mist delivered.

PROOF OF PRINCIPLE DEMONSTRATION

In order to provide a proof-of-principle demonstration of the concept an 'exploding-wire' hydrogen in air/water mist experimental scale rig was developed at LSBU to test the suppression of flammable hydrogen in air mixtures with very fine water mists.

With the existing impact ignition rigs at LSBU many controlling factors exist and the probability of ignition is often less than 1, so it is difficult to be sure if the water mist is preventing ignition. The strong igniter removes any uncertainty from testing – with the strong igniter the probability of ignition with no water mist present is always 1.

Such an exploding wire igniter is extremely powerful and is very similar to the one used in the British Standard flammability tests. The device consists essentially of a 2 μF capacitor rated at high voltage which is charged to 6 Kv through a high voltage transformer and bridge rectifier. The stored energy (~30J) is then rapidly discharged through a fine copper wire (0.05 mm diameter) on closing a spring loaded contact, causing it to vaporise and ignite a flammable gas mixture. Because the discharge occurs through a wire rather than the gas, the possibility of the presence of water droplets in the gas mixture interfering with the igniter action is avoided. It is unlikely that anything like such an effective ignition source could arise from a mechanical impact in a nuclear silo.

The igniter is used in an explosion cabinet (rated to IP65) of dimensions 760 mm × 560 mm × 280 mm deep (0.144 m^3). Figure 2 shows a schematic diagram of the assembly used. A hinged grid allowing access to the interior of the cabinet is fully interlocked so that the cabinet cannot be opened when energy is stored in the igniter capacitor. Thin plastic film is used to seal the grid before gases are introduced into the enclosure to provide a blow out vent when a deflagration or explosion occurs. Several inlets are used to allow introduction of hydrogen gas and the establishment of the water droplet mists. An outlet is provided to allow sampling of the gas to establish the mixture concentration.

A range of different types of water mist nozzles was initially tested to assess their suitability for suppression applications. The distribution of droplet sizes produced by each nozzle type was determined using a Malvern laser diffraction particle sizing unit. The Cold Fog nozzle was found to have the best characteristics out of those nozzles tested initially (i.e. finest droplets) and was therefore the one selected for use in the experimental rig in the initial round of suppression tests. The Cold Fog nozzle manufactured by Atomizing Systems Incorporated, New Jersey USA, uses a high-pressure water jet (70 bar) which exits through a very fine ruby orifice and strikes an impingement pin generating a very fine water mist. The ruby orifice prevents wear that would otherwise rapidly widen the size of the exit hole and degrade the performance of the nozzle. The Cold Fog also had the advantage of being a single-fluid nozzle and so did not have the problem of introducing airflow diluting the hydrogen in air mixture present in the chamber as would be the case with the twin-fluid (i.e. both air and water) type nozzles considered.

After the initial round of experimental tests was completed, further water mist generating technologies were examined, to see if any improvements in inerting capability could be made. One of the technologies considered, an ultrasonic fogger unit appeared to be capable of generating a very fine water mist and was deemed to be worthy of more detailed investigation. Subsequent experimental efforts therefore focused on investigating the use of an ultrasonic fogger unit in the suppression of hydrogen in air mixtures. An ultrasonic fogger unit is comprised of one or more piezoelectric discs which are made to vibrate at very high frequency (typically between 1 and 5 MHz). In operation these elements are situated beneath a column of water. At a suitable depth (below the surface) the high frequency vibration of the piezolectric discs generates violent cavitation and capillary waves at the water surface. This results in the formation of a "fountain"

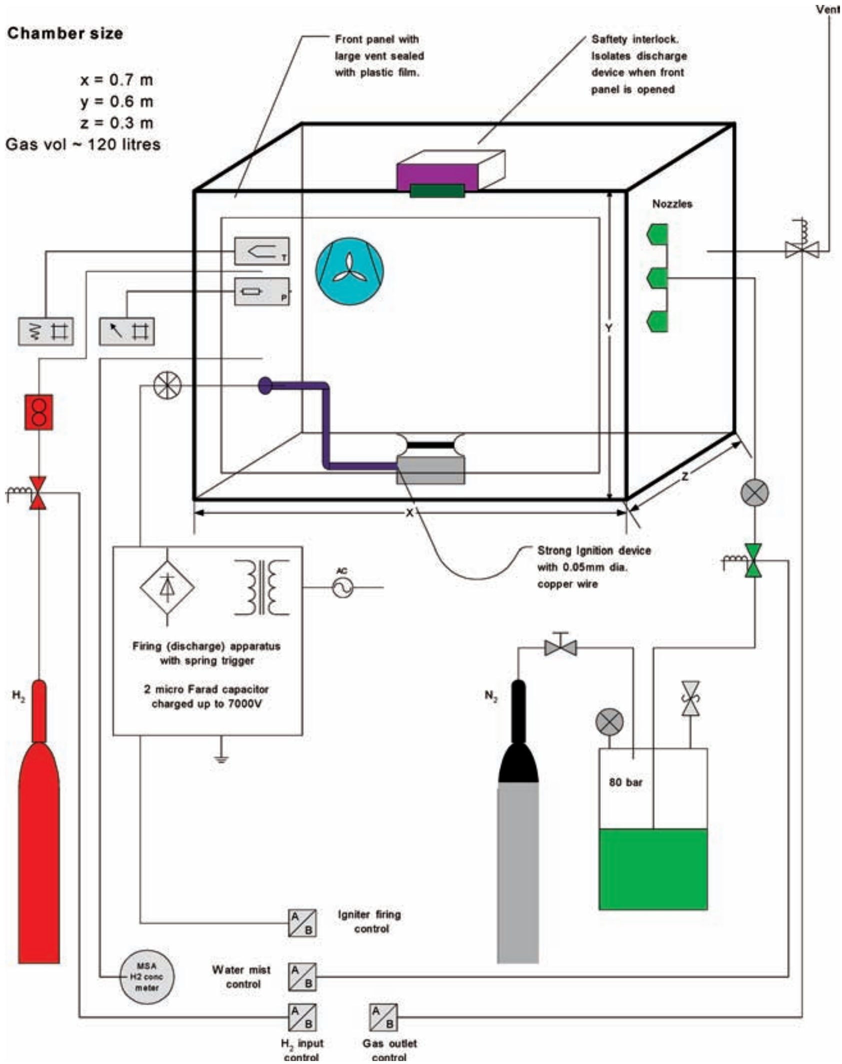

Figure 2. Schematic diagram of the strong ignition source water mist suppression apparatus

above the surface comprised of very fine water droplets, along with much larger droplets, which can be several millimetres in diameter [2]. If the unit is positioned too far below the water surface the efficiency of the unit is impaired reducing the size of the fountain and the amount of fine water mist generated. In this sense the ultrasonic unit can be thought of as being analogous to an optical lens which must be situated in the correct location (i.e. at the correct focal length) to focus the ultrasonic vibration energy at the water surface and optimise the droplet generation mechanism.

Initial experimental trials with the fogger unit in the experimental rig revealed that the fine water mist produced would form a dense layer close to the floor of the rig chamber. A fan was therefore operated in subsequent experiments to circulate the mist throughout the rig chamber and produce a more uniform distribution of mist. The water mist produced by the fogger was also characterised with the Malvern particle sizing unit. The results suggest that (providing the very large drops are filtered out) the water mist produced is very fine (sub 10 micron droplets) and approximately monodisperse in nature. For such a very fine water mist the inerting map suggests that a water mist density of 0.025 kg/m^3 is required to inert an 8% hydrogen in air mixture.

The water mist used in the experimental tests was generated using either one or more Cold Fog nozzles or a 5 disc Ultrasonic Fogger unit. The Cold Fog nozzle(s) were located on the right-hand side of the cabinet. The fogger was located in a water container placed on the floor on the right hand side of the cabinet. By using a combination of either two or three Cold Fog nozzles operating together, it was determined that hydrogen in air mixtures of between 7% and 8% could be successfully suppressed. Thus proof-of-principle of water mist suppression of a flammable hydrogen in air mixture was successfully established. However, despite a number of further tests it did not prove possible to raise the limit in the experimental rig chamber beyond this limit. The water mist obscuration levels in the rig chamber (which provide an indication of the density of water mist present and the visibility level in the chamber) were also monitored as a function of time using the Malvern particle-sizing unit. The obscuration levels in the chamber were observed to saturate (i.e. reach a maximum steady state concentration) after between one and two minutes.

In subsequent experimental tests, using the 5 disc ultrasonic fogger unit to generate water mist, it was found that an upper limit of 8% hydrogen in air mixture could be successfully suppressed. The obscuration levels in the chamber were observed to saturate after between 1.5 and 5 minutes. In this case (since the water mist delivered is approximately monodisperse in nature) the average water mist density in the rig chamber could also be estimated to be around 0.02 kg/m^3.

CFD SIMULATIONS OF THE STRONG IGNITER/WATER MIST RIG

The CFD (Computational Fluid Dynamics) model is used to simulate the distribution of water mist droplets as they are generated and circulated around the rig chamber in terms of both the size of droplets present and corresponding density of water mist attained. A Lagrangian Particle Tracking technique is used to trace the path of the droplets as they move [3, 4]. Criteria obtained from the inerting map can then be applied to predict the "inerting potential" of the mist produced in the rig chamber and hence the level to which the flammable limit can be raised. These predictions can be compared with the experimental results to both validate the model and provide insight into the inerting behaviour exhibited.

A series of simulations of the scale experimental rig were performed using a CFD-Particle Tracking code and employing the water mist drop distribution characterised for both the Cold-fog type nozzle and the Ultrasonic fogger. The dimensions of the model chamber used in the CFD-Particle Tracking simulations were 0.8 m in length, 0.3 m in width and 0.6 m in height. One or more water nozzles were positioned at one end of chamber for the Cold Fog and on the floor of the chamber for the ultrasonic fogger.

The inerting map suggests that for a very fine water mist (i.e. sub 10 micron mist in the small drop limit) a water mist density of $0.025\ kg/m^3$ or better would need to be achieved in order to inert an 8% hydrogen in air mixture. The results predict that the water mist density produced by the ultrasonic fogger in the rig chamber should be just capable of inerting an 8% hydrogen mixture at the igniter location after an operating period of at least 2–3 minutes duration to allow a sufficient concentration of mist to accumulate. These predictions are consistent with experimental results, which indicate that the water mist produced by the fogger is able to successfully suppress up to 8% hydrogen in air mixtures in the scale rig, that the obscuration level saturates after between 1.5 and 5 minutes and that an estimated water mist density of around $0.02\ kg/m^3$ is achieved in the cabinet.

Other improved water mist production mechanisms are currently under investigation. Theoretical analysis and computer simulations suggest that these have the potential to inert significantly higher hydrogen concentrations, of the order of 15%. It should also be re-emphasised that a very strong ignition source has been used in the experiments described here. More recent experiments with a (weaker) impact ignition source that is more representative of that encountered in a typical silo have demonstrated that higher concentrations of hydrogen (of the order of 10%) can be successfully inerted using the same water mist as has been described in this paper.

Table 1. Summary of the experimental results found using water mist to suppress hydrogen-air mixtures in the LSBU strong ignition rig

Type	Description	Limit % H_2 suppressed	Time till obscuration saturation	Average water mist density in chamber
Cold fog	2–3 nozzles	7%–8%	1–2 mins	–
Ultrasonic fogger	5 disc unit	8%	1.5–5 mins	$0.02\ kg/m^3$

CONCLUSIONS

1. Proof-of-principle of the water mist suppression concept has been demonstrated with the successful suppression of 7–8% hydrogen in air mixtures in the strong ignition source experimental rig using water mist generated by either 2–3 Cold Fog nozzles or by using a 5 disc ultrasonic fogger
2. More recent experiments with a (weaker) impact ignition source that is more representative of that encountered in a typical silo have demonstrated that higher concentrations of hydrogen (of the order of 10%) can be successfully inerted using the same water mist as has been described in this paper
3. Results of CFD simulations of the LSBU scale water mist rig have also been described. The model predictions obtained using characteristic droplet distributions for both Cold Fog nozzles and the ultrasonic fogger are consistent with the experimental results found for the scale rig
4. Both theory and experiment suggest that the inerting potential of the water mist generated is crucially dependent upon the distribution of very-fine water mist droplets less than 10 microns in diameter
5. Improved water mist production mechanisms are currently under investigation, which have the potential to inert significantly higher hydrogen concentrations, of the order of 15%.

ACKNOWLEDGMENTS

The Explosion and Fire Unit at London South Bank University would like to acknowledge the financial and technical support of British Nuclear Group, Sellafield.

REFERENCES

1. Luangdilok, W. and Bennett, R.B., Fog Inerting Effects on Hydrogen Combustion in a PWR Ice Condenser Containment, Transactions of the ASME, 117, 502–507, 1995.
2. Rajan, R. and Pandit, A.B., Correlations to predict droplet size in ultrasonic atomisation. Ultrasonics, 39, 235–255, 2001.
3. Crowe, C.T., Sharma, M.P. and Stock, D.E., The particle-source-in-cell model for gas-droplet flows. ASME, Journal of Fluids Engineering, 99, 325–332, 1977.
4. Jackman, L.A., Sprinkler spray interaction with fire gases, Ph.D. thesis, South Bank University, London, 1992.