Journal of Loss Prevention in the Process Industries 40 (2016) 188–198

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Water vapour explosions – A brief review

Rolf K. Eckhoff

Department Physics and Technology, University of Bergen, Norway

ARTICLE INFO

Article history:
Received 29 October 2015
Received in revised form
20 November 2015
Accepted 20 November 2015
Available online 2 December 2015

Keywords:
Explosion hazards
Confined water-vapour explosions
Unconfined water-vapour explosions
Fine molten-metal fragmentation
Explosion prevention
Explosion mitigation

ABSTRACT

There are basically two kinds of water vapour explosions, viz. confined and unconfined. Confined explosions can occur in various situations in industry. Unconfined explosions typically occur when very hot molten metal accidentally makes contact with water. In order to explain the extremely rapid production of water vapour that can then occur, "fine fragmentation" of the molten metal must take place. The paper first presents some early suggestions for the nature of the fine fragmentation process. In more recent theories the Weber number, We, is used as a measure of expected extent of molten-metal fragmentation in a given situation. Film boiling plays a central role. Attempts at developing mathematical models of unconfined water vapour explosions have been made. The next section of the paper is devoted to case histories of unconfined water vapour explosions. Then various kinds of confined water vapour explosions are discussed, including water boiler explosions, water vapour BLEVEs, and water vapour explosions in the paper industry. Some case histories of confined water vapour explosions are also given. The final section of the paper is devoted to measures for preventing and mitigating water vapour explosions in industry.

Contents

E-mail address: rolf.eckhoff@ift.uib.no.

http://dx.doi.org/10.1016/j.jlp.2015.11.017

1. Outline of topics covered

Water vapour explosions can be either unconfined, or partly or fully confined. In the present paper the main focus is on unconfined explosions. These very violent explosions typically occur in metallurgical industries when hot molten metal accidentally makes contact with water. In the nuclear reactor industry the possibility of such explosions is a concern wherever molten core metal can make contact with cooling water in accidental core melt-downs. Unconfined water vapour explosions resulting in extensive property damage and personal injuries have also occurred in paper pulping mills.

Confined/semi-confined accidental water vapour explosions are caused by excess water vapour pressure being produced by heating of fully or partly confined spaces containing water/moisture. Due to the confinement, the rates of evaporation required for generating destructive and hazardous overpressures are mostly considerably lower in such cases than in the case of unconfined explosions.

The present paper is essentially identical with one of the new chapters in Eckhoff (2016).

2. Unconfined water vapour explosions

2.1. Basic nature

In the present context an unconfined water vapour explosion is defined as the extremely violent generation of water vapour that can arise from accidental contact between a hot metal melt and liquid water. As already pointed out by Witte et al. (1970) 45 years ago, this is in most cases a purely physical process. 25 years later Bergstrøm (1995) specifically discussed water vapour explosions resulting from contact between molten steel and ferro-alloys, and water. He re-emphasized that the nature of such explosions is basically physical. This means that the energy driving the explosion is an extremely rapid heat transfer from the molten metal to the water. The water then vaporizes at an explosive rate whereby the cloud of water vapour generated can attain very high pressures even in fully unconfined locations.

In their review 44 years after the publication by Witte et al. (1970), Meignen et al. (2014) re-confirmed that this kind of water vapour explosion is indeed most often a purely physical process. Heat is transferred at extremely high rates from the hot, more viscous molten metal to the less viscous, cool water. The resulting explosive evaporation of the water gives rise to generation of extremely high local vapour pressures before displacement of vapour into the surroundings gets under way. At sufficiently high local instantaneous pressures, strong shock waves will be produced and emitted into the surroundings. In a way this is similar to the initiation of detonation in explosive gas mixtures, explosive clouds of mists/sprays and explosive dust clouds. Sometimes, therefore, violent unconfined water vapour explosions are also named “thermal detonations”. The very violent nature of these explosions was observed experimentally by Long (1957). He conducted a series of out-door pilot-scale experiments by pouring molten aluminium into water. He characterized the resulting water vapour explosions as being “similar to the detonation of explosives”. They appeared to occur very rapidly after the pouring of the aluminium had started. One experiment was conducted at night without artificial light sources. Three observers agreed that they could not detect any flash or fire during the explosion or immediately after, except for the glow of the red, hot molten aluminium.”

However, if this latter visual observation implies that there was no exothermal chemical reaction involved in the explosion, it contradicts with the findings of Epstein et al. (2000). They concluded that in very violent explosions caused by contact between hot molten aluminium and water, exothermal oxidation of the metal also contributes significantly to the heat transfer to the water. They based their argument on experiments showing that drops of molten aluminium were quite resistant to being fragmented by even very strong shock waves, and therefore physical heat transfer alone cannot explain the explosive development of water vapour observed in aluminium/water explosions. Exothermal chemical oxidation of the metal probably also plays a central role.

For very strong unconfined water vapour explosions to occur purely by physical heat transfer, the time scale for transfer of heat from the molten metal to the water has to be significantly shorter than the time scale for the establishment of a shock wave moving away from the high-pressure region. Such extreme heat transfer rates cannot be explained unless it is assumed that the hot molten metal in some extremely fast way gets dispersed into micro droplets of diameters of the order of 10 μm. This crucial process has been named “fine fragmentation” and will be discussed in section 2.2 below. The strong supersonic blast waves that can be generated under such circumstances can kill and injure people, and demolish and damage mechanical structures including buildings.

For the sake of completeness a quite different situation in which very violent “physical” unconfined vapour explosions can occur, should be briefly mentioned. This is when liquefied natural gas (LNG) is accidentally spilled on water. In this case the water constitutes the hot, more viscous partner (like the molten metal in the discussion above), whereas the liquefied methane is the less viscous cold partner that evaporates at an explosive rate (like the water in the above discussion).

2.2. Some early suggestions for the nature of the fine fragmentation process in unconfined water vapour explosions

By the time of the review by Witte et al. (1970) the following three hypotheses had been proposed for explaining the fine fragmentation of the hot molten metal in essentially physical water vapour explosions.

2.2.1. Water entrapment between initial metal globule and containment bottom

When the initial molten metal globule approaches the bottom of the water containment, some water becomes trapped between the globule and the bottom surface of the containment. The trapped water vapourizes violently and the explosively expanding vapour cloud tears the molten metal globule apart into the microscopic droplets required for further explosive evaporation.