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Modelling the Consequences from Water Explosions in Molten Metal

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Across the metal industry the risk of explosions due to liquid water trapped in molten metal is very real. Accidents, often killing one or a few employees, or blowing out walls, are common in the metal industry. Despite awareness of such explosions it can be challenging to predict consequences and thus evaluate vulnerability and design safety measures. In a recent risk assessment an attempt was made to estimate consequences from water explosions in molten metal furnaces using a combination of spreadsheet calculations and a CFD-tool. With the spreadsheet source terms for blast waves were estimated, calculating how pockets of water within milliseconds could accelerate and throw molten metal at high velocities out of the furnace, and at the same time generate strong pressure waves. Using the CFD-tool FLACS the pressure wave propagation was calculated. The effect of a heavy metal hood above the furnace, with a limited area door opening in one direction would help protect the building and employees against projectiles. The hood would also prevent damaging shockwaves from the explosion to reach wall/roof surfaces in directions of main concern. Using this modelling methodology the amount of water entrained in molten metal required to cause critical damage to building was estimated. Based on a qualitative/quantitative assessment it was thereafter concluded that the potential for water explosions to severely damage the building with the actual furnace design and hood was very limited. The study approach and results from calculations are described in this article.

1. Introduction

In November 2017 a strong explosion in an aluminium furnace took place at Eina, North of Oslo, Norway. The plant was recirculating scrap aluminium. The accident happened 6.20 in the morning, two employees were killed, two seriously injured, and the facility damaged beyond repair. According to a news report by TV2.no (2018), the explosion was caused by rapid phase change explosion of water in the molten aluminium and experts indicated an explosion strength equivalent to 10-50 kg TNT. For water trapped in aluminium there is also a possible reduction mechanism producing hydrogen which may later explode in air, but the accident report seems to have concluded that this was not what caused the explosion. Water trapped in molten aluminium (660 ˚C) can expand 4400 times. The explosion energy of 10 kg TNT roughly corresponds to explosion energy of 1 kg hydrocarbon. To obtain a similar volume expansion from water trapped in molten aluminium about 20 kg water is required, thus the indicative explosion strength corresponds to 20-100 kg water exploding in the furnace. Explosion due to water in molten metal is a well-known hazard in the metal melting industry, and it is critical to prevent water from entering the furnaces. A risk preparedness report preparing for the rebuilding of the facility highlighted the need for shredding and preheating of scrap aluminium prior to feeding it to the furnace, see Multiconsult (2018).

The blast loads from explosions with water trapped in molten metal can at first seem impossible to predict, explosion strength would likely depend on the amount of water, the exact location and depth of the trapped volume of water, and available expansion directions for the molten metal. The metal temperature would matter, as well as the detailed heat transfer mechanism to vaporize the water. In the vaporization process the liquid water may expand 5-10,000 times, depending on melting point of metal, but due to an unknown shape of the pocket of trapped water and the Leidenfrost-effect (film-boiling) limiting heat transfer rates, it can be

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difficult to quantify how fast the phase transition takes place, and what maximum pressures that may result during the vaporization and expansion process. If the overpressure after the vaporization of water is higher than the strength of the containment, i.e. the furnace, the furnace wall will likely fail at the nearest possible location to the trapped water, and molten metal between the trapped water and the failing wall will be accelerated and ejected as heavy (density 5-10 kg/litre), hot (1,000-1,500˚C), deadly projectiles followed by sometimes strong blast waves.

The facility considered in this study is preparing copper powder, and it thus not a typical high capacity melting plant. The furnaces have a regular cylindrical shape (0.5m diameter, 1.5m deep) placed into a solid floor. With the assumption that the furnace bottom and sidewalls are infinitely strong, so that any expansion and ejection of molten metal can only happen through the open top, an attempt to estimate blast effects was done. A spreadsheet approach was used to estimate the blast source term (volume and pressure of expanded, evaporated water vapour when leaving the furnace), and a CFD-tool was thereafter used to calculate the 3D blast propagation into the surrounding building. Two different metals were considered, most of the time the furnace is filled with copper, but at regular intervals iron is filled in the furnaces.

2. Estimate of source terms for blast and projectiles

2.1 Parameters and assumptions

The source term calculations are based on the following assumptions:

- Cylindrical shaped furnace (H=1.5m, D=0.5m, V=0.3m^3), fully open upwards (D=0.5m) and strong walls
- Furnace filled with molten Fe (ρ=7100 kg/m^3, T=1500 ˚C) or Cu (ρ=7800 kg/m^3, T=1250 ˚C)
- Trapped water pockets of 0.2 kg to 5.0 kg were evaluated
- Depth of the trapped water of 0.25m, 0.50m and 0.75m was investigated
- Fast heat transfer is assumed, water change phase and is heated to metal temperature
- Maximum vapour pressure of 220 bar (Critical pressure of water) is assumed
- 1D piston assumption used for expansion, vapour pocket expanded to full cross-section of furnace

2.2 Results from spreadsheet calculations

In the spreadsheet calculations it is assumed that liquid water is rapidly evaporated to a maximum overpressure of 220 bar and a vapour bubble is generated which is accelerating all molten metal above the initial water location upwards and out of the furnace. In Figure 1 some results from the spreadsheet calculations are shown, in the left plot the vapour bubble pressure, the velocity of molten metal and the distance the front of the bubble has traveled is shown as function of time, and the simplified assessment indicates that with the assumptions done it takes only 3 ms to eject metal from the initial contact between water and molten metal. In this case the mass of metal ejected is 350 kg (~50 litre). The key parameters (molten metal projectile velocity, final vapour bubble pressure) were not sensitive to the assumption of maximum vapour pressure of 220 bar, which may indicate a certain robustness of the simplified assumptions.

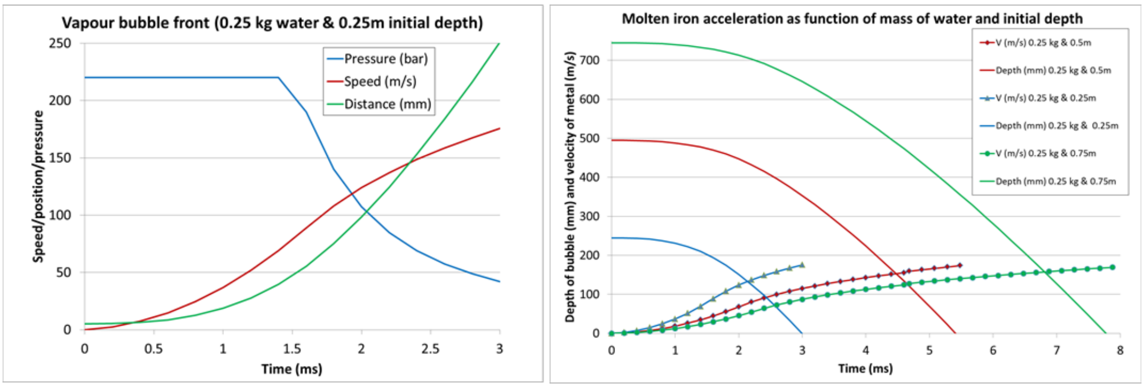

Figure 1: Estimated dynamics of vapour bubble for 0.25 kg water at 0.25m initial depth in molten iron (left) and bubble depth and molten metal velocity for initial depths 0.25m, 0.50m and 0.75m for 0.25 kg water (right)

Another very interesting observation was that the velocity of the molten metal did not depend on the depth of the deposited water, for a given metal only the mass of water seemed to matter. It can also be assumed that the blast loads will primarily depend on the amount of water, to a lesser extent on the depth the water is deposited. The amount of metal thrown out of the furnace is assumed proportional with the initial water depth. In reality the water vapour bubble would likely initially have a more conical shape, not the idealized piston, which could give slightly higher molten metal velocities and smaller bubble volume (with a higher pressure). For the blast source term estimates this is considered to be of limited importance, but the mass of molten metal could be somewhat lower, and the exit velocity somewhat higher.

In Table 1 source terms for some example scenarios are shown. Due to the higher temperature of the molten iron the blast wave source pressure is slightly higher for the scenario with iron relative to copper. The lower density of iron, and the higher pressure also give a slightly lower projectile mass and a higher projectile velocity for iron than for copper for the same scenario.

Table 1: Estimated projectile velocity (molten metal) and blast source term (water vapour volume/pressure/temperature) for selected cases

Scenario	Projectile	Volume vapour	Pressure	Temperature
0.2 kg water in Cu at 0.25m	190 kg &150 m/s	50 L	30 bar	1250 ˚C
0.6 kg water in Cu at 0.25m	190 kg & 220 m/s	50 L	90 bar	1250 ˚C
0.6 kg water in Cu at 0.75m	570 kg & 220 m/s	150 L	30 bar	1250 ˚C
0.6 kg water in Fe at 0.75m	520 kg & 230 m/s	150 L	34 bar	1500 ˚C
1.0 kg water in Cu at 0.50m	380 kg & 260 m/s	100 L	75 bar	1250 ˚C
1.0 kg water in Fe at 0.50m	350 kg & 280 m/s	100 L	83 bar	1500 ˚C
4.7 kg water in Cu at 0.50m	570 kg & 370 m/s	150 L	220 bar	1250 ˚C

There are different mechanisms that may bring water into the furnace. One typical mechanism is that water is trapped in metal parts put into the furnace. This can give a slight delay of the explosion as the surrounding metal must melt before the extensive heat transfer to the water begins, and the explosion may take place well below the surface of the furnace. A second mechanism that water from cooling coils surrounding the furnace can leak into the furnace in connection with a through-burn of the walls. Due to the high density of the molten metal, limited water pressure and dimension of the coils, it is hard to imagine that significant rates of water will enter the molten metal of the furnace, thus while such a scenario may lead to a spectacular scenario with noise and projectiles, this is not foreseen as a likely scenario to generate strong blast waves. Yet another scenario will be that molten metal is falling out of a collapsing furnace trapping significant amounts of water.

3. CFD modeling of blast waves into the facility

The facility studied is located in an urban area with offices and close to traffic. The furnaces are located into the floor with the open top at floor level.

For the CFD-study the explosion model FLACS is used. FLACS is the globally leading tool for calculations of explosions on oil and gas platforms, and in the process industry. FLACS has been validated for blast wave modeling from gas explosions, see Hansen et al. (2010) and Hansen and Johnson (2015). Simplified models have been developed to predict blast waves from high explosives and high pressure gas volumes, see e.g. Hansen (2000) and Skjold et al. (2012). If the source term for the blast waves is defined properly the pressure propagation into the surrounding building should be predicted with good precision.

The main damaging effect from water vapour explosions in furnaces are molten metal projectiles and blast pressures. The molten metal projectiles can be massive and with a high velocity, and may damage most structures in their path. Due to their high temperature the projectiles may also cause fires. Due to the design in the floor the trajectory of the molten metal projectiles will be upwards from the actual furnaces, thus, one efficient mitigation measure against these projectiles is to put a massive metal hood above the furnace. This will stop molten metal projectiles ejected from the furnace. In order to have access to the furnaces there is an open front door in the metal hood. Blast waves generated from an explosion will propagate hemispherically from the open top of the furnace, with somewhat stronger loads straight up from the furnace than sideways. In case there is a protective metal hood, the blast waves can only exit the hood through the door opening, and will do so in several pulses. First pulse is the part of the blast wave directly hitting the door opening, thereafter a number of gradually weaker reflected waves may exit the door opening.

The direct blast wave hitting the opening may be of the order 1 barg with duration of only a couple of milliseconds for a typical explosion caused by 0.5 kg water exploding in the furnace. Further away from the opening the blast wave will be more smeared with significantly lower pressures and durations of 5-10 ms. These durations are very short, windows may break, but quite significant pressure levels may be required to damage building structures.

In Figure 2 predicted maximum blast wave strength onto floor, walls, ceiling and other structures can be seen from an explosion of 0.6 kg water in molten copper. The effect of the metal hood is convincing, most of the blast energy is stopped by the hood. Outside the hood the maximum overpressure predicted only exceeds 100 mbar the first 5m into the room. The maximum pressure locally onto the ceiling is around 50 mbar, and only 40 mbar onto the walls. The wall behind the hood is covered with windows, and in this direction the loads are much lower, mostly below 10 mbar, above 20 mbar only very locally in corners. With the very short blast duration these loads will likely give no damage to the relatively robust windows. It can therefore be expected that such a scenario would not give any significant damage to structures or people outside the protective metal hood.

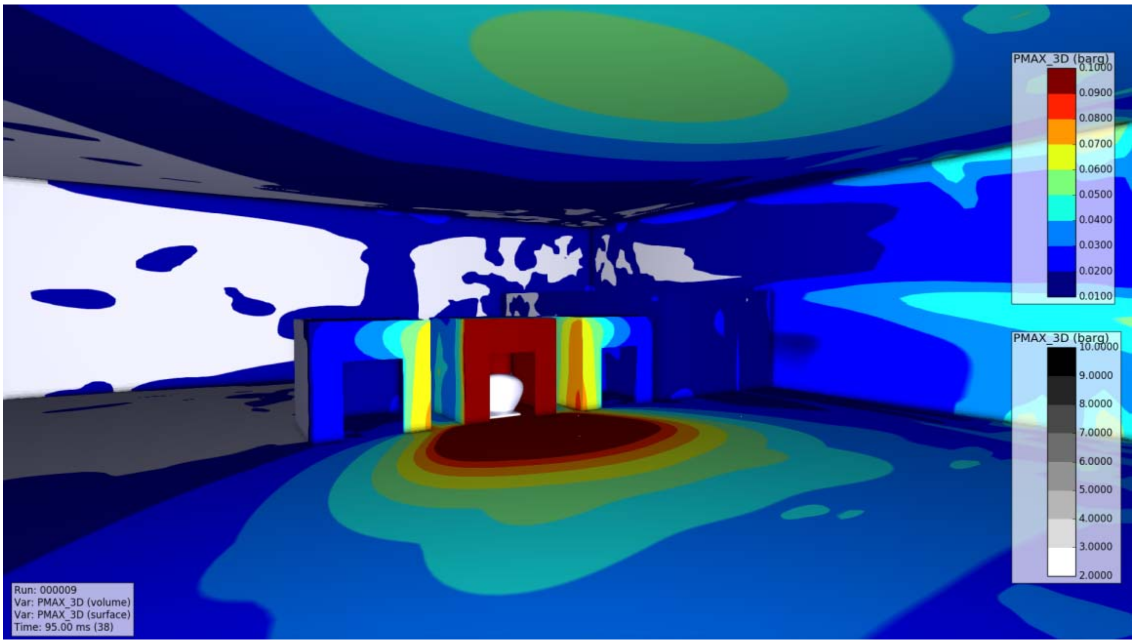

Figure 2: Explosion from 0.6 kg water trapped in molten copper with protective metal hood above furnace. Maximum blast pattern onto surfaces is shown. White volume above furnace inside hood shows region with blast pressures higher than 2 barg.

During certain operations the protective hood over the furnaces may be removed. If an explosion incident would take place in this situation the consequences could be more severe. Firstly, projectiles could be sent upwards, through ceiling and represent a hazard in the vicinity of the facility. More significant blast waves could also be seen inside the facility building. In Figure 3 the predicted maximum blast loads from 0.6 kg water in molten iron incident are shown with no protective hood in place. The loads from incidents in iron are predicted to be marginally higher than for copper, due to the higher temperature in the furnace. The difference is however not significant for the same amount of water.

The maximum loads are seen onto the concrete floor and adjacent metal hoods, which should both be robust to withstand the loads. The ceiling above the furnace receives a predicted maximum pressure close to 200 mbar and will likely be damaged, even if the blast wave duration is short. As previously mentioned projectiles may already have damaged this part of the structure severely. Loads onto most other walls are lower, a control room in the corner could see some damage from loads around 100 mbar, but likely nothing severe due to short load duration. Other solid walls would likely not be significantly damaged from such an incident. The nearest wall behind the original protective hood contains several windows, and the predicted loads close to 100 mbar would likely blow out numerous windows and potentially represent a hazard to people outside. From this type of scenario with no protective hood one could fear major damage to the building and risk to people inside and outside due to projectiles of molten metal and broken windows. Except for very close to the furnace the blast waves themselves should not pose too much risk to people.

For the actual facility calculations like this can give insight in the robustness of the building to handle incidents of varying severity, and the potential hazard to people. The value of the protective hood is also clearly illustrated. With an understanding of how various amounts of water may pose a risk routines could be designed to prevent that problematic amounts of water is entering the furnaces, with and without the protective hood. In the current study simulations were performed with different amounts of water. Based on these scaling relations can be developed to predict the effects for varying amounts of water. According to normal scaling rules for explosion (Cubic root law, i.e. Scaled distance ~ $\text{Energy}^{1/3}$) a given explosion pressure is seen at the double distance if explosion energy is multiplied by factor 8. For far-field blast waves in the open some distance away from the source, the overpressures would typically be reduced by factor two by doubling the distance. Combining these relations a simplified assumption could be that overpressures would be proportional to the squareroot of the amount of water exploding. The predicted blast loads as function of distance could be like seen in Figure 4 using this relation, i.e. $P \sim \text{SQRT}(W_{water})$. The results from the scenarios simulated are illustrated with squares.

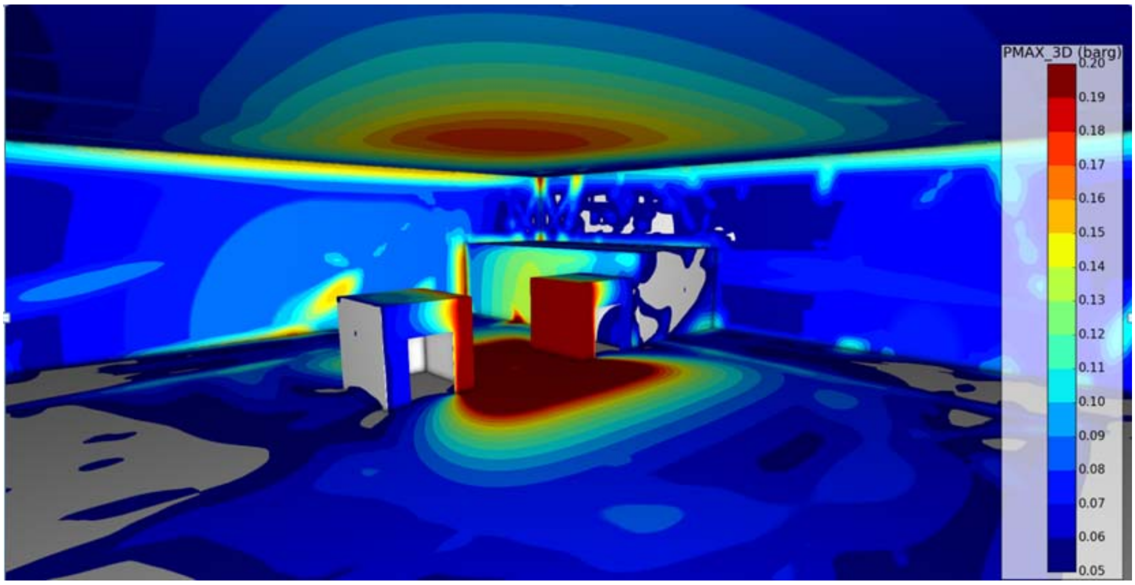

Figure 3: Explosion from 0.6 kg water trapped in molten iron with no protective metal hood above furnace. Maximum blast pattern onto surfaces is shown.

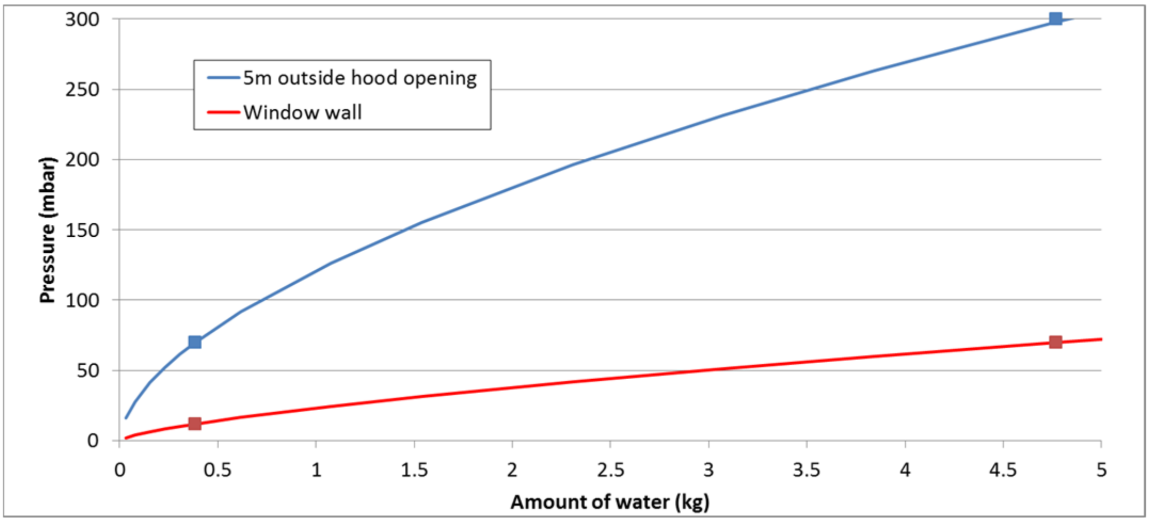

Figure 4: Predicted maximum overpressure 5m outside protective hood door opening and onto wall with windows as function of amount of water trapped in molten metal, scaling relation $P \sim \text{sqrt}(W_{water})$ is used. Squares indicate results from simulations used to calibrate the model.

The simplified source term assessment for the explosions indicates that the explosion strength is primarily governed by the amount of water trapped in metal, and less influenced by unknown parameters like the exact depth and location of the trapped water. These conclusions resulted from idealized 1D piston considerations and are likely valid due to the idealized shape of the furnace studied. It could also well be that these observations would be valid for furnaces of more general shape. If so, the source term approach developed could be applied to understand blast load potential for facilities with less idealized furnace shapes, and help optimize building strength to be robust against possible accident scenarios. The method could also be applied to investigations of actual accidents to help understand amount of water being trapped in furnace, and exact location of incident, based on observed blast damages to buildings.

4. Conclusions

Explosions due to water trapped in molten metal represent a significant concern for the metal melting industry. In this article an attempt is done to quantify the 3D blast loads and projectile effects potentially resulting from such incidents. Due to the significant number of parameters that can be assumed to influence the blast loads, including exact location and depth of the trapped water, the quantification of such blast loads is challenging. The authors are not aware of any published quantitative approaches to do so. In the current work explosions in a cylindrical furnace were studied, a simplified piston approach was applied to estimate possible projectile generation and source term for blast overpressures. Thereafter a CFD-model was used to simulate the blast loads inside the facility. Scaling relations were used to estimate pressures at different locations as function of amount of water. Interesting observations from the work were that the blast pressure source term and the projectile velocity seemed to depend primarily on the amount of water, the depth of trapped water may be of secondary importance. These observations may indicate that the simplified source relations developed for the cylindrical furnaces may have a more general validity, also for other shapes of furnace. If so, a similar approach could be used studying facilities with alternative furnace shapes, including incident investigations.

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