

Explosion of a Circulating Fluidized Bed Furnace for Coal and Biomass

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This article describes an incident that occurred on 12th March 2019 in the Solvay factory at Rheinberg in Germany. It caused the explosion of circulating fluidized bed furnace for coal and biomass.

The investigation showed that corrosion and erosion of a tube in the heat exchanger section led to the entry of 25 metric tons of water into the furnace. The operators shut down the furnace and tried to eliminate the water by circulating air, following the standard procedure detailed in the operating manual. Due to an unforeseen combination of circumstances, the furnace exploded. It was shown that the explosion was not caused by the presence of flammable gas. It was rather a physical explosion, linked to the presence of about 12 tons of water at 100 °C, suspended above the ash bed at 850 °C. The explosion occurred when the hot bed of ashes was suddenly suspended by the circulating air and came into contact with the suspended water, generating up to about 15,000 m³ of steam instantaneously inside the furnace (free volume 380 m³).

The article details the construction and other measures which are necessary to avoid this type of accident.

1. Introduction

The furnace at the Rheinberg site is a 52.5 MWh Circofluid unit built by Babcock in 1989. It supplies 65 metric tons per hour of steam at 525 °C and 118 bar. Its furnace is rectangular in shape: 4 m wide, 4 m deep and 40 m high. It is fed with a mixture of coal and biomass (i.e. wood chips). It works on the principle of a circulating fluidized bed, which is a specialized technology designed to maximize the heat derived from solid fuels, especially those of poor quality (Dell'Orco 2018). In normal running, the furnace is fed with coal, lime, biomass and preheated air. Part of the air is fed to the bottom of the furnace in order to keep the ash bed in suspension and circulating in the system. A 2.5 % aqueous solution of ammonia is fed to the post combustion section to reduce emissions of nitrogen oxides. For a start-up from cold, natural gas is used to heat the system up to the normal operating temperature of about 900 °C. Once the furnace temperature has been stabilized at 900 °C, biomass is introduced progressively up to roughly one third of the fuel loading in terms of mass flow rate.

The pressurized part was constructed as a natural circulation boiler. The heat is absorbed by exchangers which are incorporated in the walls of the furnace. These consist of tubes where water is first heated and then vaporized to form steam (see Figure 1). Once every 30 minutes, steam is blown onto the outside of the tubes to dislodge soot deposits.

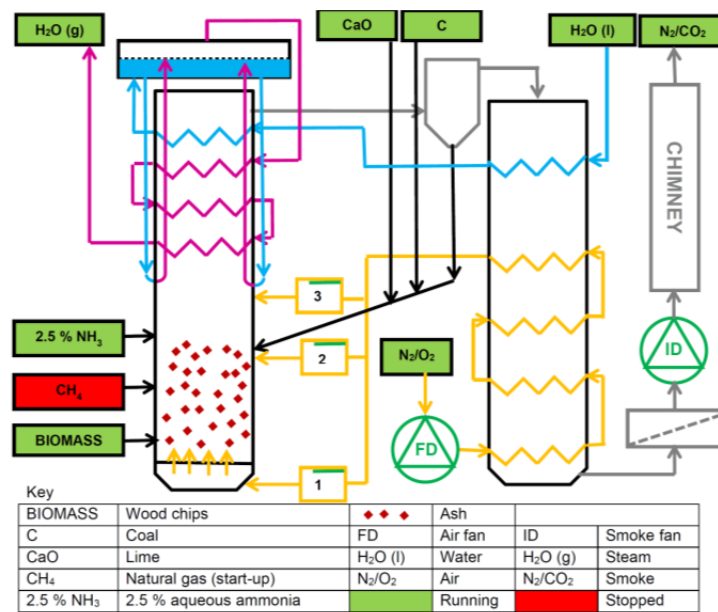


Figure 1: Schematic diagram to show the installation under normal running conditions.

2. Description of the incident

The incident occurred during a start-up, at the point where the system was at about 850 °C, close to the normal operating temperature. The natural gas supply had already been shut off. Suddenly, a high pressure trip shut down both air fans. The level of moisture in the burnt gases was very high, indicating that water had entered the furnace. The operators followed the normal procedure for this case, which is to try to get hot air circulating and dry out the system, whilst maintaining the flow of water to the tubes to cool them and prevent further damage. But various interlocks stopped the fans from operating. After about one hour they were able to run the forced draft air fan. At this point the furnace exploded.

Table 1: Sequence of events

Time	ID Fan	FD Fan	Remarks
13.20	Running	Running	Start-up of furnace feeding with natural gas only
17.23	Running	Running	Bed at 850 °C - feeding with coal & lime (natural gas stopped)
18.52	Stops	Stops	Bed at 850 °C - high pressure trip stops fans & feeds of coal etc.
18.58	Stopped	Stopped	NH ₃ stops. Natural air flow only, so ash bed is not suspended. The level of water in the drum is low but the flow of water is maintained.
19.00	Stopped	Stopped	Steam production stops
19.03	Stopped	Stopped	1 st attempt to restart fans fails due to interlocks
19.23	Stopped	Stopped	Water drum at minimum level and operator stops the flow of water to it.
19.32	Stopped	Stopped	2 nd attempt to restart fans fails due to interlocks
19.34	Stopped	Stopped	3 rd attempt to restart fans fails due to interlocks
19.55	Stopped	Stopped	4 th attempt to restart fans fails due to interlocks
20.00	Starts	Starts	5 th attempt to start fans succeeds but still no primary air flow
20.02	Running	Running	Primary air flow increases suddenly and boiler explodes

3. Observations after the incident

3.1 Damage to the installation

The furnace had ruptured along a vertical corner seam. The sides of the furnace had been pushed out by up to 0.5 m at mid height. Thick steel sections of flooring had been distorted, in the places where the sides of the furnace had buckled outwards. The ash bed had been ejected from the furnace onto the floor of the building. The walls of the building were not affected, except that all of the windows had been blown out.

3.2 Composition of samples of solid

28 samples of solid, including deposits from the boiler tubes, ash from the bed and flue dust were characterized by X-ray fluorescence and by X-ray diffraction. The main conclusions are as follows:

- Only highly oxidized mineral phases were found, that are typical for the regular operation of an incineration plant (using hard coal plus biomass as regular fuel)
- The ash samples (bed and flue dust) and the deposit samples only show minor differences,
- As expected, deposit samples taken at different heights of the boiler show differences in composition and mineral phases.
- No mineral phases were found that indicate that the boiler had been operated in substoichiometric or other atypical conditions.

3.3 Metallurgical examination of boiler tubes

A horizontal tube of the evaporator had a 3 cm diameter hole, as shown in Figures 2 and 3. The metal had thinned, then been pushed outwards, forming a pattern rather like the petals of a flower.

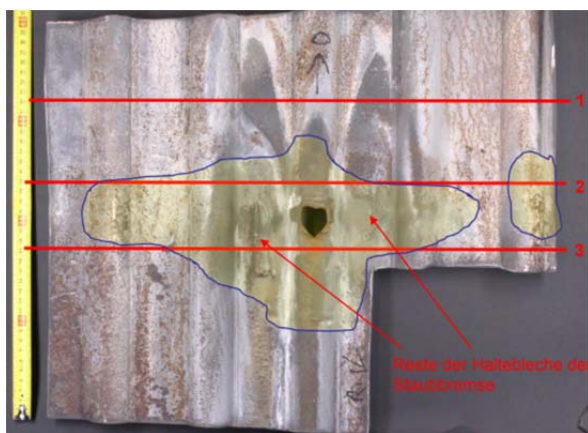


Figure 2: Damaged section (40x60 cm) cut out from the side of the boiler showing the hole in the evaporator tube.

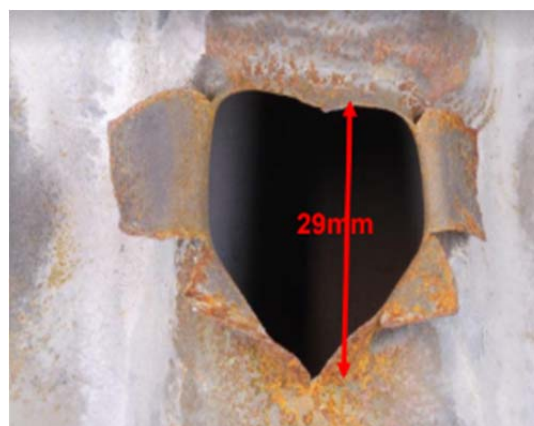


Figure 3: Close-up of the hole in the evaporator tube

A drawing of the fluidized bed boiler, indicating the position of the fluidized bed and the approximate position of the leak is shown in Figure 4. The leak was at a height of about 20 m in the evaporator tubes forming the left wall of the boiler. It was located just above a soot blower, which is shown in Figures 6 to 8.

Microscopic examination showed that the metal on the furnace side had been worn away and polished. The reduction in thickness in areas around the leak was as much as 3 mm as shown in Figure 5 (the normal thickness of the boiler tubes was 7-8 mm).

The composition of the deposit residues on the furnace side analysed did not indicate that any high-temperature corrosion mechanisms were at work. The material structure present is normal for the low-alloy pipe material used, showing no signs of higher levels of thermal stress.

The deposits on the inside of the pipes in the damaged section showed localized interstitial phases of calcium phosphates from minerals dissolved in the water. The measured thicknesses of the deposits were between 30 and 45 μ , again not suggesting any higher levels of thermal stress.

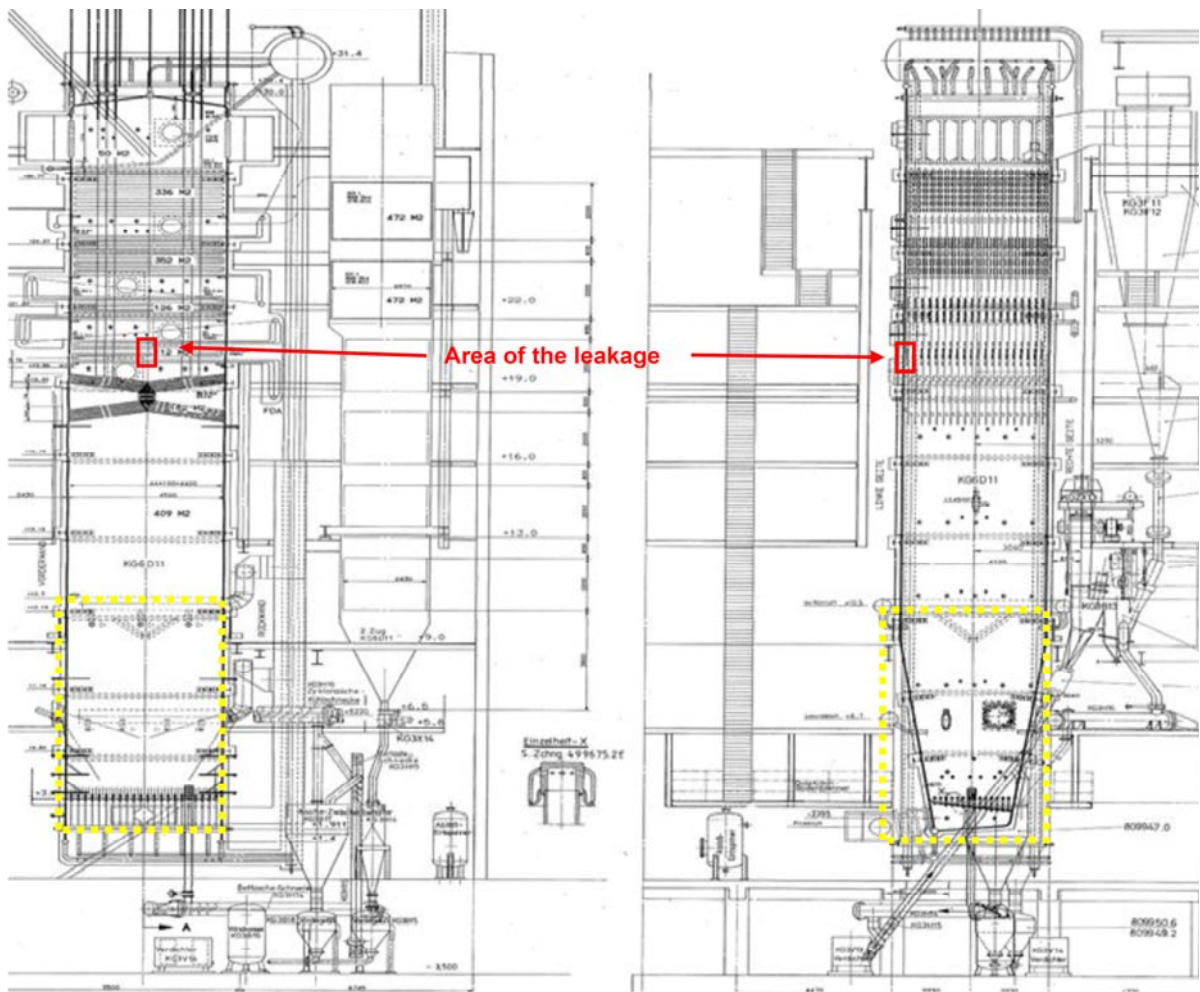


Figure 4: Position of the leakage (red) and of the fluidized bed (dotted yellow)

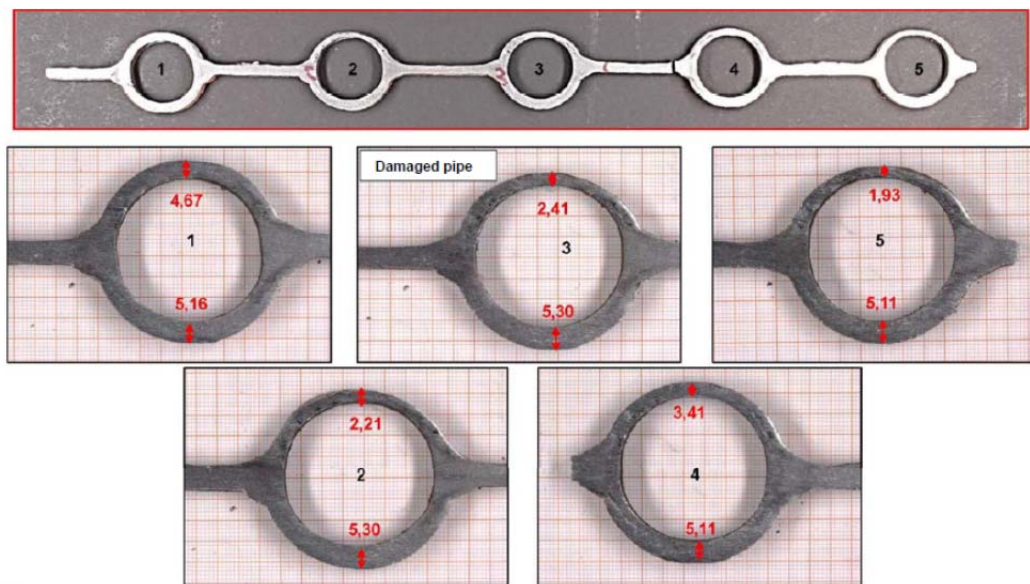


Figure 5: Thickness measurement of the boiler tubes at five points around the leak



Figure 6: Evaporator wall:

- the area top left, where the leak occurred, has been cut out (see figure 2)
- the red arrow shows the location of the soot blower (see figures 7 & 8),
- the metal of the tubes above the soot blower is thinner than elsewhere.



Figure 7: soot blower after removal from the furnace.



Figure 8: lance head of soot blower shows signs of wear.

The examinations carried out indicate that the material of the evaporator wall tubing on the furnace side had been eroded, causing the leak. This thinning of the tubes was localised above a soot blower. Therefore, we believe that a malfunction of the soot blower, such as premature or faulty blowing must have occurred. The investigation revealed no other causes for the higher levels of depletion on the furnace side, such as high-temperature corrosion, overheating or faulty material.

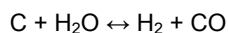
4. Possible explosion mechanisms

4.1 Gas explosion

The possibility of a gas phase explosion of a mixture of air and flammable gas was considered. Flammable gas can form from coal in two ways.

Firstly, heating coal gives rises to a gas mixture with the following typical composition: CO₂ 36 % v/v, CO 29 % v/v, H₂ 16 % v/v, CH₄ 16 % v/v, C₂H₆ 3 % v/v (Moghtaderi 2001). Despite the presence of carbon dioxide, such a gas mixture is flammable and forms explosive mixtures with air.

Secondly, heating coal with steam at temperatures around 850 °C generates a mixture of hydrogen and carbon monoxide, known as water gas.



The reaction is reversible and endothermic. The equilibrium favors the left hand side at low temperatures and the right hand side at high temperatures. The reaction is catalyzed by the surface of the coal and it is sufficiently rapid, at temperatures such as 850 °C, to form the basis for an industrial process for coal gasification (Rollinson, 2018).

The mass of the circulating ash bed is estimated at 48 metric tons. Under normal running conditions, the mass fraction of unburnt coal is estimated at 0.5 to 1 %, depending on the load. In the run-up to the incident, the load on the furnace was about 60 % of nominal, so that we can estimate the mass of coal present as 300 kg at the point where the furnace shut down.

From then on, we estimate that it was in contact with a natural draught of fresh air for at least 10 minutes. During the next 60 minutes, it is more likely to have been in contact with steam than with air. Either way, in the 70 minutes between the shut-down of the furnace and its explosion, the coal present would have been completely consumed by reaction with air or steam or both and any flammable gas purged from the system. Also, the injection of 2.5 % aqueous ammonia was stopped 6 minutes after the furnace was shut down, so it could not have contributed in any way.

Therefore, we do not believe that this explosion was caused by flammable gas.

4.2 Physical explosion

When the leak occurred, various interlocks stopped the fans, so the ash bed fell to the bottom of the furnace. Previously only small water leaks had occurred in this installation. Such leaks occurred roughly once every year and were dealt with using the procedure recommended by the manufacturer of the furnace. This involved restarting the fans, blowing air through the ash bed and using the heat this contained to dry out the system. But this time a tube of the heat exchanger had ruptured, releasing 25 metric tons of water at 323 °C/118 bar into the furnace over 30 minutes. Of this, 13 metric tons would have vaporized rapidly, leaving 12 metric tons in the form of droplets of liquid water at 100 °C, suspended on a cushion of steam above the ash bed at 850°C. The suspension of liquid droplets above a hot surface is the “Leidenfrost effect” (Leidenfrost 1756). Many people will already have observed this in their household when water was spilled onto a very hot cooktop. The water hovers (“dances”) on a cushion of steam, which also impairs the heat transport to such an extent that the water cannot evaporate quickly and completely. This ties in with the following observations during the period between the high pressure trip at 18.52 to the explosion at 20.02:

- The relative humidity of the flue gas remained at 100 %
- The temperature of the bed (measured at several points) stayed at about 850 °C
- The temperature above the bed dropped rapidly to 100 °C then stayed at this value.

After one hour the operators were able to start the forced draft air fan for long enough to suspend the bed of hot ash. So 48 metric tons of hot ash at 850 °C was suddenly mixed with 12 metric tons of suspended water droplets at 100 °C. This generated up to about 15,000 m³ of steam instantaneously inside the furnace (free volume 380 m³) causing it to explode.

5. Conclusions

The evidence points to a physical explosion, caused by the sudden mixing of 48 metric tons of ash at about 850 °C with 12 metric tons of suspended water droplets at 100 °C, as the explanation of the explosion.

The tube rupture seems to have been caused by problems with a nearby soot blower. Such problems are commonplace in such furnaces and it is essential to carry out regular inspections at suitable intervals and to measure wall thicknesses etc. in order to detect it and to correct it before significant damage occurs. This is a considerable challenge for the maintenance team and we can recommend no simple cheap methods to do it.

In such a case of tube rupture, the correct procedure is to feed air above the ash bed (positions 2 and 3 in figure 1) until the suspended water droplets have been removed and the level of relative humidity in the flue gas is well below 100 %. Then and only then, should air be fed in under the ash bed (position 1 in figure 1) to raise it and start the circulation. As this unit was a prototype, it had only one forced draft fan, making such a procedure difficult, if not impossible, to follow. In more modern installations, there are three separate forced draft air fans: one each for the primary, secondary and tertiary air flows. Having separate fans enables the operator to control such incidents more reliably.

References

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