Analysis of ‘5.29’ blast furnace burst accident of Fangda special steel

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Abstract. On May 29, 2019, a blast furnace explosion occurred in the iron making plant of Jiangxi Nanchang Fangda Special Steel Technology Co., Ltd. in Qingshanhu District, Nanchang City, Jiangxi Province. The corrugated compensator of No.2 blast furnace gas riser burst, resulting in 6 deaths, 4 injuries and direct economic losses of more than 27.24 million yuan. Through the analysis of the amount of water drawn from the top of blast furnace, this paper concludes that this is a physical explosion caused by overheating, rapid boiling expansion and over-pressure of liquefied water. Through the qualitative evaluation of the accident by Bow-tie model, the specific causes and consequences are analyzed, and the physical model is used to carry out a further quantitative analysis of the consequences, the hazard area is determined, and the countermeasures to prevent the burst accident of corrugated compensator are put forward, which is helpful to prevent the recurrence of such accidents.

1. Introduction

On May 29, 2019, a blast furnace explosion occurred in the iron making plant of Jiangxi Nanchang Fangda Special Steel Technology Co., Ltd., resulting in 6 deaths and 4 injuries, with a direct economic loss of more than 27.24 million yuan.

The accident device is the corrugated compensator of gas rising pipe. In the process of water pumping and cooling at the top of blast furnace, a large amount of over-pressure in the furnace causes the bellows compensator to burst. Blast furnace, as the most important device in modern iron making, has high accident frequency, and the blast furnace gas produced has the characteristics of flammable, explosive and toxic, which is of great danger. Table 1 lists the blast furnace explosion and leakage accidents in recent years.

Taking the blast furnace explosion accident of Fangda Special Steel Co., Ltd. as an example, this paper studies the causes of the accident, puts forward corresponding preventive measures, and
simulates the consequences of the accident, providing guidance for the safety management of metallurgical enterprises.

| Time       | Events                                                                 | Casualties       | Reason                                                                                   |
|------------|------------------------------------------------------------------------|------------------|------------------------------------------------------------------------------------------|
| 2006.3.30  | The top of No.5 blast furnace in Tangshan Guofeng Iron and Steel Co., Ltd. Exploded. | 6 dead and 6 injured | After the top of the blast furnace is pumped water, air and liquid water fall into the furnace and explode in case of high-temperature gas. |
| 2006.10.15 | Gas Leakage Occurred in Blast Furnace Condenser Pipe of Hefei Hegang Group. | 2 people were poisoned | When the blast furnace workers repaired the leaking parts, they did not carry out effective protection, resulting in poisoning. |
| 2018.2.5   | Gas Leakage Occurred in No.7 Blast Furnace of Guangdong Shaogang Songshan Co., Ltd. | 8 dead and 10 injured | Blast furnace workers operate in violation of regulations, without effective protection, resulting in a large number of gas leakage. |
| 2019.11.1  | Jilin Henglian Precision Casting Technology Co., Ltd. No.1 Blast Furnace Downcomer Explosion Occurred. | 1 dead and 2 injured | The blast furnace is subject to material collapse, over temperature and over-pressure at the top of the furnace, and the mixture of high-temperature oxygen-containing gas, gas and dust removal dust leads to explosion. |

2. Accident Description

2.1. Brief Introduction of No.2 Blast Furnace

![Figure 1. Drawing of No.2 blast furnace](image1)

Figure 1. Drawing of No.2 blast furnace

![Figure 2. Blast furnace diagram](image2)

Figure 2. Blast furnace diagram

2.2. Accident Process

At 16:20 on May 29, 2019, due to the abnormal condition of No. 2 blast furnace, the air reduction operation was started. At 16:20, the air volume was reduced from 1199 m³ / min to 1026 m³ / min, and the furnace top pressure was 88.9 kpa; at 16:21, the second air reduction was carried out, and the air volume was reduced to 869 m³ / min; at 16:22, the air volume decreased to 770 m³ / min, and the furnace top pressure increased to 99.2 kpa; at 16:23, the data was missing after the furnace top pressure suddenly increased to 300 kPa, and the furnace top temperature rapidly increased from 152°C to 696°C. About 0.4 seconds later, the bellows compensator at the bottom of two top gas risers in Southeast and southwest directions burst, causing 10 casualties.
3. Cause Analysis of Accident

According to the accident investigation report, it can be known that the blast reduction was carried out before the accident of No.2 blast furnace. Assuming that this is a gas explosion accident, the gas and oxygen need to be mixed to reach the explosion limit. However, when there is a collapse in the furnace, the release valve on the top of the furnace is not opened, and there is no large amount of air mixed into the gas. Moreover, the normal temperature of the furnace top is 200-300°C. Even before the accident, the furnace top temperature rises from 152°C to 696°C. At this temperature, water cannot be decomposed to produce enough oxygen, so there is no premixed gas reaching the explosion limit.

Through the above analysis, the author thinks that this is a steam explosion accident. Due to the excessive water after a long time of continuous water pumping, when the material collapse occurs in the furnace, the vaporized water contacts the high temperature coke, the liquid water overheats and boils rapidly, and the volume expands rapidly by about 1200-1500 times. The pressure in the blast furnace rises suddenly and explodes. The specific reasons are as follows:

(1) Hot coke and gas. In the process of iron making, cold air and oxygen are heated by hot blast stove and then sent into blast furnace, which makes coke burn and produces high temperature gas above 200°C. The rising gas flow and burden conduct dynamic balance heat exchange. When the furnace condition is abnormal, after the measures of reducing air and pumping water on the top of the furnace, the material will collapse and the high temperature airflow will accumulate on the top of the furnace, which will break the heat balance and prepare for the steam explosion.

(2) Excess liquid water. From the accident, it can be found that the temperature at the four risers of the day shift blast furnace on May 29 is 157~500°C (the top temperature here is 400°C), and then the temperature drops to 152°C before the accident by drawing water. It is assumed that the approximate composition of blast furnace gas is CH4=0.3%, CO=23.5%, H2=1.8%, N2=56.9%, CO2=17.5%, and the gas generation amount QCoal = 252968.92 m³/h[1]. When the water boils, it is 100°C, and the heat released by the process of lowering the temperature of the water gas to 152°C is completely absorbed and vaporized into water vapor by the water, and the temperature of the water entering the furnace is 30°C. The total amount of water pumped into the blast furnace by the top water pumping device is calculated by the following formula:

\[
Q_w = \frac{(h_{g400} - h_{g152}) \cdot Q_g}{0.004 \cdot (100 - 30) + Q_g + (h_{g152} - h_{g100})} \cdot 1000
\]

where, \(Q_w\) is the requirement of water. \(h_g\) is the enthalpy of gas. \(Q_g\) is the amount of gas produced. \(Q_S\) is the heat of vaporization of water. \(h_S\) is enthalpy of water vapor.

It can be obtained by calculation, the water consumption of No.2 blast furnace is 34.2726 t/h. The amount of water injected by the theoretical water fetching device is far less than the actual amount of water, thus it can be obtained that a large amount of water injected into the top of the furnace is not atomized at the furnace throat, the accumulated liquid water falls on the burden, and the collapse caused by the air reduction operation makes the high-temperature gas gush up, while the water-bearing burden falls into the high-temperature area at the lower part of the blast furnace, vaporizes rapidly, and the body expands rapidly and explodes.

4. Bow-tie model analysis

Bow-tie model is an analysis method composed of fault tree and event tree. It not only combines the characteristics of fault tree, but also introduces the possible consequences of the accident by using clear and detailed logical relationship. It has important guiding significance for subsequent measures to control and prevent the accident.

Before the analysis, the author defined the top event as the burst of bellows compensator of blast furnace riser. According to the literature[2-4], it is found that there are three main reasons for the burst of bellows compensator in blast furnace, including leakage, over-pressure and defects. According to these three aspects, fault tree analysis is carried out to find out the possible causes of the accident.

The burst of bellows compensator in blast furnace was caused by over-pressure in large area or
whole. Combined with the properties of materials and equipment in the blast furnace, the possible accident consequence was steam cloud explosion and poisoning.

See figure 3 below for the specific Bow-tie model, in which the events corresponding to the fault tree code are shown in the following table 2.

![Figure 3. Bow-tie model of ripple compensator](image)

| Code | Events                      | Code | Events                      |
|------|-----------------------------|------|-----------------------------|
| A1   | Leakage                     | X5   | Corrosion damage            |
| A2   | Over-pressure               | X6   | Lining failure              |
| A3   | Equipment Defects           | X7   | Damage of lining            |
| B1   | Stress corrosion            | X8   | Excessive alternating stress load |
| B2   | Corrosion perforation       | X9   | It takes too long to fetch water |
| B3   | Fatigue corrosion           | X10  | Collapsing material         |
| B4   | The water vaporized sharply | X11  | The atomization effect is not good |
| B5   | Safety valve not open       | X12  | Not periodically checked    |
| B6   | Design and Manufacture      | X13  | Discharge valve is not interlocked with furnace top pressure |
| B7   | Installation                | X14  | Excessive pressure debugging |
| C    | Safety valve damaged        | X15  | Material Selection Error    |
| X1   | Lining restraint stress     | X16  | Structural stability is not strong |
| X2   | Bending stress              | X17  | Insufficient structural strength |
| X3   | Tensile and compressive stress | X18 | Poor installation quality |
| X4   | Coating failure             | X19  | Mechanical damage           |

There are 14 minimum cut sets obtained by fault tree analysis, that is, \{X1\}; \{X2\}; \{X3\}; \{X4, X5, X6\}; \{X7, X8\}; \{X9, X10, X11, X12\}; \{X9, X10, X11, X13\}; \{X9, X10, X11,X14\}; \{X15\}; \{X16\}; \{X17\}; \{X18\}; \{X19\}; \{X20\}. 
5. Analysis of Event Consequences

5.1. Gas poisoning
CO accounts for 23.5% of blast furnace gas, which will cause anoxia and asphyxia of human tissues in a closed environment, resulting in terrible poisoning deaths. According to the gas leakage model\([5, 6]\) analyze the consequences of gas poisoning. When the gas flow speed is sound speed, the following conditions are met:

\[
P_0 \leq \left( \frac{2}{K+1} \right)^{\frac{K}{K-1}}
\]

\[
Q_g = C_d \cdot S \cdot P \cdot \sqrt[1+K]{\frac{M_{w} \cdot K \cdot 8.314 \cdot t}{(K+1)}}
\]

where, \(P_0\) is the ambient pressure. \(P\) is the riser pressure. \(K\) is the adiabatic index. \(Q_g\) is the discharge capacity of gas. \(S\) is the leakage area. \(P\) is the Pipeline pressure. \(t\) is the gas temperature.

The value of \(K, C_d, M_w\) were 1.4, 1, 30. When an accident occurs, the gas temperature \(t=696^\circ\text{C}\), the leakage port is 1700 mm in diameter and the pipeline pressure is 230 kpa. The formula is substituted to calculate, \(Q_g = 21804.2\, \text{kg/s}\), and the instantaneous leakage time is 0.01 seconds, then the leakage amount is 218.042 kg.

\[
R = \frac{2}{3} \frac{Q_{CO}}{\prod C}
\]

where, \(Q_{CO}\) is the CO leakage. \(R\) is the radius of death. \(C\) is the lethal concentration of CO.

According to the calculation, the blast furnace gas leaks under certain conditions, and the injury radius of CO poisoning accident is 22.82 meters.

5.2. team cloud explosion
The blast furnace gas leaking from the burst opening of the corrugation compensator may explode with steam cloud if it encounters open flame in the air. The calorific value of blast furnace gas is generally 3300 KJ/m\(^3\)-4200 KJ/m\(^3\). Here, the calorific value of blast furnace gas is 3763 KJ/m\(^3\), and TNT equivalent method is used. The explosion energy and damage radius of vapor cloud explosion are calculated as follows:

\[
M_{TNT} = \frac{A_c \cdot V_c \cdot Q_c}{Q_{TNT}}
\]

where, \(M_{TNT}\) is the amount of TNT at the time of vapor cloud explosion. \(A_c\) is the TNT equivalent coefficient. \(V_c\) is the Volume of blast furnace gas. \(Q\) is the Calorific value. The value of \(A_c, Q_c, Q_{TNT}\) were 0.04, 3.5 MJ/m\(^3\), 4.52 MJ/m\(^3\).

\[
R_1 = 13.6 \left( \frac{M_{TNT}}{1000} \right)^{0.37}
\]

where, \(R_1\) is the radius of death caused by the explosion. After calculation, the blast furnace gas leaks from the rupture of the riser for 3 minutes, \(M_{TNT} = 391.61\, \text{kg}\). If the protection is not in place within the radius of 9.6 meters, there is a possibility of death.

\[
\frac{P}{P_0} = 0.137Z_i^{-3} + 0.119Z_i^{-2} + 0.269Z_i^{-1} - 0.019
\]

\[
Z_i = R_{i1} \left( \frac{A_c \cdot V_c \cdot Q_c}{P_0} \right)^{1/3}
\]
where, $P_i$ is the over-pressure value of vapor cloud explosion. $Z_i$ is the intermediate factors. $P_0$ is the standard atmospheric pressure. $R$ is the radius of serious injuries caused by the explosion. The value of the $P_1, P_2, P_0$ is 44 kpa, 17 kpa, 101.3 kpa.

After calculation, after the blast furnace gas leaks from the rupture of the riser for 3 minutes, serious injuries will be caused to personnel within the radius of the leakage source of 28.45 meters. Within the radius of the leakage source of 28.45 to 50.95 meters, personnel are likely to be slightly injured, and personnel are safe beyond 50.95 meters from the leakage source.

6. Conclusion
Blast furnace is the core of iron making plant. Firstly, this paper analyzes the amount of water pumped at the top of the furnace and proves that the cause of the accident is over-pressure explosion caused by instantaneous boiling of liquid water. Then, Bow-tie model is used to more comprehensively identify the cause of the accident and speculate on the consequences of the accident. The analysis shows that the material, structure and manufacturing process of blast furnace corrugation compensator are the potential causes of the accident. After the ripple compensator of the gas riser burst, steam cloud explosion and poisoning are the possible types of accidents. Finally, the accident consequences of the most harmful poisoning and steam cloud explosion are simulated, and the calculation shows that when the blast furnace gas leaks instantaneously, the injury radius of the poisoning accident caused by CO is 22.82 meters. When the rupture time of the gas riser is 3 minutes, the damage radius caused by the steam cloud explosion is 50.95 meters, of which the radius from the leakage source is within 9.6 meters, with the possibility of death, and within the range of 28.45 meters, serious injuries to personnel may be caused.

Blast furnace explosion accidents occur frequently in iron making industry and have serious consequences. Therefore, in order to reduce the occurrence of such accidents, on the basis of this accident, the author puts forward the following suggestions and measures:

- When the blast furnace draws water, it is necessary to improve the water spraying method, enhance the atomization effect, and control the total amount of drawing water. Excessive drawing water is not allowed.
- Improve the materials and structure used in the corrugation compensator for blast furnace gas riser, adopt correct installation and manufacturing processes, improve the quality of the equipment itself, fundamentally solve the problems of corrosion and failure, and regularly replace and check to prolong the service life.
- The relief valve on the top of the furnace shall choose the automatic operation mode, which can be opened in time to relieve pressure when over-pressure occurs.
- Metallurgical enterprises should strengthen the safety knowledge training of on-site operators so that the operators fully understand the safety risks caused by abnormal furnace conditions. At the same time, safety management rules and regulations need to be improved, and the supervision of blast furnace dangerous workplaces and operators should be strengthened.

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