Analysis on an electrostatic accident due to hydrogen gas ejection

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Abstract. The article discusses a hydrogen flash explosion accident, and the mechanism of hydrogen charging and discharging; and analyses the stress condition at the anchoring points of the blowdown line. Moreover, the load-bearing capacity of the blowdown line and the maximum explosion pressure in flash explosion of hydrogen gas were calculated. It can be concluded that the electrostatic discharge of high pressure ejected hydrogen was the main reason for the accident.

1. Introduction
On January 5, 2012, the hydrogen compressor in the hydrotreating plant of a petrochemical company was in switching operation, and suddenly, hydrogen gas at a high pressure of 6.0 MPa was ejected out of the vent line with its relief valve not closed. The ejected hydrogen caused flash explosion in the space and pushed over the vent line. One operator was knocked and injured by the falling vent line and finally died although first-aid treatment was given.

There were two vent lines at the field which were located on the northern wall of the compressor building. One of the vent lines DN80 (Φ89×3.5, length: 12.3 m, weight: 91 kg) was provided for venting of the compressors Nos. 1 and 2, and the other one DN50 for venting of the connecting barrel of the compressors Nos. 1, 2, 3 and 4. The top of the vent line DN80 for the compressors Nos. 1 and 2 was 15 m above ground and its bottom 3.15 m above ground. There were 5 clamps totally for clamping the DN80 and each of them was fastened with 2 anchor bolts (Φ8 mm). The outlet of the line faced towards west and opposite to the upper platform with the inclined ladder. The vent line DN50 had the height equivalent to DN80. The top of the parapet wall, the northern wall of the building, was 15.6 m above ground. It is estimated that the top of the line DN50 and that of DN80 were 0.6 m lower than the top of the parapet wall of the building.

It was found at the field that 3 clamps were damaged and the anchor bolts for the clamp No. 1 (0.8 cm dia.) were corroded and pulled out completely. The bottom plate and anchor bolts for the clamp No. 2 were welded falsely and broken due to bad corrosion. Both anchor bolts for the clamp No. 3 were pulled and broken, as shown in figure 1.

2. Mechanism of electrostatic charging and discharging in hydrogen ejection
In theory, pure hydrogen would not cause electrostatic charging when it is ejected. However, if solid
particles, liquid drops or other foreign substances were entrapped in the gas, electrostatic charging may occur in case of high-speed impact, crashing or friction and such space charge would be built up leading to discharge, as described below: (1) If there are insulated or non-conductive objects in the space with gas ejection, such “charge collectors” would build up static leading to discharge; (2) With its dimensions and density developing over some extent, the “charge cloud” on scattering objects may cause brush discharge or lightning discharge to grounded objects around; (3) If the machine or nozzle is ungrounded or the nozzle is insulated, the machine or nozzle would cause spark discharge (to metal body) or propagating brush discharge (to insulated body).

3. Looking into the cause of electrostatic charging at the field
At the accident field, the compressor had been operated for 126s nitrogen replacement before hydrogen entered into the compressor. As nitrogen contained trace of moisture, water grains were entrapped in hydrogen after 6.0 MPa hydrogen was led in and electrostatic produced in case of high-speed impact and friction, as shown in figure 2.

![Figure 1. Hydrogen vent line diagram.](image1.png)

![Figure 2. Diagram of electrostatic charging in hydrogen gas ejection.](image2.png)

Safety Guide for Static (Japan) [1] says that when its diameter is greater than 0.7 m and the average electrical field strength in space charge cloud is 1 kVcm⁻¹, the gas space charge cloud can cause brush discharge with the min. ignition energy of 0.1~1.0 mJ from the space charge cloud to a grounded conductor. The space charge density is calculated with the equation as follows:

\[
p = \frac{3eE}{a} = \frac{3 \times 1 \text{kVcm}^{-1} \times 0.0026 \times 8.86 \times 10^{-12} \text{Fm}^{-1}}{0.35 \text{m}} = 7.6 \mu\text{Cm}^{-3}
\]  

(1)

Where, \(E\) represented safety limit of field strength for the space charge cloud, \(\varepsilon\) represented dielectric constant of the medium and \(a\) represented a half of the diameter of ball charge cloud.

The quantity of electrostatic charge built up in the hydrogen space charge cloud with the diameter of 0.7 m is:

\[
q = \rho v = 7.6 \times \frac{4}{3} \times 3.14 \times 0.35^3 = 1.36 \mu\text{C}
\]  

(2)

The grounded conductor with tip closest to the hydrogen space charge cloud at the field was the
nozzle of vent line, to which the space charge cloud discharged. The hazard of discharge depended on the quantity of charge transfer in a single discharge.

Electrostatics - Code of Practice for the Avoidance of Hazards due to Static Electricity CLC/TR 50404-2000 (European Committee for Electrotechnics Standardization) [2] says that the quantity of charge transfer in discharge greater than 10 nC can ignite Class IIC substances such as hydrogen gas.

The charge quantity in the hydrogen space charge cloud with the diameter of 0.7 m at the field was 1.36 μC which is far greater than 10 nC so that the space charge cloud formed in hydrogen ejection discharged to the nozzle of the vent line causing hydrogen explosion in the space.

4. Stress analysis and calculation of load-bearing capacity of the anchoring points for vent pipeline

According to the process description, both lines were provided for venting and unused normally with low venting capacity and pressure. The clamp installation and fastening at the field showed that the vent line clamps were used mainly for clamping and supporting the lines to prevent from displacement without the function of load bearing. The vent lines DN80 and DN50 weighed 135.7 kg totally.

4.1 Calculation of the designed value of load-bearing capacity of the anchoring point for static load

For the stress condition with static loads and without alternate loads in consideration, the clamp bore permanent loads (dead weight of the structure, soil pressure, prestress and so on) according to Load Code for the Design of Building Structures (GB50009-2001) [3] and therefore it is unnecessary to consider variable loads (live load on floor, live load on roof, dust load, crane load, wind load, snow load and so on) and incidental loads (explosion force, collision force and so on).

The anchor bolts for clamp were in the stress condition of composite pull shear load according to Post-Anchoring Construction for Concrete (JGJ145-2004) [4]. The design value of load-bearing capacity of anchoring is:

\[ R \geq \alpha R_A \times S = 1.1 \times 135.7 \times 1.35 = 201.6 \text{kg} \]  \hspace{1cm} (3)

where, \( R \) - the design value of load-bearing capacity of anchoring; \( \alpha \) - the coefficient for importance of anchoring (taken as 1.1 as the anchoring are rated to Safety Class II); \( S \) - the design value of composite load effect for anchoring, \( S = r_G S_{ck} \) (where, \( r_G \) is the coefficient for permanent load taken as 1.35, and \( S_{ck} \) is the standard value of permanent load.)

4.2 Calculation of the actual load-bearing capacity at a single anchoring point

It was found at the accident field that the anchor bolts for clamp were made of Φ8mm rebar. It can be considered that the load-bearing capacity at a single anchoring point means the tensile limit if they were installed and fastened properly. In general, anchor bolts are made of Class II steel (the tensile strength for Class I, II and III steels are 210, 300 and 360 N mm\(^{-2}\), respectively).

As a result, the max load-bearing capacity at a single anchoring point is:

\[ F = 300 \times \left(\frac{8}{2} \times \frac{8}{2} \times 3.14\right) \times 2 = 30144 \text{N} = 3076 \text{kgf} \]  \hspace{1cm} (4)

4.3 Stress analysis on the anchoring points and calculation of the resistance to explosion force

The vent line was turned over due to the anchor bolts broken by the force of explosion applied on the vent line. The clamps Nos. 1, 2, 3, 4 and 5 were fixed onto the wall. The accident should occur such that the clamps were broken under the action of explosion force sequentially in the order of Nos. 1, 2 and 3 (It was impossible that No. 2 was destroyed and displaced with Nos. 1 and 3 fixed. In such a way, it was impossible that No. 3 was damaged before Nos. 1 and 2. Therefore, the clamp No. 1 should be damaged as the first one.)

We have a lever with the two points A and B fixed and applied with the force \( F_1 \) at Point O. Calculate the stress at Point A. With Point B as the fulcrum, we have the following equation from the
lever principle:

\[ F_a \times (L_1 + L_2) = F_A \times L_2 \]  \hspace{1cm} (5)

So, the stress at Point A is: \( F_1 \) or \( F_0 \)

\[ F_A = \frac{F_a \times (L_1 \times L_2)}{L_2} \]  \hspace{1cm} (6)

**Figure 3.** Lever stress diagram.

4.3.1 Analysis on actual stress of the anchoring point No. 1 and calculation of the resistance to explosion force

According to the lever principle, the actual stress condition at the anchoring point No. 1 was the anchoring point No. 2 acting as the fulcrum. Therefore, the actual resistance to explosion force at the anchoring point No. 1 was:

\[ F_{anti-explosive1} = \frac{F_1 \times L_1}{L_1 + L_2} = \frac{30144 \times 1.5}{1.8 + 1.5} = 13702 \text{N} = 1398 \text{kgf} \]  \hspace{1cm} (7)

\( F_1 \) is the max load-bearing capacity (30144 N/3076 kgf) at a single anchoring point.

4.3.2 Analysis on actual stress of the anchoring point No. 2 and calculation of the resistance to explosion force

According to the lever principle, the actual stress condition at the anchoring point No. 2 was the anchoring point No. 3 acting as the fulcrum. Therefore, the actual resistance to explosion force at the anchoring point No. 2 was:

\[ F_{anti-explosive2} = \frac{F_1 \times L_1}{L_1 + L_2 + L_3} = \frac{30144 \times 2.4}{1.8 + 1.5 + 2.4} = 12692 \text{N} = 1295 \text{kgf} \]  \hspace{1cm} (8)

**Figure 5.** Stress diagram for the anchoring point No. 2.

4.3.3 Analysis on actual stress of the anchoring point No. 3 and calculation of the resistance to explosion force
According to the lever principle, the actual stress condition at the anchoring point No. 3 was the anchoring point No. 4 acting as the fulcrum. Therefore, the actual resistance to explosion force at the anchoring point No. 3 was:

\[
F_{\text{anti-explosive 3}} = \frac{F_1 \times L_4}{L_1 + L_2 + L_3 + L_4} = \frac{30144 \times 3.0}{1.8 + 1.5 + 2.4 + 3.0} = 10394 \text{N} = 1061 \text{kgf}
\]  

5. Analysis and calculation of the explosion force of hydrogen on the vent line

The diameter of brush discharge from hydrogen cloud was 0.7 m. Considering that the cloud diameter was 0.7 m and the cloud had the ball shape for simplifying the calculation, the sectional area of the upper part of the gas pipe in the influence of explosive cloud should be 0.35 m\(^2\)×0.08 m. See Figure 2. According to the test made by the authority, the pressure of hydrogen gas (35%) was 1 atm initially, while the max. explosion pressure was 7.3 atm in explosion. The max explosion pressure went up at a rate of 2703 atm s\(^{-1}\) meaning that the hydrogen gas could reach the maximum explosion pressure in 0.027 s.

For the hydrogen cloud with initial pressure of 1 atm, the max explosion pressure was 7.3 atm in its explosion. In this case, the max thrust of explosion to the upper part of the hydrogen pipeline was:

\[
F_{\text{thrust}} = PS = 7.3 \times 1.033 \times 10^4 \times 0.35 \times 0.08 = 211 \text{kgf}
\]  

It is concluded from the above analysis that the resistance to explosion force at the anchoring points Nos. 1, 2 and 3 are 1398 kgf, 1295 kgf and 1061 kgf respectively. However, the field showed that both anchor bolts for the clamp No. 3 only were pulled to break, meaning that the force applied on the anchoring point No. 3 was greater than 1061 kgf in flash explosion. They should not be damaged as the composite force applied on the anchoring point Nos. 1 and 2 in flash explosion was not greater than 1050 kgf totally. However, they were damaged indeed. It was only one case that there were serious defects in the anchoring points Nos. 1 and 2 having the resistance to explosion force far lower than the designed value.

It was found in the field investigation that the anchor bolts for clamp No. 1 had been corroded and pulled out completely and the bottom plate and anchor bolt for the clamp No. 2 were welded falsely and broken due to serious corrosion. It is proved that the above analysis is correct.

6. Conclusion

(1) Ejected hydrogen at a high pressure (6.0 MPa) would form space electrostatic “charge cloud” causing brush discharge to grounded objects and ignited hydrogen in the space finally.

(2) There were defects in the clamps at the anchoring points Nos. 1 and 2 with poor quality. The anchor bolts and the bottom plate were not welded securely. The clamps were not treated for anti-corrosion properly, leading to serious corrosion and therefore pulled to break under the action of impact from flash explosion of hydrogen.

References

[1] Safety Guide for Static (Japan)
[2] Electrostatics - Code of Practice for the Avoidance of Hazards due to Static Electricity (CLC/TR 50404-2000)
[3] Load Code for the Design of Building Structures (GB 50009-2001)
[4] Post-ANCHORING Construction for Concrete (GJ 145-2004)