Thermal Radiation Superimposed Hazard Analysis of Elevated Flare under Accident Condition

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Abstract. In order to ascertain the hazard of thermal radiation during the overhead flare combustion under accident conditions in an enterprise, the CFD simulation is used to obtain the thermal radiation superposition nephogram under the water failure of the whole plant with two flare discharge and combustion at the same time. According to the regulation of maximum operating heat radiation value of flare system in Standard SH3009 -2013, the influence range of different thermal radiation intensities is calculated, which provides a basis for the height design of overhead flare system and the determination of reasonable safety distance between elevated torch system and surrounding facilities and personnel concentration places.

Keywords: Overhead flare system, Water failure of the whole plant, Thermal radiation superposition, CFD simulation.

1. Introduction

The main function of the large-scale petrochemical facility's venting flare system is to burn a large amount of waste that is released during commissioning, start-up or shutdown, or in an accident state of production plant, thereby ensuring the safe and stable operation of the petrochemical production facility [1]. Under accident conditions, for example the whole plant's water or power outage may result in multiple sets of devices to release large amounts of gas, the radiant heat generated by the flare combustion may cause serious harm to the surrounding operators, equipments and process units [2]. Therefore, it is necessary to study the hazard of the thermal radiation of the flare burning under the accident condition.

At present, the calculation of flare combustion heat radiation is mainly based on relevant empirical formulas, and it is only applicable to the calculation of single torch heat radiation. There are few studies on the superposition of heat radiation caused by the simultaneous discharge of multiple torches under the plant-wide accident conditions. In order to study the influence range of thermal radiation produced by multiple flares under accident condition of power outage or water outage, this paper used a computational fluid dynamics model to obtain thermal radiation nephogram of the two flares before and after the reconstruction, and determined the hazardous influence range of the thermal radiation superposition.
2. Overview of elevated flare system

2.1. Operation status before reconstruction of flare system

Before reconstruction, the petrochemical enterprise had 3 sets of elevated flare systems, namely F1, F2, and F3. The F2 flare has been out of service for many years, and F1 and F3 are the elevated flare systems in use. Exhaust gas from butyl, bromobutyl and other devices are discharged to the F3 flare, while exhaust gas from acetonitrile extraction, DMF extraction, MTBE synthesis, styrene, rare earth cis-butadiene, nickel-based cis-butan and other devices are discharged to the F1 flare. The specific conditions of each flare system are shown in Table 1.

| Flare Name | Accident condition | relieving capacity | Height of Flare stack |
|------------|--------------------|--------------------|----------------------|
| F1         | Power outage of the whole plant | 664,982kg/h | 20m |
| F1         | Water outage of the whole plant | 707,455kg/h | |
| F1         | Biggest single accident | 100,885kg/h | |
| F2         | (Out of service) | | |
| F3         | Power outage of the whole plant | 314,593kg/h | 80m |
| F3         | Water outage of the whole plant | 327,816kg/h | |
| F3         | Biggest single accident | 314,249kg/h | |

Under the current operating conditions, the controlled operating condition of the enterprise is water outage of the whole plant, and the F3 flare relieving capacity is 327.816t/h, while the F1 flare relieving capacity is 707.455t/h.

2.2. Reconstruction of flare system

Due to insufficient discharge capacity, the F1 flare is reconstructed. After Adding HIPS systems to the devices whose waste gas are discharged into F1, the relieving capacity under water outage of the whole plant is reduced from 707.455t/h to 275t/h. The enterprise's existing F2 flare is removed, and a new elevated flare system F4 with the capacity of 275t/h and supporting facilities are newly built near F2's original location. After the new elevated flare system F4 is completed and ready for commissioning, the existing F1 flare will be removed.

3. CFD Stimulation Calculation Model

3.1. Physical Model

Based on the actual situation, a three-dimensional physical model of the elevated flare system of petrochemical enterprise is established, including flare system F1, F2 flare and F3 flare. The flare system of the enterprise is located on a high mountain, and the elevation of the F3, F1 and F2 flare are 239.13m, 252.12m and 260m correspondingly. The current three-dimensional model of the flare system is established using the flare F2 center corresponding to the ground as the coordinate origin (0, 0, 0), as shown in Figure 1. The F3 flare is located at the Z = -21m plane and the F1 flare is located at the Z = -8 plane.
3.2. Calculation Model
When accidental discharge occurs, a large amount of flare gas release through the burner of the elevated flare, which is classified as turbulent flow. In order to describe turbulent flow, the most popular k-ε double equation model is adopted [3]. The Eddy Dissipation Concept (EDC) model proposed by Magnussen is used as combustion model, which has been verified through experiments. The heat transfer calculation adopts the Discrete Transfer Model (DTM model) proposed by Shah and LockWood [4].

Taking the center of the newly constructed elevated flare F4 as the coordinate origin (0, 0, 0), the calculation domain takes the value of X coordinate from -800 to 800m, Y coordinate from -800 to 800m and z coordinate from 0 to 500m. The calculation domain uses hexahedral structured grid, and the grids near the burner nozzle of the elevated flare are dense while the grids away from the combustion area are sparse.

3.3. The Setting of Calculation Parameter
The area where the enterprise is located has an average annual wind speed of 1.9m/s. Its dominant wind direction is SSW and the average annual temperature is 11.6°C. The relevant parameters of the flare gas are shown in Table 2 below.

| Flare | Temperature (°C) | Flow (t/h) | Discharge aperture (mm) | Weight of molecule (g/mol) | Height of flare (m) |
|-------|------------------|-----------|-------------------------|---------------------------|--------------------|
| Before reconstruction | F1 79 | 707.455 | 500 | 57.2 | 20 |
|          | F3 93 | 327.816 | 1200 | 42.5 | 80 |
| After reconstruction  | F4 75.35 | 275 | 1400 | 54.23 | 90 |
|          | F3 93 | 327.816 | 1200 | 42.5 | 80 |

4. Thermal radiation superposition calculation result
4.1. Calculation of superposition of thermal radiation before reconstruction
The petrochemical enterprise currently operates two elevated flares, namely F1 and F3. When the condition of water stoppage occurs in the whole plant, the relieving capacity of F1 and F3 are 707.455t/h and 327.816t/h correspondingly. Under the condition of simulated wind direction SSW,
wind speed 1.9m/s, ambient temperature 11.6°C, the flame height and thermal radiation effect results of F1 and F3 emission at the same time are as shown in Figure 2.

![Figure 2. The flame height of F1 and F3 flares under water stoppage of the whole plant.](image)

Flame height usually refers to the length of the visible flame, which is directly observed by a well-trained observer through the average length of the visible flame from a series of instantaneous flame length photos. However, for the CFD simulation, the flame height, which cannot be directly determined by human, is usually found by the temperature method, i.e. obtaining the flame height using a certain temperature contour surface as the flame profile [4]. For the value of temperature, different researches have provided different values, mostly 1200K-1400K, where the 1200K contour surface is used as the flame profile to determine the flame height [5].

Taking the 1200K contour surface in the CFD simulation results as the flame profile to determine the flame height, the flame height and flame shape of F1 and F3 simultaneously discharging under the water stoppage of the whole plant are obtained. It is shown that the combustion flames don't interfere with each other when the two flares are discharged at the same time. F1 flare has a large gas relieving capacity, a small relieving aperture, a high flammable gas discharge speed, and a large initial momentum [6, 8]. Therefore, the combustion flame is straight and long, about 148m. In contrast, F3 flare has a small gas relieving capacity and large discharge aperture. Its combustion flame is inclined to the ground by the wind speed, with about 89m flame height.

![Figure 3. Thermal radiation field of F1 and F3 flares under water stoppage of the whole plant.](image)
With reference to the requirements for flare thermal radiation in the “Code for Design of Flammable Gas Emission System for Petrochemical Industry” (SH3009-2013), the impact range of flare combustion thermal radiation is calculated as $1.58\text{kW/m}^2 \sim 9.0\text{kW/m}^2$ as shown in Figure 4 below.

Figure 4. The impact range of thermal radiation simultaneously discharge by F1 and F3 flares under water stoppage of the whole plant.
Table 3. SH3009 Regulations on the maximum operating hear radiation value of the flare system.

| Allowance of thermal radiation (kW/m²) | Conditions |
|---------------------------------------|-------------|
| 1.58                                  | Residential areas, public welfare facilities, villages and other public areas outside the plant. |
| 2.33                                  | Densely populated areas of neighbouring enterprises and oil depots of the same industry, administrative management areas of experimental chemical enterprises. |
| 3.0                                   | Densely populated area adjacent to similar enterprises and oil depots, trees and other vegetation outside the plant. |
| 3.2                                   | Production equipment and facilities inside the petrochemical plant |
| 4.73                                  | Allowable thermal radiation intensity of the top platform of the flare during maintenance |
| 6.31                                  | When the value is exceeded, the layout areas such as liquid separation tank, water sealing tank and pump shall be set up with safe escape places for operation or maintenance personnel |
| 9.00                                  | Liquid separation tanks, water sealing tanks, pumps and other relevant areas |

From the simulation results of flare combustion thermal radiation, it is illustrated that the flame is deflected to the northeast due to the influence of the wind direction SSW. The thermal radiation of the two flares affect each other and superimpose each other, and the thermal radiation impact range of the leeward of flame is smaller.

Among the results, the maximum impact range of 1.58kW/m² surface thermal radiation is about 500m from the horizontal distance of F2 flare (with the origin of the centre corresponds to the ground). The maximum impact range of 2.33kW/m² surface thermal radiation is about 360m horizontally from F2 flare. The maximum impact range of 3kW/m² surface thermal radiation is about 270m horizontally from F2 flare. The maximum impact range of 3.2kW/m² surface thermal radiation is about 230m horizontally from F2 flare. The maximum impact range of 4.73kW/m² surface thermal radiation distance is about 190m horizontally from F2 flare. The maximum impact range of 6.31kW/m² surface thermal radiation distance is about 160m horizontally from F2 flare. The maximum impact range of 9.0kW/m² surface thermal radiation distance is about 60m horizontally from F2 flare. From the above results, it is demonstrated that the flare combustion thermal radiation has a broader impact range and is more hazardous when the petrochemical enterprise discharges during the water stoppage of the whole plant.

4.2. Calculation of Superposition of Thermal Radiation after Reconstruction

After the reconstruction of the two elevated flares, F1 flare was replaced by the newly constructed elevated flare F4. The relieving capacity of F4 is 275t/h whereas the relieving capacity of F3 flare is 327.816t/h. The flame height and combustion field results of F4 and F3 flares under the condition of simulated wind direction SSW, wind speed 1.9m/s, ambient temperature 11.6°C and water stoppage of the whole plant are as shown in Figure 5.
Figure 5. The burning field of F4 and F3 flares under water stoppage of the whole plant.

According to the 1200K flame contour surface, the flame height and flame shape of the simultaneously discharged flares under water stoppage of the whole plant are obtained. It is shown that the newly constructed flares have a lower processing capability and an increased discharge aperture after the reconstruction [7]. Compared to F1 flare before reconstruction, the flame height of F4 is about 78m, which has greatly been reduced and is deflected by wind speed. The flames of F3 and F1 burning flares do not interfere with each other, with the flame height of F3 remaining at 89m.

Figure 6. Thermal field of F4 and F3 burning flares under water stoppage of the whole plant.
(1) Influence range of thermal radiation value $1.58\text{kW/m}^2$

(2) Influence range of thermal radiation value $2.33\text{kW/m}^2$

(3) Influence range of thermal radiation value $3.0\text{kW/m}^2$

(4) Influence range of thermal radiation value $3.2\text{kW/m}^2$

(5) Influence range of thermal radiation value $4.73\text{kW/m}^2$

(6) Influence range of thermal radiation value $6.31\text{kW/m}^2$

(7) Influence range of thermal radiation value $9.0\text{kW/m}^2$

**Figure 7.** The thermal radiation impact range of simultaneously discharged F4 and F3 flares under water stoppage of the whole plant.
According to the requirements of flare thermal radiation in the “Design Specification for Flammable Gas Emission System of Petrochemical Industry” (SH3009-2013), the impact range of flare combustion thermal radiation is calculated to be $1.58 \text{kW/m}^2$ ~ $9.0 \text{kW/m}^2$ as shown in Figure 7.

The maximum impact range of $1.58 \text{kW/m}^2$ surface thermal radiation is about 280m horizontally from the newly built F4 flare. The maximum impact range of $2.33 \text{kW/m}^2$ surface thermal radiation is about 150m horizontally from the F4 flare. After reconstruction, the surface thermal radiation between the newly built F4 and F3 flares can reach $3.0 \text{kW/m}^2$, in which the thermal radiation may affect the ground vegetation.

The impact range of $4.73 \text{kW/m}^2$ and $9.0 \text{kW/m}^2$ thermal radiation is above the $Z = 25$ plane ($Z = 0$ plane after the reconstruction of the new flare ground). The thermal radiation meets the requirements of maximum operating thermal radiation value of the liquid separation tank, water sealing tank and pump in SH3009, which will not affect the ground liquid separation tank, water sealing tank and pump.

5. Conclusion

(1) When the F1 and F3 flares simultaneously discharge because of the water stoppage of the whole plant before reconstruction, the thermal radiation of the two flares superposed on each other, leading to a broader impact range and great harm. The maximum impact range of $1.58 \text{kW/m}^2$ ~ $9.0 \text{kW/m}^2$ surface thermal radiation is between 500m to 60m horizontally from F2 flare.

(2) Reconstruction of the flare system adopted strategies, such as widening the distance between two flares, increasing the height of flares and using HIPS to reduce the amount of discharge, to greatly minimise the hazard of thermal radiation from two simultaneously discharging and burning flares under the water stoppage accident of the whole plant [9]. The maximum impact range of $1.58 \text{kW/m}^2$ ~ $2.33 \text{kW/m}^2$ surface thermal radiation is between 280m to 150m horizontally from the newly constructed F4 flare. The ground heat radiation between F3 and F4 can reach $3.0 \text{kW/m}^2$. The maximum impact range of $4.73 \text{kW/m}^2$ ~ $9.0 \text{kW/m}^2$ thermal radiation is above $Z = 25$ plane.

(3) The method of CFD simulation can accurately calculate the impact range of the multi-flare combustion thermal radiation superposition, which can be used for the design of the height of elevated flares and spacing arrangement, and determine the reasonable safety distance between the elevated flare system and the surrounding facilities and populated areas.

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