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Reduction of thermal radiation by steam in flare stack system

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Abstract−A flare system is installed for the enhancement of process safety, and the stable combustion is one of the most important elements. The main function of the flare system is the combustion of the flammable or toxic materials into non-hazardous materials, but combustion heat is released from a flare system. In this study, the effect of the external and internal steam injections in the flare stack on the reduction of the thermal radiation was investigated. The ignition possibility by the change of steam amount and the effect of the steam on the thermal radiation were also analyzed by using consequence analysis software. In case of thermal emission of oil refinery plants through improved steam injection, the injection of 120% steam rather than the conventional method enabled the reduction of the flare stack height. It could reduce the height of flare stack by 20%.

Key words: Flare Stack, Thermal Radiation, API 521, Steam, Jet Fire

INTRODUCTION

At the beginning of the 20th century, population explosion and the subsequent surge in consumer demand accelerated mass production systems for chemical processes. This increased the numbers and sizes of chemical process equipment and caused more materials and energy to be accumulated in the processes. Difficulties arose with respect to process control, which caused many accidents in the 1960s that led to the installation of many safety devices and more elaborate process control. The recent trend towards the installation of more devices and utilities to achieve energy efficiency has made plant structures more complex. With such structural complexity and the increase in the diversity and quantity of materials came more interference between processes, and numerous incidents occurred that showed that errors in a partial process could affect the whole plant.

The importance of safety devices for preventing accidents and diminishing risks is increasing as loss of human lives and materials becomes larger. Generally, the gas leak out in a process not only causes great damage such as from an explosion, but also happens at a high frequency. Thus, the disposal of large surplus gas, which has a greater risk of leaking, is very important. The blowdown stack, one piece of the equipment used in chemical factories, is known to possibly cause leaking of raw materials into the atmosphere when it is used to control pressure and emission. An example of a flammable gas leak followed by an explosion is the accident at BP in Texas, USA in 2005. Fifteen people died and 170 were injured in the explosion and fire that occurred during the preparations for the reoperation of the Isomerization Unit in BP's oil refinery. The accident started with a pressure increase inside a splitter due to the malfunction of the liquid-level meter of a raffinate splitter. The raw materials in the process were released to prevent pressure build-up, which caused their accumulation in the emission devices of the blowdown drum and stack. The emission devices had to release hydrocarbon vapor into the atmosphere, and a nearby vehicle was found to have ignited the explosion [1]. After this accident, many industries started to use the closed relief system or the flare system for improved safety.

In the oil and gas industry flaring is seen to be a safe and reliable method for disposal of residual gas to be burned in the open air using a special device called a torch. Gas flaring is needed to depressurize eruptive wells and hydrocarbon plants through burning excess gases [2]. Despite the use of these safe systems, however, an accident can still occur. Thus, the equipment must be continuously improved to minimize accidents.

The flare system prevents the direct emission of the waste gas from a process. Because the emitted gas from petro-chemical products tends to form a steam cloud and causes a fire or explosion in or near a factory, the flare system removes the waste gas by combustion. How to keep this thermal radiation caused by combustion from affecting the equipment in the process is the most important criterion in factory design [3].

When designing a plant, installing a flare stack outside the process or locating the flare stack at a high position is considered to minimize the effect of the thermal radiation caused by the flare system on the process or the operators.

The stack height of a flare system, the emission capacity and speed of the waste gas, the length of the flame, etc., generally follow the API 521 regulation. Studies are being conducted on the risks of the flare system such as thermal radiation and non-combustion to prevent their occurrence inside a process. Especially, studies on the reduction of thermal radiation attempt to quantitatively analyze ther-

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mal radiation by analyzing the shape of the flame or reducing of flare gas by flare gas recovery unit [4-6]. Some researchers have studied mechanical methods for reducing thermal radiation [7], like surrounding the flare tip by metal sheet.

In this study, the effect of the steam in the flare stack on the reduction of the thermal radiation, which has never been studied so far, was investigated. Though the steam's original role is to assist in the full combustion of the waste gas to prevent air pollution from an incomplete combustion, it affects the reduction of the thermal radiation, as it is injected at a temperature lower than that of the flame. The structure of the flare system was reviewed and the flare load for the calculation of the thermal radiation was estimated. The ignition possibility by the change of steam amount and the effect of the steam on the thermal radiation were also investigated.

THEORETICAL BACKGROUND

1. Flare System

1-1. General Information

Flare systems are largely classified into ground flare systems and elevated flare systems. The stack is almost at ground level in ground flare systems, but the stack is high in elevated flare systems. The choice of system depends on the situation in a factory, and elevated flare systems are commonly used in South Korea because they are more economical.

The ground flare system, unlike the elevated flare system, emits the combusted gas at a low height. Mostly operated as an enclosed-type multi-jet flare system, this system not only allows relatively stable combustion due to the circumstantial factors on the ground, but also minimizes the noise and the effect of the thermal radiation. It has the advantage of using less steam than in the elevated flare system. Its disadvantages, however, are that it requires a larger area for its installation, it costs three to four times as much to operate, the shape of the hot emission gas is unknown, it is difficult to operate due to the high fluctuation of the emission gas, and it often causes emergencies. Basically, the two systems have similar equipment, but the ground flare system has the flexibility that it can be combined with the elevated flare system [8].

The elevated flare system is the most general flare system used in chemical factories. It has a significant thermal radiation effect, since it goes through the combustion process in the atmosphere, and it causes noise problems due to its use of a large amount of steam and its emission of waste gas. The stack must also be located higher to set the flame at a high position so as to minimize the effect of the thermal radiation. The elevated flare system is mainly used in large-scale chemical factories, as it has a higher capacity and consumes less installation space and operating cost. The flare system consists of a knock-out drum, a molecular seal, a flare stack, a steam line, and an ignition device, among others (Fig. 1).

The flare system generally collects the emitted gases from the safety valve, the relief valve, or the emergency transfer equipment, and sends them to the knock-out drum, where the liquid and solid components are removed. This prevents the dropping of the materials during the combustion process at the flare tip. Molecular seals are installed on the flare stack to prevent a backfire, and combustion devices such as a flare tip are installed at the upper part of the flare stack. The ignition devices and steam lines are installed inside or outside the flare stack.

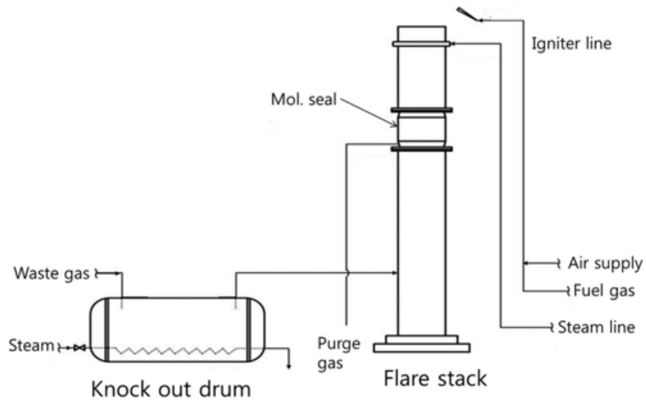

Fig. 1. Diagram of a flare system.

1-2. Flare Stack

The main functions of the flare stack are the combustion (oxidation) of the flammable, toxic, or corrosive vapors that are released from the relief valves, rupture discs, and pressure control valves at a refinery or a petro-chemical factory, and their transformation into a non-hazardous state. For the basic process design of the elevated flare stack, after the flare load is estimated, the major review items, such as thermal radiation, smokeless operation, flare size or capacity, flame stability, ignition system, flashback protection, noise level, knock out drum, and seal drum, that can affect the safety of the flare system are analyzed.

The adequate release speed and the capacity of the waste gas are stipulated for the safe flames on the flare stack [9]. This is to prevent incomplete combustion, wherein under the condition of a low estimate of the flare load, the excessive flow of gas can form a flame much higher over the flare tip or extinguish the flame itself. On the contrary, the combustion can happen inside the flare tip or can be extinguished by wind under a high-level flare load. For these reasons, flare gases are designed to emit adequate momentum. The flame from the flare stack takes the form of a jet fire due to the flow speed of the waste gas emission.

1-3. Flare Load Estimation Procedure

A chemical factory consists of several unit processes and utilities that provide electricity, heat energy, cooling, and steam to each process. Safety devices such as safety valves and rupture discs are installed in each process or equipment to prevent the formation of excessive pressure during an abnormal operation. These safety devices release the whole or over-pressurized portion of the gas out of the process in case of an overpressure.

To estimate the capacity of the flare stack, the amounts of the waste gas emission due to the overpressure in each unit process or device linked to the flare stack are listed. The causes of the overpressure generally include the interruption of the coolant or the electricity supply, a fire, and a cut-off of process streams.

The amount of the flare load is determined using the following procedure [10].

① List the capacity of each safety valve in a unit factory.

② Select the safety valves that emit the gas to the flare stack from the aforementioned list and fill in on a separate sheet the safety valve number, the protective device number, and the set-up pressure as

Table 1. Recommended design for total radiation

Permissible design level (K)		Conditions
BTU/hr·ft^2	kW/m^2	
5000	15.77	Heat intensity on structures and in areas where operators are not likely to be performing duties and where shelter from radiant heat is available (for example, behind equipment)
3000	9.46	Value of K at design flare release at any location to which people have access (for example. at grade below the flare or a service platform of a nearby tower); exposure should be limited to a few seconds, sufficient for escape only
2000	6.31	Heat intensity in areas where emergency actions lasting up to 1 minute may be required by personnel with. out shielding but with appropriate clothing
1500	4.73	Heat intensity in areas where emergency actions lasting several minutes may be required by personnel without shielding but with appropriate clothing
500	1.58	Value of K at any location where personnel with appropriate clothing may be continuously exposed

well as the release amount by each pressure increase factor such as the interruption of the coolant or the electricity supply, a fire, and a cut-off.

③ Calculate the subtotal of the release amounts by considering each pressure increase factor and the average molecular weight.

④ Calculate the total release amount by each pressure increase factor for a whole factory using a separate sheet; set the biggest amount as the flare load.

1-4. Calculation of the Flare Stack Height

The height of the flare stack is determined from the amount and type of the waste gas released from a unit factory as well as the temperature, pressure, and surrounding circumstances. According to the state of the waste gas, single or multiple flare stacks are designed, constructed, and operated. Flare stacks are designed according to API 521, and the height of the flare stack is usually determined from the thermal radiation of the waste gas [11].

The method suggested in API 521 determines the height of the flare stack according thermal radiation of the emitted waste gas, so that the operators should not experience any hazardous effect. The procedure is as follows.

① Calculate the emission speed of the waste gas.

② Estimate the diameter of the flare tip.

③ Analyze the flare shape (length, axes, and center point).

④ Calculate the thermal emission.

⑤ Calculate the distance from the center of the flare to a point where the thermal radiation is 4.73 kW/m^2.

The height calculated in this procedure prevents the thermal radiation from affecting the operators working underneath, even when the flare amount reaches its peak.

2. Thermal Radiation

2-1. General Information

Chemical factories release the gas in the process due to the reasons behind the abnormal operations, such as control failure, and behind the planned shutdown, and the gas is emitted from the process after it is transformed into a non-reactive state, through combustion. This process yields high heat. In the design of the flare system, the effect of thermal radiation on the operators and equipment must be evaluated, and the height of the flare stack should be estimated after the level of the thermal radiation around the flare is estimated. The height must be such that the thermal radiation on the ground is not more than 4.73 kw/m^2. At this level of radiation, people start to feel pain within 16 seconds. The experiment of Stoll and Greene [Personal correspondence with Korean Gas Safety Corp.] was referred to in setting this criterion. Since the allowable thermal radiation is a function of the exposure time, such factors as the response time and the human movement must be considered. In an emergency emission, it takes 3-5 seconds for the response and 10 seconds for an individual to find a protective cover or to evacuate the area. As a result, the exposure time takes 13-15 seconds overall. An explanation of the intensity of the thermal radiation stipulated in the API 521 Code is shown in Table 1 [11].

2-2. Calculation of the Thermal Radiation and View Factor

The thermal radiation decreases with the distance, and the range of its effect varies according to the atmospheric status. The thermal radiation is expressed as a multiplication of heating value, view factor and the fraction of transmission through the atmosphere:.

$$q = Q \times VF \times \tau \tag{1}$$

The heat emitted from the flame of a jet fire varies depending on the distance between the flame and the observer. As shown in Fig. 2, the view factor is calculated as an integral over the surface of the observer as follows [12]:

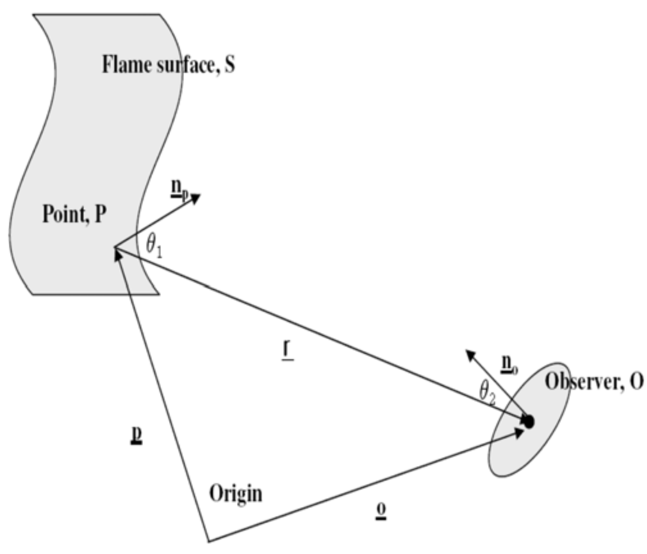

Fig. 2. View factor.

$$VF = \iint_{A_1} \frac{\cos\theta_1 \cos\theta_2}{\pi r^2} dA_1 \quad (2)$$

2-3. Coefficient of Atmospheric Transmission

The coefficient of atmospheric transmission is a very important factor of thermal radiation. The thermal radiation is absorbed or dispersed while it is transmitted in the atmosphere. For this reason, the thermal energy from a heat source decreases while it is conveyed. The coefficient of atmospheric transmission is inversely proportional to the distance, r, between the heat source and the observer, as well as to the vapor pressure, r_h, in the atmosphere [13]:

$$\tau = 0.79\left(\frac{1}{r_h}\right)^{\frac{1}{16}}\left(\frac{30.5}{r}\right)^{\frac{1}{16}} \quad (3)$$

2-4. Smokeless Operation

The waste gas is emitted from the upper part of the flare stack to the atmosphere and ignited by the flame that comes up through the ignition line. The waste gas, however, can contain the liquefied hydrocarbon that is formed while the waste gas is moving up along the main pipe of the flare stack or as the liquid hydrocarbon passes through the knockout drum. The combustion of liquids, unlike of gases, may emit dropping sparks or instantly increase the size of a flare and heat, which can harm the workers. Also, the shortage of oxygen results in an incomplete combustion that produces soot.

Smokeless operation is normally the overriding requirement when designing the burner for a flare system. Almost every flare design is aimed at inducing smokeless operation under a certain set of flare gas or utility availability conditions. To promote even air distribution throughout the flames (and thus prevent smoke formation), energy is required to create turbulence and mixing of the combustion air within the flare gas as it is being ignited. This energy may be present in the gases, in the form of pressure, or it may be exerted on the system through another medium such as injecting high-pressure steam, compressed air, or low-pressure blower air into the gases as they exit the flare tip. To create conditions favorable for smokeless combustion, flare designs range in complexity from a simple open pipe with an ignition source to integrated staged flare systems with complex control systems [11].

Table 2. Suggested rates of steam injection

Gases being flared	Steam required (pound of steam per pound of gas)
Paraffins	
Ethane	0.10-0.15
Propane	0.25-0.30
Butane	0.30-0.35
Pentane plus	0.40-0.45
Olefins	
Ethylene	0.40-0.50
Propylene	0.50-0.60
Butane	0.60-0.70
Diolefins	
Propadiene	0.70-0.80
Butadiene	0.90-1.00
Pentadiene	1.11-1.120
Acetylenes	
Acetylene	0.50-0.60
Aromatics	
Benzene	0.80-0.90
Toluene	0.85-0.95
Xylene	0.90-1.00

The maximum permissible steam injection in the flare stack is subject to the molecular weight and the carbon-hydrogen ratio of the waste gas. The typical ratio of the steam to the flare gas is 0.15-0.50. The heavier the molecular weight of the hydrocarbon is, the more smoke is generated and the more steam is required. Table 2 shows the steam injection amount suggested in the API 521 Code.

Since chemical factories use hydrocarbon as a feed, their waste gas contains hydrocarbon. Most flare systems have a steam supply line that prevents the generation of soot that can be formed during the combustion of the waste gas.

3. Flammable Zones

3-1. Lower Flammable Limits (LFL)/Upper Flammable Limits (UFL)

This is the range of flammability for a mixture of vapor in air at normal conditions, that is, the minimum and maximum concentrations of vapor in air that will propagate a flame [14]. The flammable limits and explosive limits have the same meaning. In general, when the range between the limits is large, it means more dangerous. Flammable limits are not an inherent property of a material but are dependent on the surface to volume ratio and velocity or direction of air flow under the test [15].

The combustion limit value of a mixed vapor can be obtained from various references or via direct measurement in an experiment, or it can be calculated using the Le Chatelier formula shown in Eqs. (4) and (5) [16]. Since this formula was empirically derived from the property of pure components, it cannot cover a wide range of non-ideal mixture applications.

$$LFL_{mix} = \frac{1}{\sum_{i=1}^{n} \frac{y_i}{LFL_i}} \quad (4)$$

$$UFL_{mix} = \frac{1}{\sum_{i=1}^{n} \frac{y_i}{UFL_i}} \quad (5)$$

Within the flammable range the following conditions usually fit, and the above equations can be used to calculate the combustion range of a mixed gas [16].

- The product heat capacities are constant.
- The number of moles of gas is constant.
- The combustion kinetics of the pure species is independent and unchanged by the presence of other combustible species.
- The adiabatic temperature rise at the pure species is the flammability limit is the same for all species.

3-2. Vapor Emission

General emission systems have flammable materials that are mixed with enough air when they are emitted to the atmosphere to keep the density of the flammable materials under the LFL level for the prevention of an explosion. On the other hand, flare stacks must maintain sufficient gas density within the range of combustion, since it removes the waste gas through combustion.

The factors that affect the range of combustion of the emission gas are as follows [9].

There are empirical formulas that can calculate the range of combustion, particularly according to the temperature and the pressure, among the factors that affect the range of combustion. Eqs. (6) and (7) calculate the effect of the temperature, and Eq. (8) calculates the effect of the pressure on the range of combustion [16].

$$LFL(T) = \frac{LFL_{25} - 0.75(T-25)}{H_c} \quad (6)$$

$$UFL(T) = \frac{UFL_{25} - 0.75(T-25)}{H_c} \quad (7)$$

$$UFL(T) = UFL_{25} + 20.6(\log P + 1) \quad (8)$$

The range of combustion generally extends according to the temperature, i.e., with every 100 °C temperature increase, LFL decreases by 8% and UFL increases by 8%. The pressure has nearly no effect on LFL, except when it is below 50 mmHg of absolute pressure. On the other hand, an increase in the pressure affects UFL in such a way that the range of combustion undergoes drastic extension.

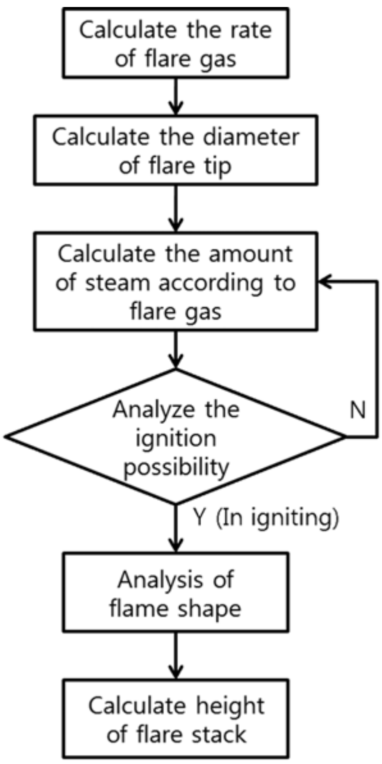

Fig. 3. Calculation procedure of the flare stack height for method 1.

REDUCTION OF THERMAL RADIATION BY IMPROVED STEAM INJECTION

1. Method 1: External Steam Injection

1-1. General Information

In this study, the composition and the peak emission amount of the waste gas from the GCDU (General Crude Distillation Unit) were confirmed, and it was analyzed whether or not steam injection, within a range that does not interfere with the stability of the flame, decreases the thermal radiation. Also considering the ignition possibility, the calculation of the height of the flare stack in our suggested method is shown in Fig. 3.

In an actual flare stack, when the waste gas is emitted to the atmosphere, steam is injected from each direction toward the gas so that the gas, steam, and air mix and ignite. The API 521 Code stipulates the steam amount according to the type of waste gas and that the steam injection is usually less than the amount of the waste gas. In an actual oil refining process, however, the waste gas is a mixture rather than having a single component. Since there is no guidance in this case, the possibility of combustion for a mixture must be checked in advance. Therefore, in Method 1 we checked if the full mixture of the waste gas and the steam maintains the flammability to be ignited. Also, the shape of the flame formed by the ignition, the effect of the steam amount on the reduction of the thermal radiation, and the height of the flare stack were analyzed.

1-2. Combustion Possibility According to the Steam Amount

While the waste gas of GCDU is flammable, steam is not. Thus, the mixture has a lower degree of flammability. Under the worst-case assumption, with all conditions the same, the temperature variation of the flare gas according to the steam injection amount was observed. Consequently, the effect of the steam amount on the reduction of the thermal radiation was studied.

The basic information on the waste gas emitted to the flare stack

Table 3. Flammable limits of common petroleum materials under normal conditions

Materials	Range of LFL [vol%]	Range of UFL [vol%]
Hydrogen	4.0	75.6
Ethane	3.0	15.5
Methane	5.0	15.0
Propane	2.0	9.5
Butane	1.5	8.5
Pentane	1.4	8.0
Hexane	1.7	7.4
Heptane	1.1	6.7

Table 4. Basic data of flammability of the gas

Components	N_2	CO_2	H_2S	C_1	C_2	C_3	i-C_4	n-C_4	i-C_5	n-C_5	n-C_6	H_2O	C_7
Mol%	0.09	6.93	6.36	77.33	2.11	0.97	0.2	0.4	0.18	0.23	0.2	4.92	0.08
Temperature	45 °C												
Pressure	1 bar												
Flow	317,203 kg/hr												
MW	20.45												

is shown in Table 4.

The API 521 Code suggests the speed of the waste gas, v_j, and the diameter of the flare tip, D. This is to ensure the continuation of the combustion of the waste gas against the external conditions such as a strong wind. The formulas are as follows.

$$v_j = \mathrm{Mach} \times 91.2 \times \left(\frac{kT}{M_f}\right)^{0.5} \tag{9}$$

$$D = \sqrt{\frac{0.001185W}{\mathrm{PMach}}}\sqrt{\frac{T}{kM_f}} \tag{10}$$

where k: specific heart ratio, W: mass velocity, M_f: molecular weight. After the speed of the emitted waste gas was set at Mach 0.2, the speed of the waste gas and the diameter of the flare tip were calculated as 81.4 m/s and 1.34 m, respectively.

In the case of Mach 0.2, the flame length was determined using Eq. (11) [8].

$$L = 118D \tag{11}$$

Waste gas that was mixed with 0%, 10%, 20%, 30%, 50%, 70%, 100%, and 120% steam of 310 °C on the mass basis of the waste gas, was emitted from the flare tip, and the possibility of combustion was checked. In chemical processes, also use at 310 °C steam. (As shown in Fig. 4(h), the red-color area having the value of the UFL becomes small enough to ignite the fame close to the flare tip, resulting in the possible destruction. Thus, the mix of steam greater than 120% cannot be a real choice for consideration.)

The mixture of the waste gas and steam was emitted to the atmosphere at the speed of 81.4 m/s through a hole with a diameter of 1.34 m, and the flammable zone at the moment was checked using PHAST 6.5. UFL, LFL, and 1/2 LFL were confirmed as shown in Fig. 4.

It was found that combustion was still possible with the mixture of up to 120% non-responsive steam with the flammable waste gas.

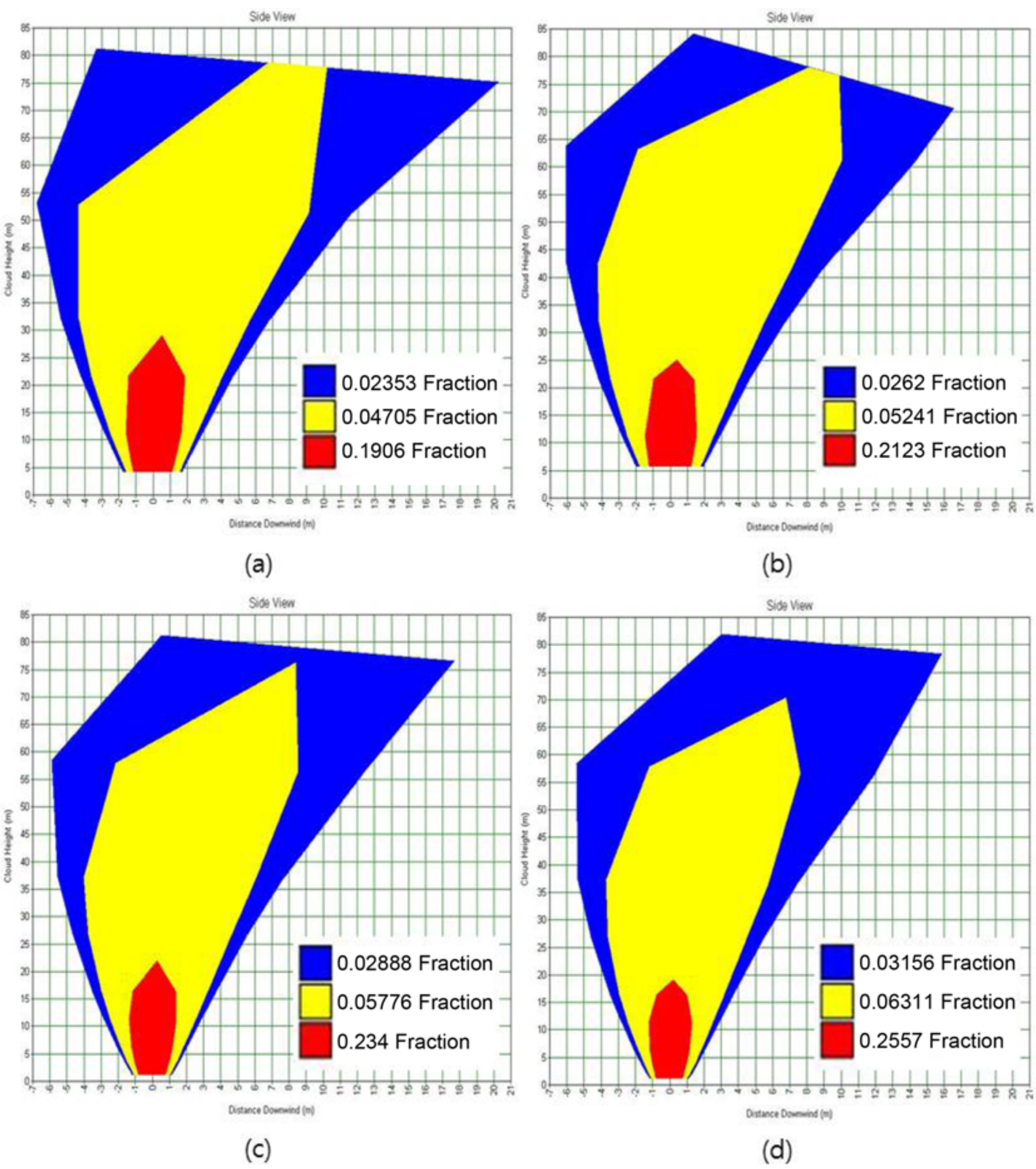

Fig. 4. Flammable limits range (method 1) (a) 0%; (b) 10%; (c) 20%; (d) 30%; (e) 50%; (f) 70%; (g) 100%; (h) 120%.

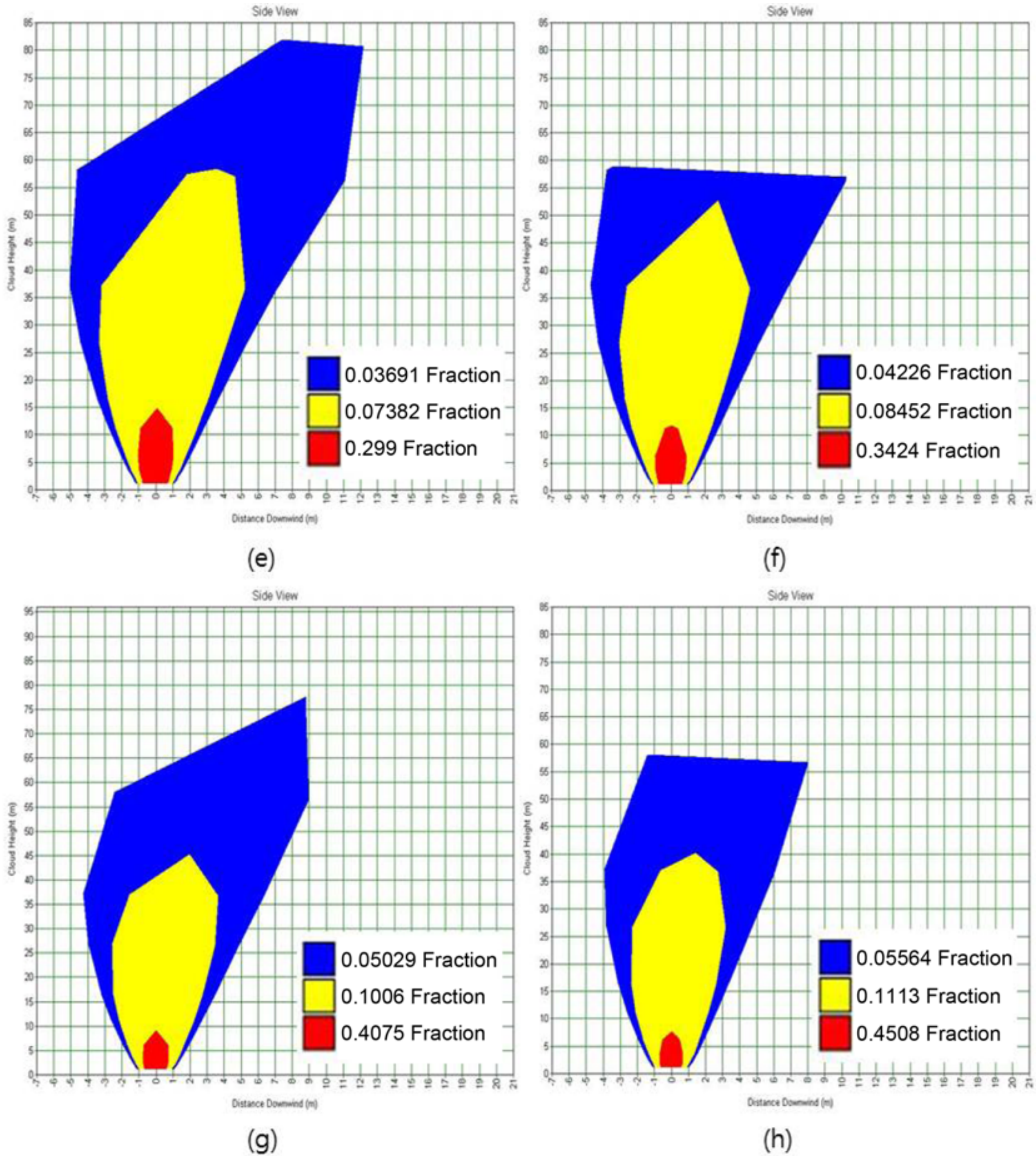

Fig. 4. Continued.

It was also analyzed that an increase in the steam diminished the UFL range, and made immediate ignition possible after the emission of the waste gas. Moreover, it was found that an increase in the steam injection further prevented the effect of the wind. This can be interpreted to mean that an increase in the mass velocity of the vertically emitted waste gas reduces the effect of the wind.

1-3. Confirmation of the Reduction of the Thermal Radiation According to the Steam Amount

Non-responsive steam was injected into the flammable gas, and PHAST 6.5 was used to check the reduction in the thermal radia-

Table 5. Mass flow rate and temperature of the mixed gas

Mixture ratio (%)	0	10	20	30	50	70	100	120
Mass flow rate (kg/s)	88.11	96.92	105.73	114.54	132.17	149.79	176.22	193.84
Temperature (°C)	45.00	67.66	86.74	103.04	129.41	149.82	173.04	185.12

Table 6. Flame emissive power and distance (method 1)

Mixture ratio (%)	0	10	20	30	50	70	100	120
Flame emissive power (kW/m^2)	124.27	124.22	124.17	124.12	124.04	123.96	123.85	123.78
Distance (m)	92.06	89.53	86.51	84.52	81.32	77.1	74.61	73.24

Table 7. Data of gas mixtures

Mixture ratio (%)	0	10	20	30	50	70	100	120
Temperature (K)	318.15	340.81	359.89	376.19	402.56	422.97	446.19	458.26
Mass flow rate (kg/s)	88.11	96.92	105.73	114.54	132.17	149.79	176.22	193.84
Diameter (m)	1.34	1.43	1.51	1.59	1.74	1.87	2.06	2.17
Flame length (m)	158.12	168.74	178.18	187.62	205.32	220.66	243.08	256.06
Jet velocity (m/s)	81.40	84.24	86.57	88.51	91.56	93.85	96.39	97.69

Table 8. Flame emissive power and distance (method 2)

Mixture ratio (%)	0	10	20	30	50	70	100	120
Flame emissive power (kW/m^2)	124.27	108.53	96.89	87.06	72.28	62.31	51.1	45.93
Distance (m)	92.06	77.13	62.21	50.38	33.65	24.32	17.09	14.3

tion according to the amount of the steam. The distance at which receiving the 4.73 kW/m^2 radiation suggested in API 521 was calculated.

Since the flame in the flare stack forms the shape of a jet fire from the momentum of the waste gas, the caloric value and the thermal radiation were calculated by applying the API 521 Model as a jet fire in PHAST. In an actual flare stack, the steam is emitted from each direction after the emission and ignition of the waste gas, which offsets their momentum.

In Method 1, the temperature and mass velocity of the waste gas were analyzed according to the increase in the steam, with the flame length and the diameter of the flare tip fixed. The flame emissive power and the distance of the 4.73 kW/m^2 radiation are shown in Table 6.

Based on the conditions in Method 1, the 124.27 kw/m^2 thermal emission without steam decreased to 123.78 kw/m^2 with 120% steam. In other words, the distance of the 4.73 kW/m^2 radiation, i.e., the estimated height of the flare stack, decreased. The use of 120% steam was deemed to have decreased the height of the flare stack by 20%.

2. Method 2: Internal Steam Injection

2-1. General Information

In Method 1, it was confirmed that the complete mixture of waste gas and steam can form a flame. Also, the effect of the steam amount on the reduction in the thermal radiation was confirmed. In Method 2, a flare stack was designed for the emission of a mixture of steam and waste gas from the upper part of the flare stack. In such a case, the conditions of the flare stack, such as the diameter of the flare tip, the flame length, the jet velocity, and the mass flow rate, must vary according to the steam amount variation. With these conditions, the thermal emission and the subsequent variation in the height of the stack were investigated.

2-2. Basic Data According to the Steam Amount Variation

For the waste gas that was completely mixed with 0%, 10%, 20%, 30%, 50%, 70%, 100%, and 120% steam on the mass basis of the waste gas, the tip diameter, flame length, mass flow rate, temperature, jet velocity, etc., were calculated considering the overall waste gas emission.

It was found that, with the increase in the steam amount, the mass flow rate of the mixed gas, the diameter of the flare tip, and the flame length also increased. Based on these data, the flammable zone was compared with that in Method 1 using PHAST.

Similar to Method 1, the mixture of the flammable waste gas with up to 120% non-responsive steam was found to have been flammable.

2-3. Confirmation of the Reduction of the Thermal Radiation According to the Steam Amount

As in Method 1, the reduction in the thermal radiation according to the steam amount and the distance of the 4.73 kW/m^2 thermal radiation were calculated using the API 521 Model in the PHAST 6.5 software.

The thermal emission of 124.27 kw/m^2 without steam decreased by 63% to 45.93 kw/m^2 with 120% steam. In other words, the distance of the 4.73 kW/m^2 thermal radiation, i.e., the estimated height of the flare stack, decreased. The use of 120% steam was deemed

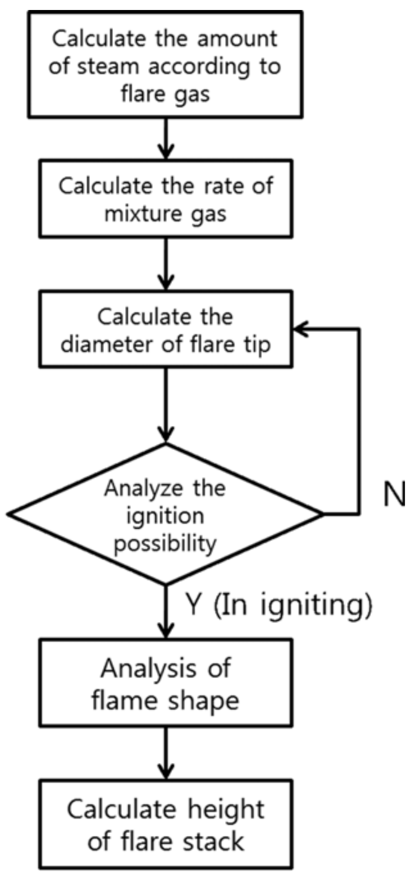

Fig. 5. Calculation procedure of the flare stack height for method 2.

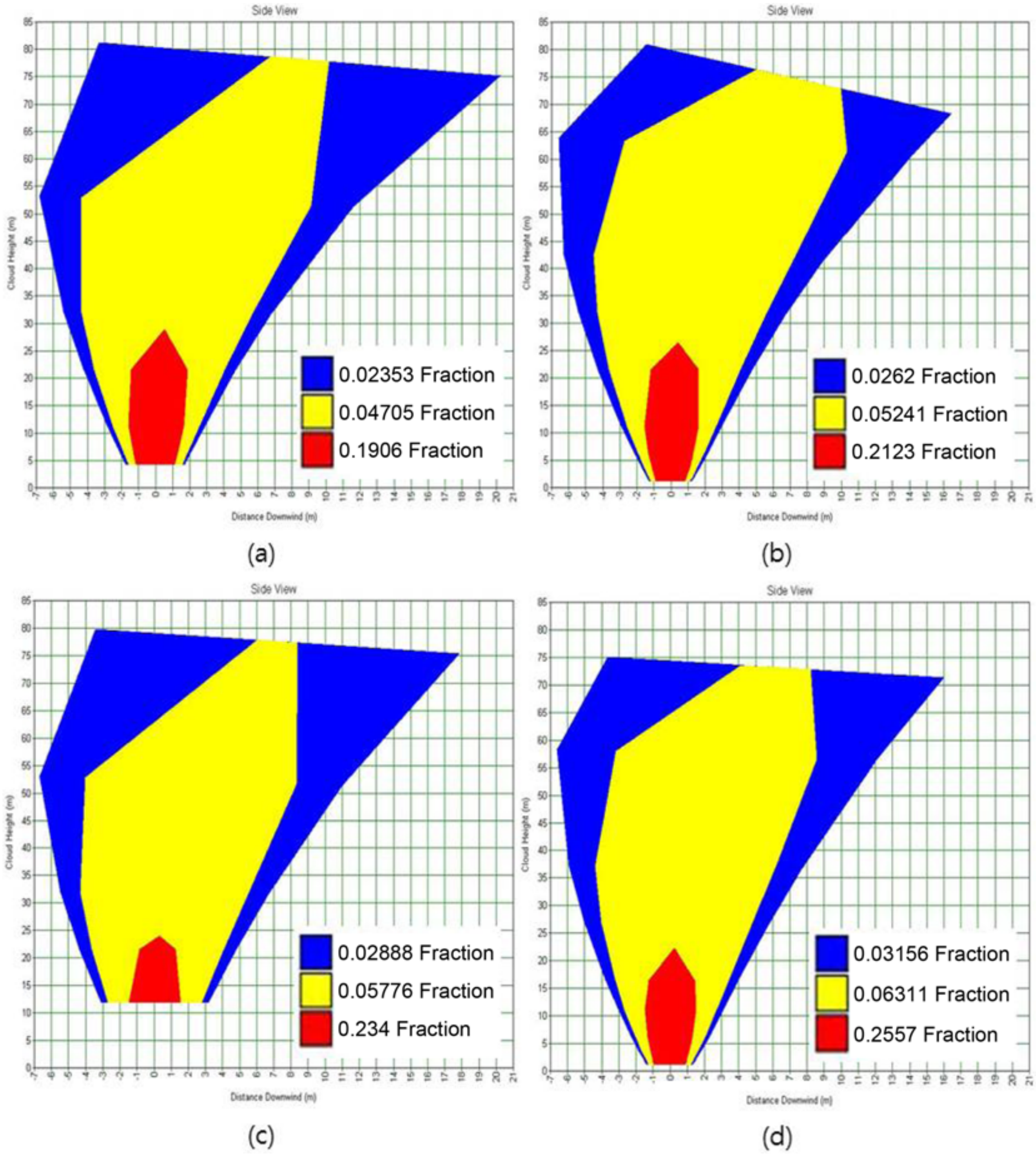

Fig. 6. Flammable limits range (method 2) (a) 0%; (b) 10%; (c) 20%; (d) 30%; (e) 50%; (f) 70%; (g) 100%; (h) 120%.

to have reduced the height of the flare stack by 84%.

CONCLUSION

In this study, the risk factors in the flare system were confirmed, ways to reduce these risk factors were determined, and the ensuing reduction in these factors was confirmed. Thermal radiation was recognized as having an adverse effect on the flare system, by adversely affecting the operator. Thus, the possibility of using steam, also as a means of smokeless combustion in the flare stack, to reduce thermal radiation was analyzed.

In Method 1, when the mixture gas (waste gas and steam) was ignited from the flare tip, the possibility of combustion and the reduction in the thermal radiation were analyzed. Since the over-injection of steam into the waste gas could lead to non-ignition and could result in a more serious accident, the mixed gas must be ignited with the steam injection. The possibility of the ignition was analyzed under the assumption that "the mixed gas forms a complete mixture through high-speed emission." The case of 120% steam injection contributed to only 0.49 kW/m^2 reduction, but the height of the flare stack was reduced by 73.24 m, resulting in 20% height reduction.

In Method 2, steam was mixed with the waste gas inside the flare, and the mixed gas itself was emitted from the flare tip. The thermal emission and the height of the flare stack decreased more than in Method 1. The flame length increased due to the increase in the mass flow rate in Method 2. This caused the center of the flame to form at a higher position and led to the possibility of lowering the height of the flare stack, which could still reduce the effect of the thermal radiation on the operators. The increase in the gas to be treated in the flare stack, however, could cause structural problems in the flare stack equipment. While flare stacks are designed to process the maximum amount of waste gas, Method 2 showed that a greater amount must be estimated due to the addition of steam. This could result in the design of a main pipe with a wider diameter.

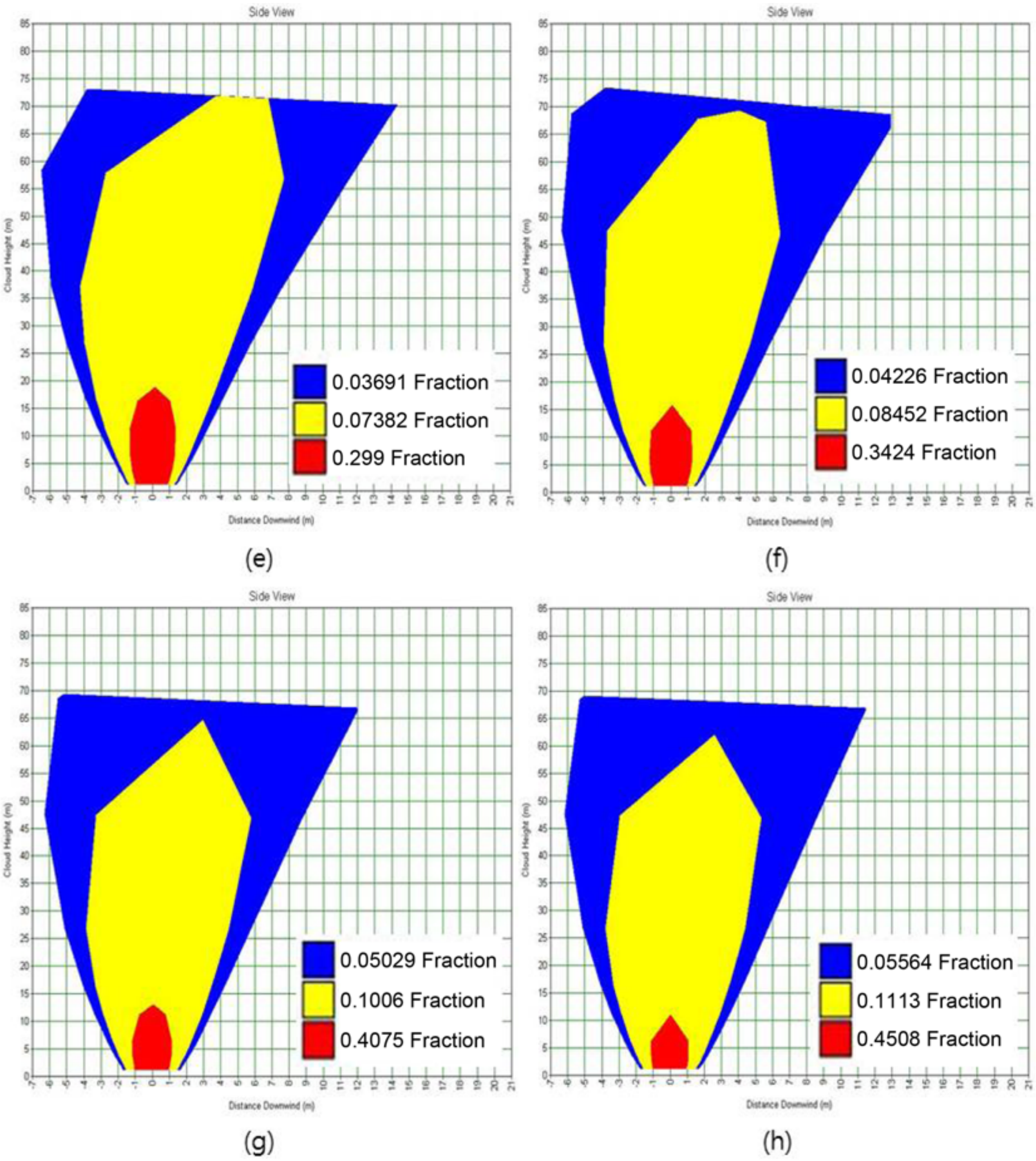

Fig. 6. Continued.

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NOMENCLATURE

q : kilowatts per square meter [kW/m^2]
Q : heating value
VF : view factor
θ_1 : the angel between the $\underline{n}_p$ to the flame suface at P, and d
θ_2 : the angel between the $\underline{n}_o$ to the obsever at O, and d
A_1 : surface of observer
r : path length distance from the flame surface to the target
r_h : the fractional ambient relative humidity
y_i : the mole fraction of component i on a combustible basis
ΔH_C : the heat of combustion for the fuel [in 10^5 kJ/mol]
v_j : velocity of flare gas at the flare tip [m/s]
Mach : 340.29 m/s
k : specific heat ratio (C_p/C_v)
T : temperature [K]
M_f : molecular weight
D : flare tip diameter [m]
W : velocity of mass [kg/hr]
P : pressure [kPa]
L : length of flame [m]

Greek Letters

τ : fraction of transmitted through the atmosphere

REFERENCES

1. M. Kalantarnia, F. Khan and K. Hawboldt, *Process Safety and Environmental Protection*, **88**, 191 (2010).

2. D. Mourad, O. Ghazi and B. Noureddine, *Korean J. Chem. Eng.*, **26**, 1706 (2009).
3. H.-S. Lee, B.-S. Kim, S.-Y. Jung, J.-H. Yoo, C. Park and J.-W. Ko, *KIGAS*, **13**, 49 (2009).
4. G. A. Chamberlain, *Chem. Eng. Res. Design*, Transactions of the Institution of Chemical Engineers, **65**, 299 (1987).
5. P. Benard, V. Mustafa and D. R. Hay, *Int. J. Hydrog. Energy*, **24**, 489 (1999).
6. O. Zadakbar, A. Vatani and K. Karimpour, *Oil & Gas Sci. Technol.*, **63**(6), 705 (2008).
7. Saudi Arabian Oil Company, United States, US-0069348 (2008).
8. K. Banerjee, *Flare gas systems pocket handbook*, Gulf Publishing Company (1985).
9. EPA/625/6-91/014, US EPA.
10. KOSHA code, D-32-2003 (2003).
11. API 521 (2000).
12. J. Cook, *J. Loss Prevent. Proc. Ind.*, **3**, 150 (1990).
13. T. A. Brzustowski, *Proceedings of the 38th Meeting of the American Petroleum Institute*, 38 (1973).
14. Center for Chemical Process Safety, *Guidelines for chemical process quantitative risk analysis*, Wiley-Interscience (1999).
15. Nolan, Dennis P, *Handbook of fire and explosion protection engineering principles: For oil, gas, chemical, and related facilities*, William Andrew Publishing (2010).
16. Daniel A. Crowl, *Chemical process safety* (Second Ed.), Prentice Hall, Upper Saddle River, NJ (2002).