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SMOKELESS FLARING AT HIGH RATES

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ABSTRACT

Process flares handle a wide range of waste gas flows and compositions. In order to comply with environmental regulations, this flaring must be smokeless and complete. Flare operating range, turndown, smoke formation and control are discussed. Improved methods of mixing ambient air with the flare stream for smokeless flaring at high rates are emphasized.

INTRODUCTION

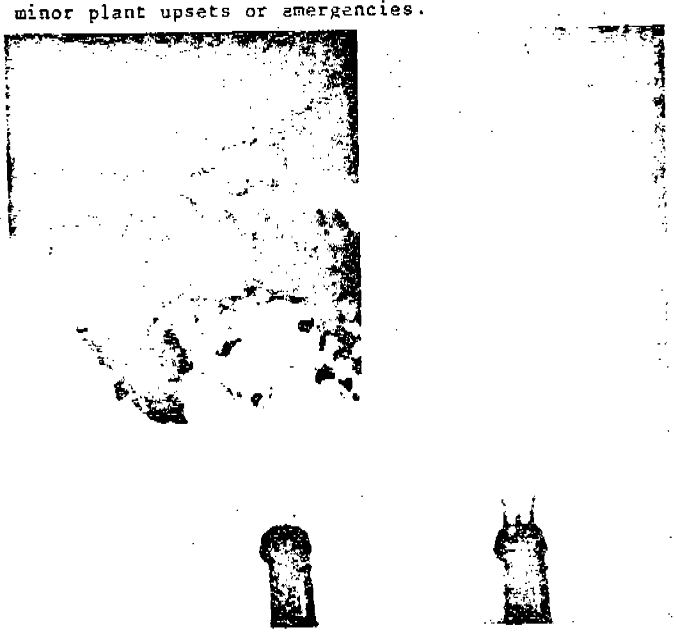
Flaring has been the traditional method of safely eliminating unwanted gases and vapors in the oil drilling and production industry since the early 1920's. With the development and expansion of both the oil refining and petrochemical industries, flaring has become more important, since it provides a safe, reliable and environmentally acceptable method of eliminating process and emergency waste gas streams.

Process flaring waste streams consist of small quantities of gas leakage through safety relief valves; moderate quantities of product gas or vapor for unit maintenance; and moderate to large flow rates for shutdown or start-up of the process units.

Emergency flaring waste streams consist of large quantities of gases and sometimes volatile liquids or condensate from unexpected equipment failures, such as: compressor failure; overpressure in a process vessel, or instrument failure; and major plant emergencies, such as power failure, plant fire, or complete cooling water loss.

In order to ensure compliance with present enviromental regulations, smokeless and complete combustion of the flare waste gas is required. As shown by flare emission testing (References 1,2), smokeless operation is the prerequisite for complete combustion. Smokeless flares are required for any hydrocarbon in the paraffin series above methane, and all olefins, diolefins and aromatics. Methods of smoke control are: injection of steam, water spray, compressed air or high pressure gas; forced air mixing; utilization of high waste gas pressures for air entrainment and mixing; distribution of the waste gas stream in multiple smaller burners; application of the natural draft driving force of a stack; or the employment of "ion winds' from an electric field.

As the air quality regulations governing smoke (Figure 1) and hydrocarbon emissions apply more control over the degree and the duration of emission, and also the process or emergency reasons for the emission, proper smokeless flare design at high flow rates is important for compliance. A flare must also be able to handle waste gas flow rate turndowns, from the low process waste rates due to valve leakage to moderate and large rates from process maintenance and minor plant upsets or emergencies.



(Without Steam) (With Steam)

Figure 1 -- Flaring Propylene

For a typical refinery flare, flow rates could range from 100 - 200 lb/hr (45 - 90 kg/hr) for relief valve leakage, to 1000 - 2000 lb/hr (450 - 900 kg/hr) for normal process blowdowns, to 55,000 - 77,000 lb/hr (25 - 35 t/hr) for unit maintenance or major unit failure, and finally to full plant emergency rate of 1.5 MM lb/hr (700 t/hr). The required flare turndown ratio for this typical case is better than 15,000:1, which does not include the additional turndown if only the purge gas flow for the stack and header is to be considered. Typical purge gas flow for this refinery flare would be 15 kg/hr (33 lb/hr) of natural gas, which triples the turndown requirement for smokeless and complete combustion.

Turndown and performance are the day to day requirements, but reliability and long life are the requirements for continuous compliance. The process and mechanical design must be carefully carried out on a conservative basis with proper combustion and field experience. Improper design allowances can result in early or even catastrophic failure that would require plant shutdown for repair or replacement of the flare tip. Some of these improper and high risk design allowances are:

(1.) Internal premixing of air -- allows burning inside the flare tip and quickly destroys the tip.

(2.) Small orifices or slots for smokeless injection -- plugging from scale or other foreign matter often occurs, thereby allowing the flare to smoke. Cooling for the flare tip is prevented by this problem, while shortening the life of or destroying the tip.

(3.) Moving parts in the flare tip gas stream -- plugging or failure of moving parts, which blocks flare waste gas flow, results in complete failure of safety relief system -- "NO FLARE".

For the design of any flare, performance, turndown, reliability and life are central, but thermal radiation, noise control, and economics also must be considered. The combustion process design of smokeless flares and their mechanical design factors will be discussed to meet the need for improved flaring at higher rates.

FORMATION OF SMOKE

Most flare combustion employs a turbulent diffusion flame, or, as expressed by the industry, a "raw gas" burner. All combustion air is brought into the waste gas stream as the stream exits the tip and combustion is initiated. Taking the previous example of a refinery flare, the quantities of air needed for stoichiometric combustion of a possible propane-butane mixture are typically 180,000 - 250,000 scfm (4,800 - 6,800 Nm^3/min) for the minor unit failure and 5 MM scfm (133,000 Nm^3/min) for the full plant emergency. From the magnitude of the air volumes involved, an air deficiency in the combustion zone is likely, and therefore smoke will result. Some newer flare tips premix air with the waste gas in order to reduce the air deficiency, but the amount of air which can be practically premixed is only a small percentage of the overall requirement, even for minor unit failure cases. The premix of air with the flare waste gas also creates problems of burning inside the flare tip and flashback, especially as the flare rate varies. Study of the methods of soot formation in diffusion flames will provide a more suitable approach to smoke control. A number of possible chemical mechanisms and the formation of soot have been suggested by combustion engineers, and to a small degree, have been investigated. There is no single process by which the hydrocarbons dehydrogenate and polymerize to form large carbon particles. Some of the proposed mechanisms and findings are presented.

Measurements of the tendency to smoke (Reference 3) for various hydrocarbon series are given in Figure 2. The Carbon to Hydrogen (C/H) ratio is obviously an important parameter, but not the only one. Molecular structure is important; branched chain paraffins smoke more readily than their corresponding normal isomers, although their C/H ratios are the same. The more highly branched the paraffin, the greater the smoke tendency. Unsaturated hydrocarbons have a greater tendency to smoke than paraffins, but higher members of the unsaturated series tend to get more paraffinic with less tendency to smoke.

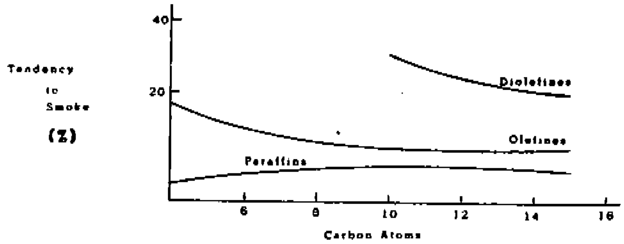


Figure 2 -- Tendency to Smoke

Effect of Pressure Generally, low partial pressures have been shown to decrease soot formation. This may be explained by the fact that the lower pressure decreases the reaction rate in the diffusion flame and gives the flame more time to approach premixed conditions, where oxidation can take place throughout the entire body of the flame instead of only at a thin surface region. The injection of steam, water, or other inert diluents will reduce the partial pressure of the hydrocarbon in the flame and therefore reduce smoke.

Effect of Temperature Changing of the flame temperature has a complex effect on soot formation. Near the point of flame ignition, higher temperatures help suppress soot formation, but for very rich flames, as is the case for flares, soot formation could be increased. Usually the change in flame temperature is produced in conjunction with other changes, such as increased turbulence, air injection, and carbon-water reaction, thereby leading to the clear conclusion that the influence of temperature change above is impossible.

Pyrolysis Carbon particles can be formed by the thermal decomposition of the hydrocarbons in the preheating zone of the flame and then grow larger to form soot. The possible growth mechanisms for the carbon particles formed by pyrolysis are: polymerisation, condensation / graphitisation, and nucleation (Reference 4). Smoke is produced as the final step by the quenching of the large soot particles.

The smoke formation is a complex mechanism and is the result of may different types of localized reactions. These varying localized zones are seen by examining the flare flame. Near the base of the flame, at the exiting point of the waste gas (the zone of highest velocities, shear forces and turbulence) the flame is highly aerated due to the entrainment of ambient air. However, if the flare is operating at low flow rates and exit velocities, this zone of the aerated flame is not present. If the wind conditions across the top of the flare are significant (10-20% of the exiting gas velocity) or severe (30% or greater) then the momentum balance between the wind and the waste gas is moving in favor of the wind's horizontal plane. Because of this, the aeration zone will be reduced or lost, resulting in smoke formation in the primary zone.

Examination of a higher level in the flare flame reveals turbulent combustion controlled by the buoyancy of the burning process. Air is entrained by the flame due to the induced draft generated by the flame itself. Depending on the hydrocarbon being burned, this final zone can either achieve complete smokeless combustion or result in incomplete combustion with soot formation and smoke. If wind is superimposed on this secondary zone, then the buoyancy forces are quickly overcome and the efficiency of burning falls. Many times the wind will tear the flame into globules of free floating flame which lose heat rapidly and result in further smoke.

In order to control smoke formation, the initial aerated combustion zone must be enhanced and maintained even in high cross winds, so that the secondary buoyancy zone is minimized.

METHODS OF SMOKE CONTROL

Smoke is not formed if the combustion is completed in the aeration zone at the base of the flame. If the flare were a premixed type rather than a diffusion process, then the problems of properly getting the ambient air into the flame zone would be eliminated. However, a premixed design flare presents other problems: (1) the possibility of the flame moving back into the premixer assembly or piping; (2) inability to give high turndown (flow rate variation). If the flare flame can be kept outside the mixer at high flow rates, the low flows associated with high turndown will definitely result in flashback and internal burning. Swithenbank (Reference 5) presents a premixed flare design with a ceramic grid to prevent flashback. The turndown and flashback considerations are resolved by the flame holding grid. In addition, older premixed flare designs (Figure 3) use large diameter venturi inspirators with a valved staging system to prevent flashback while providing high turndown. These premixed designs are approriate for relatively small flaring rates, but are not practical for the high rates presently required. One form of a premixed

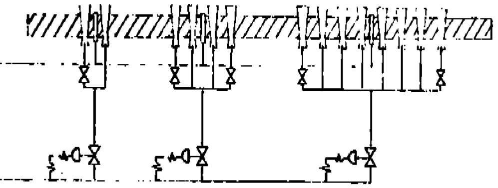


Figure 3 -- Venturi Premixed Flare

flare is shown in Figure 4a. This design gives good smokeless performance, but problems of burning inside the premixed zone (Figure 4b) result in short life which is impractical for refinery or chemical plant operations.

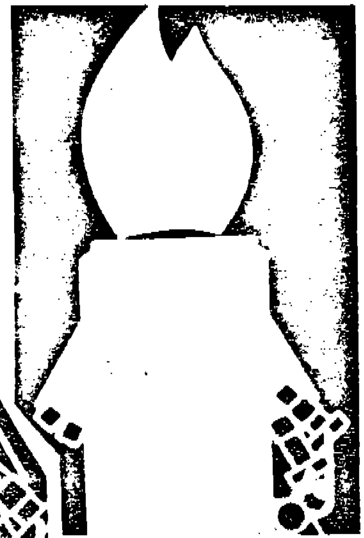


Figure 4a -- Premixed Flare

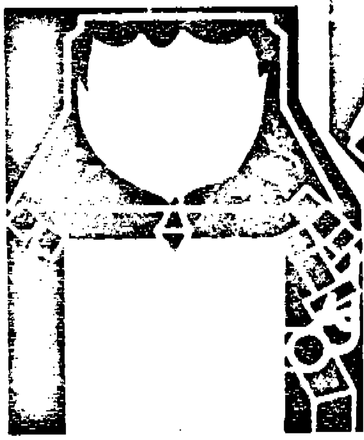


Figure 4b -- Burning Inside Flare (Too Much Air Premix)

Other methods of generating the aerated combustion zone are needed. The most common solution involves using high velocity steam jets at the top of the flare tip to inject the needed air into the waste gas stream. A typical "steam ring flare" is shown in Figure 5. The main factor in the design of the steam injection flare is optimum steam-air inspiration and

Figure 5 -- Steam Ring Flare

injection into the base of the flare flame in order to effect the aerated combustion. Many types of steam-air inspirators are available for use: (1) venturi tube; (2) Coanda design; (3) single jet; and (4) multi-jet tips. The venturi design is efficient, but due to its restricted cross sectional flow area, it has a limited ability to bring in a desired quantity of outside air. The venturi type is usually used for the primary injector in high performance (Figure 6) and high performance/low noise (Figure 7) flares. The venturi typically entrains 5 lbs. (5 kg) of air per pound (kg) of steam ejected. This rate is somewhat variable because of venturi design and pressure losses in the steam-air duct and discharge nozzle. Coanda inspirators have high air entrainment rates. However, these high rates are generated by using very small slots of less than 0.02" (0.5 mm) which may cause plugging problems due to foreign matter (rust, scale, welding slag, etc.) in the steam piping. Usually, additional Coanda inspirators are installed to allow for a planned percentage of slot plugging. Filters, strainers and knock-out sections are all used to reduce the plugging problems, but all these add more maintenance to the flare and reduce its reliability.

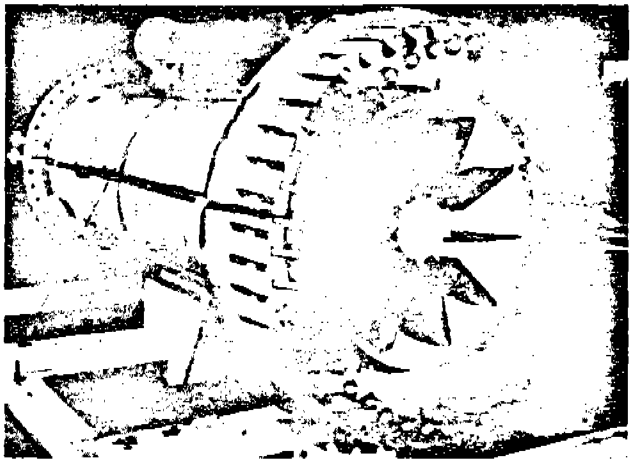


Figure 6 --High Performance Flare

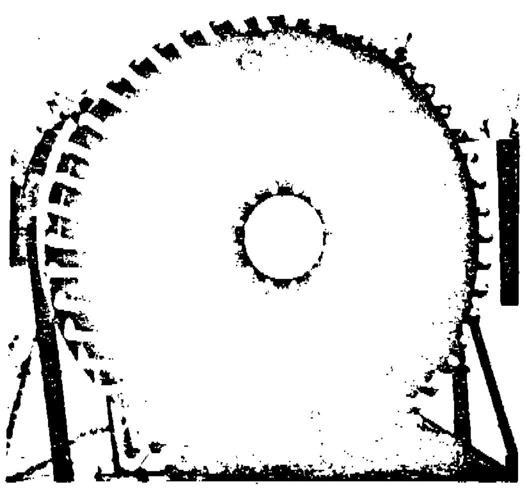


Figure 7 -- Low Noise Flare

The ring type flare shown in Figure 5 can also utilize compressed air in place of steam to give the flame its required aeration. The compressed air is quite effective, however more mass flow of compressed air is needed than would be required if steam were used. This is due to the advantage that steam can enter into a water-gas reaction, helping the smoke suppression process. Compressed air provides the necessary air mixing and turbulence for the premixed combustion process, but the water-gas reaction is lacking. Typically, 20 percent more mass flow of compressed air is needed over steam for similar performance.

Another approach that uses air injection is the "air blower" type flare (Figure 8). Here, the high pressure, high velocity compressed air (50-150 psig, kPa) is replaced by low pressure air (2" WC, 50 mm WC) from an electric blower. Since the velocities from this air stream are much lower (95 fps, 30 m/s) than the compressed air jets (1200 fps, 365 m/s), the amount of blower air must be increased to maintain the same momentum levels. The air blower will require an air to hydrocarbon mass ratio of approximately 4:1 to 6:1, while the air jets ratio is approximately 0.25 to 0.5. This ratio range depends on the hydrocarbon's tendancy to smoke. The difference between the ratios of blower air and air jets is one of momentum mixing effectiveness. However, the air blower flare has inherent design problems in that obtaining good mixing of the waste gas stream with the blower air is unlikely. Figure 9 shows the mixer head for an air blower flare. This design appears to be quite effective, but after further study and testing, it has been determined that approximately 30 percent of the total blower air supply was being wasted. It was necessary to oversize the blower in order to make the flare flame smokeless, but due to poor mixing proximity between the gas vanes and the entire air stream, the air stream became highly stratified and did not mix. Improved designs have since been developed to overcome this problem.

Figure 8 -- Air Blower Flare

Figure 9 -- Air Blower Mixer Head

Flame aeration can also be approached from a completely different way. Rather than trying to inject and mix air into the waste gas stream, the waste gas stream can be broken into many smaller streams and injected into the ambient air. These smaller streams will become aerated far more quickly and will burn smokelessly.

Many small burners can be used to distribute the waste gas over a large area (Figure 10), thereby bringing the gas to the air rather than trying to aerate the flame by air injection. The flow rate that each burner can handle is dependent on the waste gas composition to be burned. If a paraffin group waste of C_6 or below is to be flared in the multi-burner design then smokeless operation is easily achieved with a minimum number of burners and burner control stages. As the waste gas molecular weight increases and as the waste gas becomes unsaturated, the smokeless design requirements become more severe. These conditions will involve the use of a greater number smaller capacity burners and burner staging controls unless additional waste gas pressure is available, which simplifies the design.

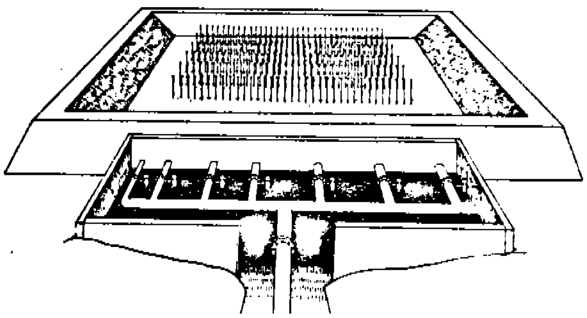


Figure 10 -- Multi-Burner Flare Pit

If a high molecular weight, unsaturated gas is only available at low flare header pressures, then an enclosed multi-burner flare may be used for smokeless operation (Figure 11). In the case, smokeless burning is achieved by means of the natural draft air flow created by the high combustion temperatures inside the enclosure. An enclosed multi-burner flare requires fewer burners, since each burner has a greater flow capacity.

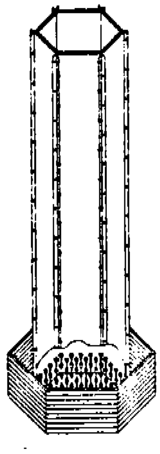


Figure 11 -- Multi-Burner Enclosed Flare

The techniques learned from the multi-burner ground level flares have been employed in elevated flares. These techniques range from simply mounting the burner tips on a small capacity elevated flare (Figure 12), to using the basic principle of spreading the gas out over a larger area for smokeless performance without steam or other assist (Figure 13).

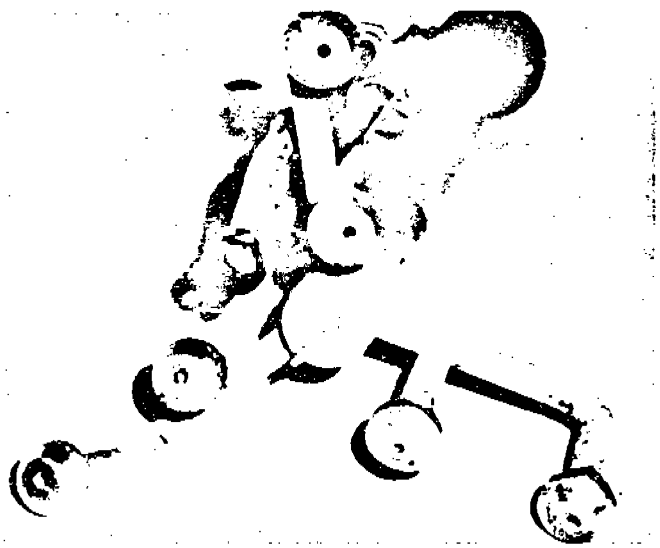


Figure 12 -- Multi-Burner Elevated Flare

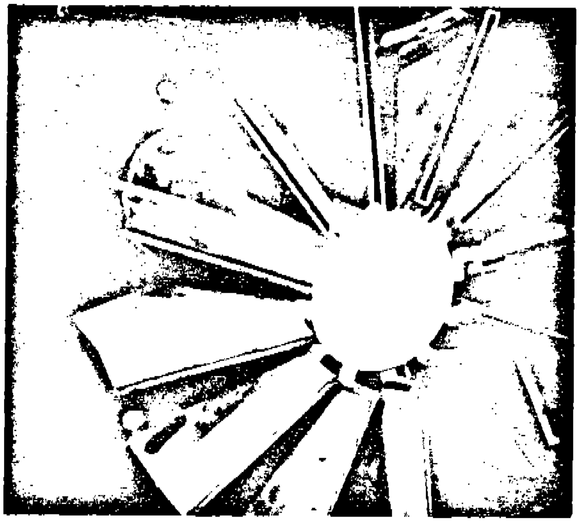


Figure 13 -- High Capacity JET MIX Flare

CONCLUSION

Smokeless flaring is required for compliance with environmental regulations. Smokeless operation can be achieved by several approaches, but basic design for effective air entrainment and mixing are the key to high performance smokeless flaring. Safe and reliable flare operation, however must be the primary consideration in design.

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