LANDFILL GAS FLARE SYSTEM DESIGN BASICS

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The power of fire to purify and transform has fascinated man since the beginning of time. Today, combustion systems are promoted as "black boxes" predictable only through extensive testing and usage. While years of experience are required to develop detailed design expertise, the combustion process is controlled by basic reaction kinetics and mixing technology. We will attempt to provide a basic framework for engineers to analyze and evaluate combustion equipment for landfill applications.

Basic Combustion Stoichiometry

Combustion alters the form of the organic materials in the landfill gas, combining them with oxygen in the air to produce harmless carbon dioxide and water vapor.[1] For all practical purposes, landfill gases consist primarily of methane, carbon dioxide, nitrogen and water vapor. Since air is 21% oxygen, the basic combustion reaction is:

$$CH_4 + 2\ O_2 + 7.52\ N_2 = CO_2 + 2\ H_2O = 7.52\ N_2 + \text{Heat}$$

9.52 SCF (Standard Cubic Feet) of air per SCF of methane is considered the "theoretical" or stoichiometric air ratio. To ensure that the hydrocarbons are completely combusted, additional air is added to enhance the reaction. The amount of air above "theoretical" is called excess air. Typically, 10 - 25% excess air is considered a minimum amount for complete hydrocarbon conversion.

As the oxidation reaction releases energy in the form of heat, the reaction must be cooled to maintain the operating temperature. The quench medium may be water, but is normally air. Air added to cool the combustion reaction is known as "quench air". Quench air is often greater than the stoichiometric air flow resulting in total excess air levels of 100 - 250% above theoretical. Higher operating temperatures require lower levels of quench air.

The following table illustrates the effect of operating temperature on flue gas flow rates and excess air levels based on 100 cfm of landfill gas (50% methane, 30% CO_2, 10% N_2, 10% H_2O):

Operating Temperature (°F)	Flue Gas Flow (scfm)	Excess Air (%)	Flue Gas Composition — vol% (wet basis) — CO2	N2	O2	H2O
1400	1690	230	4.8	74.3	13.6	7.4
1600	1440	179	5.6	73.6	12.3	8.5
1800	1250	140	6.4	72.9	11.1	9.6
2000	1100	108	7.3	72.1	9.8	10.8

Design Parameters

Although the mechanisms to combust landfill gases are well understood, the process variables for combustion are not exactly quantified[2]. Only limited field data is available to document the minimum combustion requirements to meet different emission criteria. For example, the destruction efficiency of vinyl chloride and other trace compounds has not been thoroughly developed on an industrial scale.

It is well known, however, that the combustion of any volatile organic compound depends on the "Three T's of Combustion": residence time, operating temperature and burner turbulence. The process variables are interrelated and, to some extent, dependent upon each other. For example, better burner turbulence can reduce the required residence time needed for a specific destruction efficiency, and vice versa. Operating temperature, residence time, and burner design must all be considered in the selection and evaluation of landfill gas combustion equipment.

Operating temperature should be addressed first as it is a direct function of the waste compound to be combusted. The combustion temperature should be 300 - 500°F above the autoignition temperature of the waste gas to ensure complete destruction. Since methane autoignites at 1004°F, a minimum operating temperature of 1400°F is often specified. However, since the landfill gas reaction is exothermic (no additional fuel required), the ability to combust at 1800 - 2000°F improves the hydrocarbon destruction efficiency.

In cooking, a turkey must be baked for 3 - 4 hours to be completely done. Likewise, the residence time in a combustor allows time for some hydrocarbons to "cook" and react with oxygen. Residence times for volatile organic compounds (VOCs) vary from 0.25 to 2.0 seconds. Solid particles, such as carbon, may require up to 5 seconds for total destruction. In general, chlorinated and aromatic hydrocarbons require additional residence time to avoid partial oxidation into CO and unburned hydrocarbons.

Turbulence is the final design parameter and the one most dependent upon the flare mechanics. Mixing of landfill gas and air at the burner tip is the most critical operation of the flare. Proper turbulence creates a uniform mix of landfill gas and air in the combustion zone. Poor mixing leads to flue gas stratification which contributes to high emissions and operating instability.

OPEN FLAME FLARES

Open flame flares, also known as "candle" or "pipe" flares, have been widely used on landfills for years. Often no more sophisticated than an open pipe lit periodically with a burning rag, pipe flares offer an economical method of disposing of the landfill gas. In the simplest form, the pipe flares were placed one to each relief well and operated at reservoir pressures.

As environmental and odor controls became stricter, many landfill operators have installed gas collection systems to prevent gas migration outside of the landfill boundaries. Suction wells drilled at engineered locations are tied together with common manifolds. Large blowers pull a slight vacuum and direct the landfill gas away from the property boundaries.

Likewise, the open flame flares have changed as well. A single flare is often required to serve the entire landfill. Operating at higher flow rates and tip velocities requires flame stabilizers to prevent the flame from extinguishing itself. Windshields allow the flame to establish itself and resist high wind conditions. Automatic energy saving pilots sense the landfill gas flame and automatically relight the flare if necessary.

Open flame flares are difficult to evaluate according to the Three T's of Combustion as the residence time and temperature cannot be controlled or accurately measured. The burner turbulence is a function of the landfill gas pressure drop which is often limited by the maximum stable tip velocity.

Emissions from open flame landfill flares have not been specifically studied to date. However, numerous studies have been performed on other open flame flares over the years with surprisingly consistent results on emissions. In general, the reports conclude that open flame flaring destroys over 98% of the total hydrocarbons provided that a stable flame exists.

This is an important distinction for landfill gases due to the variable inert gas levels. A study by the Chemical Manufacturers Association[3] shows a 98% or higher hydrocarbon destruction level of various compounds in a propane/nitrogen mixture during stable flare operation. As the nitrogen content was increased, a definite point of instability was reached and destruction efficiencies quickly dropped to below 95%. Thus a discussion of destruction efficiencies is academic if a landfill flare is allowed to vent instead of burn. Integrated control systems which operate the flare, blowers, block valve and relight systems will minimize landfill gas venting with little operator attention.

The main disadvantage to ALL open flame flares is the monitoring of emissions. Without a closed system design, it is impossible to accurately measure flowrates or emissions. Sample probes placed too close to the flame will measure high CO and hydrocarbon levels. Samples taken away from the flame are diluted by an unknown amount of air. If the regulatory agencies require emission sampling or testing, an enclosed type flare is needed.

ENCLOSED FLARES

Enclosed flares differ from open flame flares in that both landfill gas and the air flows are controlled. While landfill gas is "pushed" through the flame arrestor and burner tips by a blower, the flare stack "pulls" or drafts the air through air dampers and around the burner tips. Acting as a chimney, the stack height and diameter are crucial in developing sufficient draft and residence time for good operation.

Enclosed flares are used in landfill gas applications for one of two reasons. An enclosed flare may be required to simply hide all or part of the flame. Additionally, an enclosed flare may be needed to meet present or future emission limitations. An "emission control" flare requires more stringent design parameters to insure proper operation over a wide range of conditions.

Invisible Flares

Enclosed flares designed solely to hide the flame are often referred to as "invisible flares". These flares are normally characterized by a short stack height of 20 to 30 ft. Residence times are typically about 0.3 seconds.

At full landfill flow rates, the flame inside an invisible flare is often close to the top of the flare. In many cases, invisible flares are designed to enclose the "flame envelop", but allow "tails" of flame to burn above the top of the flare. As landfill gas is primarily methane and CO2, the flame tails are clear and might only be seen at night. Landfills near residential areas or heavily traveled roads may find the fire department at the gate on occasion.

Emissions from invisible flares are very dependent upon the landfill gas flow and methane concentration. At low rates, the residence times are sufficient for complete combustion and the flame height is short enough for an accurate sample. At high rates, sampling tests may yield erratic results as combustion may not be complete at the sampling location. High CO and unburned hydrocarbon concentrations are not uncommon of invisible flares at high flow rates.

From the earlier discussion of the "Three T's of Combustion", the "turbulence" or mixing energy of invisible flares is low due to the short flare height with, consequently, a low air draft at the burners. The mixing energy comes from two sources, the landfill gas pressure and the air pressure drop. As the air flow is 10 - 15 times the gas flow the importance of stack height on the burner operation becomes evident. Adding 20% to the stack height also adds 20 - 30% to the burner air mixing energy and residence time.

Moderate to high wind conditions can significantly distort the internal flame patterns on invisible flares. One side of the flare may receive too much air which cools the flame below the operating temperature while the other side of the flare operates with too little air increasing the flame temperature above 2200°F. The high temperature side may cause refractory damage as well as excess NOx while at the same time the cold temperature side may form excess CO and unburned hydrocarbon. To minimize wind effects, operators often build brick or steel barriers in front of each air opening.

As uniform operating temperatures and stack gas flow patterns depend upon good burner turbulence, operators should look closely at the burner design and verify that units of comparable height and landfill gas capacity are working satisfactorily at other locations.

Emission Control Enclosed Flares

Enclosed flares often need to minimize NOx, CO, and hydrocarbon emissions while at the same time maximize the destruction of trace compounds such as vinyl chloride and aromatic compounds. These requirements are often contradictory, requiring design compromises to maximize the flare performance. For example, high operating temperatures reduce CO and hydrocarbon emissions, but also increase the NOx levels. The enclosed flare should be designed not only to meet today's emission regulations, but should also be able to operate at more stringent conditions if needed by future regulations.

Emission control enclosed flares are characterized by a 35 - 50 ft. overall height. The additional height is a key design requirement for emission reduction as the flare height provides the draft and mixing energy for the landfill gas and combustion air. A 40 ft. enclosed flare will produce about 100% more draft than a 20 ft. enclosure. This draft is the key to completing the "Three T's" triangle of time, temperature and turbulence.

Flare height may also be needed to meet sampling location regulations. California requires sample ports to be located 1/2 diameter above the flame and 1/2 diameter below the flare outlet. Economics dictate that taller flare with a smaller diameter would be less expensive than a short, large diameter enclosure.

The increased draft from the taller flares coupled with special air damper designs will also resist the adverse effects of wind. Separate wind fences are rarely required with McGill flares of this design.

Landfill emission regulations often specify 0.3 seconds minimum residence time which is quite adequate for combustion of methane and to meet the total hydrocarbon emission standards of 98 - 99% destruction. However, trace compounds such as tetrachloroethylene and methylene chloride are more difficult to combust. Wisconsin has already enacted legislation that sets destruction efficiencies of some chlorinated hydrocarbons. In anticipation of the more stringent regulations on trace hydrocarbons, McGill designs enclosed ground flares for 0.6 - 1.0 seconds residence time.

An EPA model[4] of chlorinated and aromatic compounds indicates the relative ease of combustion between compounds at various operating temperatures, residence times and destruction efficiencies. The model does not accurately predict the absolute emission values or operating temperatures, but is useful in comparing different chemicals. For example, a comparison of methane versus tetrachloroethylene indicates that at 1600°F and high excess air levels, tetrachloroethylene requires 80% more residence time than methane for the same destruction efficiency.

Operating temperature is the third key design parameter for emission control and is often the least understood. Most regulations specify a minimum operating temperature of 1400°F which is suitable for combustion of methane and similar VOCs. In general, lower operating temperatures reduce NOx emissions by cooling the flame temperature. Increasing the operating temperature reduces CO and hydrocarbon emissions. As a rule of thumb, low CO emissions require 1600°F to ensure good conversion efficiencies. Higher residence times and good burner mixing can offset lower operating temperatures.

The same EPA model as before predicts that for equal destruction efficiency, tetrachloroethylene requires 100 - 250°F higher operating temperature than methane depending on the residence time.

The mechanical design of the enclosed flare can also limit the maximum operating temperature. McGill uses 2600°F refractory and Inconel anchors which will withstand a continuous operating temperature of 2000°F. Due to the changing nature of emission regulations, McGill recommends that enclosed flares be designed to operate from 1200°F to 2000°F without mechanical damage in order to provide the maximum user flexibility.

Other Design Considerations

Flame stability is always a concern with any combustion equipment from both an emission and a safety viewpoint. Without a stable burning flame, all other design considerations are meaningless. Flame stability is largely determined by the tip design and the landfill gas methane concentration. At concentrations of 30 - 60% methane, the flare should easily maintain stable ignition. If the methane concentration drops below 15%, auxiliary fuel injection is likely to be required as the CO2 in the landfill gas acts as a fire extinguisher on the combustion reaction. In all cases, proper tip design is critical to ensure good mixing of the landfill gas and air as well as to create a small flame zone at the tip which ignites the remaining bulk of the waste gas.

Turndown is another important operating requirement of open and enclosed flares. A stable flame should be present at 5% - 100% of the landfill gas flow. This is rarely a problem as the gas blowers usually have only an 8:1 turndown at best.

Enclosed flares should also be able to maintain the operating temperature by controlling the air flow. Single blade air dampers will allow a 2-3:1 turndown on air flow. Opposed blade louvers can provide tight control of the air flow and operating temperature from 15% - 100% of capacity (6:1 turndown).

As regulated temperature control and recording are likely to be specified in the future, McGill designs all enclosed landfill flares to accept air flow control systems if required.

Field Emission Results

McGill emission control enclosed flares have been tested at a number of locations. While most emission tests have been to verify NOx, CO and overall hydrocarbon destruction, a number of tests have also measured the destruction of trace hydrocarbons, such as vinyl chloride. In all cases, McGill flare systems have met or exceeded the performance requirements and emission regulations.

NOx emissions typically range from 0.05 to 0.1 lb/MMBTU on landfill gas. The actual emission level is greatly dependent upon the landfill gas itself as high levels of nitrated compounds, such as acrylonitrile or ammonia contribute heavily to the formation of NOx. Operating temperatures should be kept below 2000°F to minimize the thermal NOx as well.

CO emissions are very dependent upon the operating temperature and upon the amount of heavy trace hydrocarbons in the landfill gas. In most cases, operation above 1600°F with good mixing and residence time will minimize the CO emissions from even the worst landfill gas. Because CO destruction is favored by higher operating temperatures, low inlet methane concentrations are often the culprit for flame instability and high CO emissions. Trace hydrocarbons, with higher molecular weights, also contribute disproportionately to their weight due to lack of complete combustion. CO emissions can range from 0.05 - 0.60 lb/MMBTU.

Recently, emission tests for vinyl chloride were performed on McGill enclosed flares with excellent results. Operating at 1300°F to 1400°F with over 2 seconds residence time, the 40 ft. high flares destroyed virtually 100% of the inlet vinyl chloride. Similar results were obtained for benzene and trichloroethane.

Landfill flares do not generate significant amounts of particulates and convert virtually all of the landfill gas H_2S to SO_2. Please note, however, that flares do not remove any of the particulates, SO_2 or HCl emissions that enter the flare in the landfill gas or air. A dusty day or nearby construction can give misleadingly high particulate values from dust in the combustion air. For particulates, sulfur and chlorine, landfill flares operate on a "mass in = mass out" basis.

Summary

The proper selection of landfill flares depends upon the required design and operating objectives. Open flame flares provide good hydrocarbon destruction efficiencies at economical prices. Invisible flares enclose most or all of the flame and allow verifiable operating temperatures. The taller emission control enclosed flares have increased mixing energy, residence time and operating temperature capabilities to meet increasingly stringent emission regulations.

The key point is to know and advise the flare designer of the specific emission requirements and operating expectations.

ACKNOWLEDGEMENTS

[1]Bell, Ronald D., "Fundamentals of Combustion and Combustor Design", McGill Design Manual, 1982, pp 1-3.

[2]Wiley, S.K., "Incinerate Your Hazardous Waste", Hydrocarbon Processing, June, 1987, pp 51-54.

[3]Chemical Manufacturer's Association, Washington, D.C., "A Report on a Flare Efficiency Study", March, 1983.

[4]EPA-600/S2-84-138, "Determination of the Thermal Decomposition Properties of 20 Selected Hazardous Organic Compounds", Barry Dellinger, et. al., October, 1984.