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Comparison of Three Methods to Monitor Flare Combustion Efficiency

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Introduction

Industrial flares are used for safety and emissions control. When a flare performs as designed, the chemical compounds in the vent gas stream sent to the flare are combusted and the combustion products, mainly carbon dioxide (CO_2) and water, are safely released to the atmosphere. Measuring or monitoring combustion efficiency (CE) or destruction efficiency (DE) of an industrial flare is the ideal method to assess flare performance; however, directly monitoring flare CE is very challenging because the combustion occurs in the open air. The current practice is to monitor surrogate parameters, such as vent gas net heating value (NHV_{vg}) and flare tip exit velocity (V_{tip}). When the surrogate parameters are within certain limits (e.g., $V_{tip} < 60$ feet per second and $NHV_{vg} \geq 300$ British thermal units per standard cubic feet, or Btu/scf), the flare CE or DE is deemed to be in the acceptable range (typically 96.5% for CE and 98% for DE). Recent studies have found that the flare CE or DE under certain operating conditions may not be as high as previously assumed even when the surrogate parameters meet the criteria (Allen and Torres, 2011). It would be highly desirable if flare CE or DE could be directly monitored. A method for directly monitoring flare CE has been proposed (Zeng, et. al, 2016).

On December 1, 2015, the U.S. EPA promulgated a new rule for petroleum refineries following a lengthy Risk and Technology Review (RTR) process required by the 1990 Clean Air Act Amendment, hereafter referred to as Refinery RTR Rule (USEPA, 2015a). The rule imposes new requirements for monitoring flares, among other requirements, at approximately 150 refineries in the U.S. The method specified in the Refinery RTR Rule for monitoring flare performance is a surrogate method with stricter definition of the surrogate parameter, i.e., changing NHV_{vg} to Combustion Zone Net Heating Value (NHVCZ). The significance of this new rule is two-fold. First, the flare performance standard prior to this rule, which is codified in Title 40 of Code of Federal Regulation Part 60 (40 CFR 60), Subpart A, Section 60.18, paragraphs (b) through (f), and 40 CFR 63.11 (b) (USEPA, 2015b), does not require continuous monitoring. Instead, the compliance is determined by stack testing methods (Method 2 for vent gas volumetric flow rate to derive flare tip velocity; and Method 18 for vent gas composition to derive vent gas net heating value). The compliance determination by stack testing is infrequent, usually when the flare becomes subject to the regulation, the flare is modified, or periodic testing is required by a permit. Secondly, the previous net heating value is for vent gas only. The new rule requires net heating value in the combustion zone, NHV_{CZ}. In order to derive the NHV_{CZ}, flow rates for other streams, such as steam assist, air assist, and supplemental fuel (as well as the heating value of the supplemental fuel, if used), will need to be monitored. Because each of these streams will not be at the same temperature or under the same pressure, the temperature and pressure of these streams will also have to be monitored to correct the flow rate to standard conditions. Instruments will have to be installed on appropriate streams to monitor these parameters in order to derive the actual values of the surrogate parameters NHV_{CZ} and V_{tip}, and compare them against the limits for these surrogate parameters to demonstrate compliance (e.g., $V_{tip} < 60$ feet per second and $NHV_{CZ} \geq 270$ Btu/scf on a 15-minute block period basis). Under this new rule, operators have to continuously monitor (having at least one data point every 15 minutes) and react to these online analyzers to keep the flare in compliance. This will be a new burden placed on the operators which was not present in the standards prior to this rule. The cost to install, operate, and maintain these instruments in order to comply with this new rule are expected to be very significant for the approximately 150 refineries subject to this new rule.

In this paper, three potential methods to demonstrate compliance with the flare monitoring requirements under the new Refinery RTR Rule are identified. After a brief description of each method, the instruments required under each monitoring method are identified. A cost analysis is performed to evaluate the costs associated with these methods. The main purposes of this paper is to compare these monitoring methods in terms of their effectiveness and costs.

Flare Monitoring Methods

The requirements for flare monitoring in the new Refinery RTR Rule can be found in 40 CFR 63.670. At a very high level these requirements can be summarized as follows:

1. Pilot flare must be present (flame out for 1 minute in a 15-minute block is a deviation)
2. No visible emissions (no more than 5 minutes of smoke condition in a 2-hour period)
3. Flare tip velocity (V_{tip}) limit
4. Combustion zone net heating value (NHV_{CZ}) limit
5. Dilution operating limit (NHV_{dil}) for flares with perimeter assist air

The requirements 3-5 in the above list are the surrogate parameters aimed at achieving a 96.5% CE or 98% DE. The equations for calculating these parameters are specified in the new rule (40 CFR 63.670) and they are listed below;

$$V_{tip} = \frac{Q_{cum}}{Area\ x\ 900} \qquad \text{Eq. 1}$$

$$NHV_{CZ} = \frac{(Q_{vg} - Q_{NG2} + Q_{NG1}) \times NHV_{vg} + (Q_{NG2} - Q_{NG1}) \times NHV_{NG}}{Q_{vg} + Q_s + Q_{a,premix}} \qquad \text{Eq. 2}$$

$$NHV_{dil} = \frac{Q_{vg} \times Diam \times NHV_{ng}}{Q_{vg} + Q_s + Q_{a,premix} + Q_{a,perimeter}} \qquad \text{Eq. 3}$$

$$NHV_{vg} = \sum_{i-1}^{n} x_i NHV_i \qquad \text{Eq. 4}$$

Where:

V_{tip} = Flare tip velocity, feet per second (ft./sec.)
Q_{cum} = Cumulative volumetric flow over 15-minute block average period, actual cubic feet (acf)
Area = Unobstructed area of the flare tip, square feet
NHV_{CZ} = Net heating value of combustion zone gas for the 15-minute block period, Btu/scf.
Q_{vg} = Cumulative volumetric flow of flare vent gas during the 15-minute block period, scf.
Q_{NG2} = Cumulative volumetric flow of supplemental natural gas to the flare during the 15-block period, scf.
Q_{NG1} = Cumulative volumetric flow of supplemental natural gas to the flare during the previous 15-block period, scf. For the first 15-minute block period of an event, set $Q_{NG1}=Q_{NG2}$.
NHV_{NG} = Net heating value of supplemental natural gas to the flare for the 15-minute block period, Btu/scf.
Q_s = Cumulative volumetric flow of total steam during the 15-minute block period, scf.
$Q_{a,\ premix}$ = Cumulative volumetric flow of premix assist air during the 15-minute block period, scf.
NHV_{dil} = Net heating value of dilution parameter, Btu/scf.
Diam = Effective diameter of unobstructed area of the flare tip for flare vent gas flow, ft. $Diam = 2 \times \sqrt{Area/\pi}$
NHV_{vg} = Net heating value of flare vent gas, Btu/scf
i = Individual component in flare vent gas
n = Number of components in flare vent gas
x_i = Concentration of component i in flare vent gas, volume fraction
NHV_i = Net heating value of compound i, Btu/scf

In order to calculate the net heating value of the vent gas, NHV_{vg}, one of two methods can be used: (1) to install an online gas chromatograph (GC) on the flare header to analyze the composition of the vent gas and determine the net heating value based the net heating value and concentration of each compound in the vent gas [see Eq. (4) above], or (2) to install an online calorimeter on the flare header to measure the net heating value of the vent gas stream without analyzing individual compounds in the stream.

The methods using either GC or calorimeter along with multiple flow, temperature, and pressure sensors to monitor flare performance and compliance are referred to as Continuous Parameter Monitoring System (CPMS) in the Refinery RTR Rule. The real objective of the rule is to ensure high flare CE. The CPMS is specified in the rule because up to the rulemaking period there was no practical method to directly monitor flare CE. The CPMS relies on the assumption that when the surrogate parameters (V_{tip} and NHV_{CZ}) are within the specified limits, the flare is deemed to having achieved 96.5% CE or better. Whether or not this underlying assumption is valid is still a subject of debate and on-going research. If the assumption is not valid, the result could be over-regulating or under-regulating (unfavorable to industry or unfavorable to the environment).

A recent advancement in multi-spectral infrared imaging has made it possible to directly measure the flare CE from a distance instead of relying on surrogate parameters to predict flare CE (Zeng, et. al, 2016a). The remainder of this section is dedicated to discussions on the two indirect methods and the new direct method, including their advantages and disadvantages and the necessary instruments to implement these methods.

GC-Based Indirect Method

In order to acquire the data necessary to derive the surrogate parameters (V_{tip} and NHV_{CZ}), a suite of instruments must be installed. These instruments are identified in *Table 1* along with the parameters these instruments will provide to derive the required surrogate parameters.

Stream	Instrument	Relevant Parameter	Notes
Vent gas	Flow meter	Qcum -> Vtip Q_{vg} -> NHV_{cz} or NHV_{dil}	
	Temp sensor	Q_{vg} -> NHV_{cz} or NHV_{dil}	Convert acf to scf
	Pressure sensor	Q_{vg} -> NHV_{cz} or NHV_{dil}	Convert acf to scf
	Online GC	NHV_{vg} -> NHV_{cz} or NHV_{dil}	
Steam	Flow meter	Q_{s} -> NHV_{cz} or NHV_{dil}	
	Temp sensor	Q_{s} -> NHV_{cz} or NHV_{dil}	Convert acf to scf
	Pressure sensor	Q_{s} -> NHV_{cz} or NHV_{dil}	Convert acf to scf
Air - Premix	Flow meter	Qa,premix -> NHVcz or NHVdil	May not be needed depending on site conditions
	Temp sensor	Qa,premix -> NHVcz or NHVdil	
	Pressure sensor	Qa,premix -> NHVcz or NHVdil	
Air - Perimeter	Flow meter	Qa,perimmeter -> NHVdil	May not be needed depending on site conditions
	Temp sensor	Qa,perimmeter -> NHVdil	
	Pressure sensor	Qa,perimmeter -> NHVdil	
Suppl. Fuel	Flow meter	Q_{NG} -> NHV_{cz} or NHV_{dil}	

	Temp sensor	Q_{NG} -> NHV_{cz} or NHV_{dil}	Convert acf to scf
	Pressure sensor	**Q_{NG} -> NHV_{cz} or NHV_{dil}**	Convert acf to scf

Table 1. Instruments required for the GC based surrogate method.

For a typical steam flare, ten instruments will be needed to implement this method, including a GC and three sets of flow, temperature, and pressure sensors for vent gas, steam, and supplemental fuel. Some facilities install two flow meters to accommodate the large change in the flow (high turndown ratio). For air flares, required flow instruments may be less if the air flow can be calculated by using a fan curve and the accuracy is acceptable. In addition to these instruments, a climate-controlled shelter is typically needed to house the GC and associated instruments such as the sample conditioning system, calibration equipment, etc. A shelter is not required for some instruments.

The function of the GC is to provide composition analysis of the vent gases. Based on the composition, the NHV_{vg} value is calculated using Eq. (4). A GC is not a continuous analyzer. It takes one sample injection at a time. The injected sample runs through the GC column and chemical species are separated, detected, and quantified. The GC analytical cycle (or GC response time) is typically 6-12 minutes. Although this analytical timeframe meets the minimum regulatory requirement of one data point per 15 minutes, it delays corrective action when such an action is needed. For example, if a sample result shows NHV_{CZ} below the regulatory threshold, the flare operator can add supplemental fuel to bring NHV_{CZ} up to meet the regulatory threshold. However, if the GC analysis time is 6 minutes, the effect of the corrective action (adding supplemental fuel) will not show until the next sample analysis is complete in 6-12 minutes. This increases the chance of a regulatory deviation because there will be at most two data points to average within the 15-minute regulatory window – one not in compliance and one hopefully in compliance, and the average of the two is uncertain. This is assuming that the operator has sufficient time to be notified and take action immediately. A few minutes of delay will put the corrective action out of the 15-minute window. There is also inherent process delay due to the time for gas to travel through the pipeline and reach the sample intake point.

Very often flare vent gases change fairly rapidly in both flow and composition. The mismatch between the dynamic nature of the flare vent gases and the long GC response time can be problematic. In general, it is a challenge for an operator to “chase” a rapidly changing process with very spotty feedback, and it could cause unstable operations. When vent gas heating value is below the regulatory limit and supplemental gas needs to be added, the long GC response time will likely cause unnecessary use of supplemental fuel because the operator cannot reduce or stop supplemental fuel until the next result becomes available even if the process has changed and heat content in the native vent gases has reached the desired level. The unnecessary portion of supplemental fuel increases the operating cost and emissions of both conventional air pollutants and greenhouse gases (GHG).

The maintenance of the GC instruments includes periodic change of calibration gas cylinders, cleaning of sample conditioning systems, maintenance of the detector in the GC, etc. Both the GC instruments and flow measurement sensors (flow meter, temperature sensor, and pressure sensor) come in direct contact with the vent gases. Flare vent gases can be laden with materials that are not "instrument friendly," such as acid or caustic, particulate matters, high viscosity substances, etc. This may translate to a considerable level of maintenance activities. Also, because the sampling line and flow measurement sensors are installed on the flare header, maintenance work involving these components will likely require hot work permits. The initial installation of these components will also likely interfere with processes connected to the flare header and may require the shutdown of process units.

Calorimeter Based Indirect Method

This method is essentially the same as the GC based method with one exception, a calorimeter is used in place of the GC. While GC measures individual chemical species in the vent gases for the calculation of NHV_{vg} using Eq. (4), calorimeter directly measures NHV_{vg} without speciating the chemicals in the vent gas. Calorimeter is a simpler instrument than a GC and the response time is shorter, typically 2 minutes. It is possible to install a calorimeter without a climate-controlled shelter. Other than the GC, all instruments listed in Table 1 are required for this method. Therefore, the nature of operations and maintenance associated with this method is similar to that of a GC based method.

If hydrogen is expected in the vent gas and the facility wants to take the advantage of a more favorable regulatory limit [1,212 Btu/scf; see 40 CFR 60.670 (l)(3)], a hydrogen analyzer will need to be installed in addition to the calorimeter. In the GC method, most GC instruments can separate and quantify the hydrogen in the vent gases and therefore a separate hydrogen analyzer is not needed.

Direct Combustion Efficiency Monitoring Method

With this method, flare CE is directly monitored (hereafter referred to as the "Direct CE Method"). It sidesteps the assumed relationship between the surrogate parameters and CE. These assumed relationships are still debated and studied. By directly measuring the flare CE, this method minimizes the possibility that the surrogate methods may over-regulate or under-regulate, which may unnecessarily restrict facility's operations, have unintended negative environmental impacts, or both.

The direct flare CE measurement is accomplished by a multi-spectral infrared imager specifically designed for this purpose (see Figure 1). The method is based on a patented technology (Zeng, et. al., 2016b), and expanded to nine spectral bands to improve the accuracy. These spectral bands are designed to cover the infrared features of hydrocarbons (in the neighborhood of 3.2~3.4 micrometers) and CO2 (in a broader range of 3.8~4.8 micrometers), and to measure relative strength of signals representing unburned hydrocarbons and combustion product (i.e., CO2). The measurements are at the pixel level and the CE is determined based on relative concentrations of CO2 and unburned hydrocarbons for each pixel that represents a column of flare combustion gases projected on the sensor of the multi-spectral imager. The design of the imager ensures that the spectral data is captured under the same conditions and at the same time. These pixel level CE values may be lower near the center of the flare flame where the combustion process is still on-going. As the combustion progresses, more hydrocarbons are combusted until either all hydrocarbons are fully combusted, or combustion stops due to flare conditions (e.g., too much steam that cools the flame). The layer of combustion gases where combustion has stopped is referred to as a combustion envelop, which encapsulate the center of combustion. The flare CE is calculated by averaging the individual CE values of pixels that are on the combustion envelop. A validation test has shown a good agreement between the CE measured by this method and CE measured by extractive sampling as a ground truth method (Zeng, et. al., 2016a).

Figure 1. Direct flare CE monitor – a multi-spectral infrared imager specifically designed for flare monitoring (left: front view; right; rear view)

The imager is a “staring” imager instead of a scanning imager. All the pixels in the same frame are measured at exactly the same instance, so they are temporally synchronized. This is different from some other optical based multi-spectral measurement methods such as passive Fourier transform infrared (FTIR). Because all spectral bands for each pixel are captured in the identical instance, the signals for unburned hydrocarbons and combustion product are on the same basis and their relative strengths can be directly utilized to determine CE. The imager has a frame rate of 10-30 Hertz (Hz), meaning that a measurement cycle is completed in 0.033-0.10 seconds (33-100 milliseconds). Such a high frame rate can accommodate the rapid change of flare flame conditions in the atmosphere and therefore minimize potential distortion caused by less perfect temporal synchronization. The combination of the high frame rate, the perfect temporal synchronization across pixels and across the spectral bands enables measurement of relative levels of unburned hydrocarbons and combustion product (and therefore CE) without concern of mismatched spectral signals for CE measurement.

The 10-30 measurements in a second are averaged to provide a 1-second average CE value. With such a high data frequency, the problems associated with data latency in the GC Method (or to a lesser degree in the Calorimeter Method) discussed previously are drastically alleviated. The fast response time allows flare operators to adjust operating conditions (e.g., change the steam level, add/remove supplemental fuel, etc.) promptly, reducing the risk of non-compliance, minimizing the costs associated with steam and supplemental fuel, and minimizing the environmental impact (less emissions of conventional air pollutants and GHG).

Although this Direct CE Method directly measures flare CE, it has no direct contact with vent gases. The imager is installed at a distance (e.g., 100~1000 feet away from the flare depending on the size of the flare and the optics of the imager). It does not involve any calibration gases.

The entire system includes the imager, a single 110 V (or 220 V) power supply, and a small data communication box. The method to install the system is analogous to installation of an industrial grade security camera. The installation is completely independent from the operations of flare and processes that are connected to the flare. Operation and maintenance of the system is extremely simple. The only significant maintenance for the system will be to change the cooling system once every three years (or longer).

In addition to CE, the multi-spectral imager also provides other metrics that are useful to flare operators. One such metric is "smoke index" (SI). The SI increases monotonically with the level of smoke in the flare flame (Zeng, et. al., 2016). The SI can be used for two purposes. One application is for compliance with regulation 40 CFR 63.670 (h) – "Visible emission monitoring". This provision requires operators to (1) manually check, once a day, the presence of smoke using EPA Method 22, or (2) use a video surveillance camera (in the visible spectrum) to continuously record (at least one frame every 15 seconds with time and date stamps). The use of SI to determine the presence of smoke is a more robust method than either the human observation or the video camera recording because these two methods are not expected to be able to determine the presence of smoke at night. The SI is determined based on infrared characteristics of smoke and is not limited by daylight. However, a regulatory approval will be needed. Such approval is likely considering this method is more robust than the video camera method that has been allowed by the regulation.

The other use of the SI is to optimize the flare performance. For decades, steam assist or air assist has been used to reduce flare smoke. More recent research (Allen & Torres, 2011) has led to a conclusion that over assist will cause low CE and the best flare performance is when flare is operated at incipient smoke point (ISP). In practice, however, it is very difficult to operate the flare at or near ISP based on the operator's visual assessment of the flare smoke condition and it is virtually impossible to do so at night. The SI provides a tangible and objective metric to gauge the level of smoke day and night, even before smoke becomes visible. The combination of SI and CE in real time provides a practical tool to operate the flare at or near ISP conditions, optimizing the flare performance and minimizing air pollution.

Cost Analysis

Quantified Cost

A cost analysis for the three flare monitoring methods is presented in this section. The analysis is based on the following sources of relevant information:

- EPA Petroleum Refining Sector Docket (www.regulations.gov; Docket ID: EPA-HQ-OAR-2010-0682).
- Marathon Petroleum Company (MPC or Marathon). The cost data is from five Marathon refineries (20 flares). The MPC cost data can also be found in the above EPA docket.
- Information gathered by the authors.

Costs for implementing a flare monitoring system can be highly variable, especially for the GC or calorimeter-based methods due to their intrusive nature and differing site conditions. In addition to EPA and Marathon cost information, the authors of this paper also performed a cost analysis based on the authors' knowledge from installing, operating, and maintaining GC and calorimeter-based systems and extrapolated data to match what authors believe to be "normal" site conditions. It should be reiterated that the cost can vary significantly from site to site. This analysis represents the authors' best effort to characterize the costs associated with flare monitoring without complications arising from siting and installing the system.

According to statistics from EPA, 80% of the 510 flares affected by the Refinery RTR rule are steam assisted. This cost analysis focuses on the steam assisted flares.

The third flare monitoring method, the direct flare CE monitoring method (hereafter referred to as the "Direct CE Method"), is new and the associated equipment is just entering the market. Due to its remote sensing/non-contacting nature and simplicity in installation and operation, the cost for the Direct CE Method is essentially the cost of the multi-spectral flare monitor shown in Figure 1. The price for the multi-spectral flare monitor has not been announced. For the purpose of this analysis, a unit price of $600,000 is used.

This cost analysis addresses both capital costs and operating and maintenance (O&M) costs. The capital costs include equipment purchase, engineering, installation, start-up/commissioning, and other indirect costs. The annual O&M costs include labor, supplies/consumables, utilities, initial and periodic calibrations, and maintenance expenses. For each cost scenario, the initial capital cost is converted to the equivalent annual cost (EAC), which is combined with the annual O&M cost to arrive at a total annualized cost for comparisons among different flare monitoring methods with different information sources. The EAC is calculated using the equation below (Wikipedia, 2016):

$$EAC = \frac{NPV}{A_{t,r}}, \text{ where } A_{t,r} = \frac{1-\frac{1}{(1+r)^t}}{r} \qquad \text{Eq. 5}$$

Where NPV is the net present value, the initial capital cost in this case. $A_{t,r}$ is an annuity factor for equipment life span of t years and the "cost of capital" r. The cost of capital is the cost of a company's funds (both debt and equity), and it is used to evaluate new projects for a company. The cost of capital varies with time and from business sector to business sector. For this analysis, the "Cost of Capital by Sector" compiled by New York University Stern School of Business is used (Damodaren, 2016). Specifically, the cost of capital for the sector of "Oil/Gas (Integrated)" as of January 5, 2016 is 10.2% (i.e., r=10.2%). Different types of equipment have a different life time (t). As the time goes longer, the impact of each additional year to the cost analysis decreases. For the simplicity sake, a life time of 10 years is used (i.e., t=10), which is a reasonable estimate for the most expensive components of the system (e.g., the GC, calorimeter, multi-spectral imager, etc.).

Based on the methodology described above and the three different sources of information, a cost analysis is performed, and the results are presented in Figures 2, 3, and 4 for initial capital cost, annual O&M cost, and total annual cost (annualized capital cost and annual O&M cost combined), respectively. For the GC based method, five data points are presented: minimum, average, and maximum values from the five Marathon refineries (20 flares) ("MPC-GC-Min", "MPC-GC-Avg", and "MPC-GC-Max" in the figures), EPA analysis ("EPA-GC" in the figures), and this analysis ("This Analysis-GC" in the figures). None of Marathon refineries used calorimeter-based method. Therefore, there are only two data sources for the calorimeter-based method: EPA analysis ("EPA-Calorimeter" in the figures) and this analysis ("This Analysis-Calorimeter" in the figures). It is assumed that both a calorimeter and a hydrogen analyzer are needed for this method. For the direct flare CE monitoring method, two data points are given: one is based on the assumption that the direct flare monitor can cover only one flare ("Direct Monitor-1" in the figures) and the other is based on the assumption that the direct flare monitor can cover two flares ("Direct Monitor-2" in the figures).

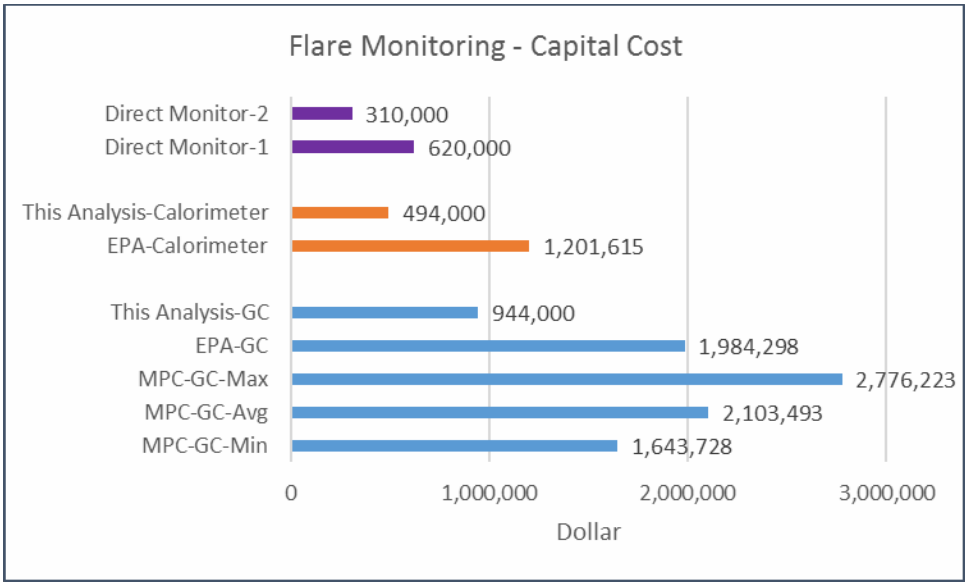

Figure 2. Capital cost of flare monitoring

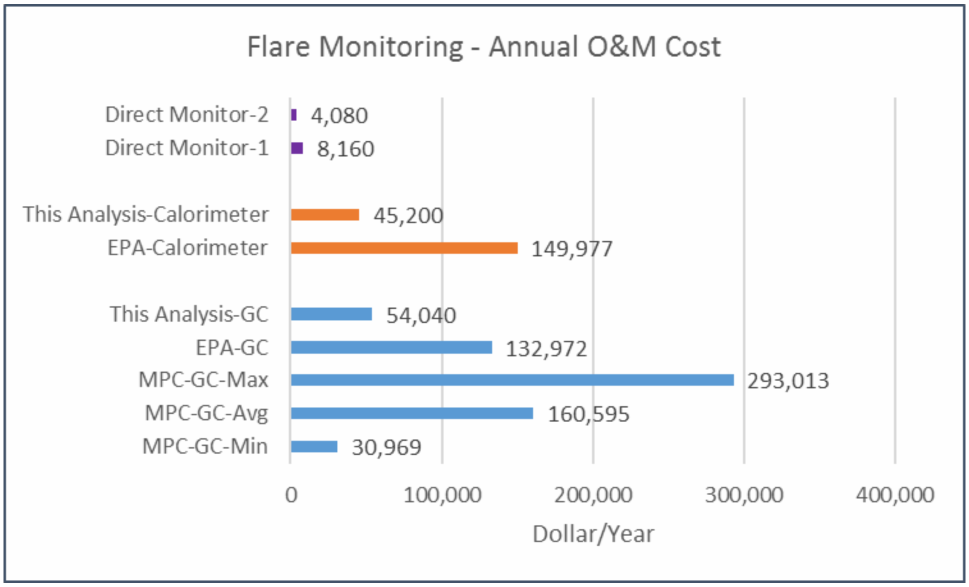

Figure 3. Annual O&M cost of flare monitoring

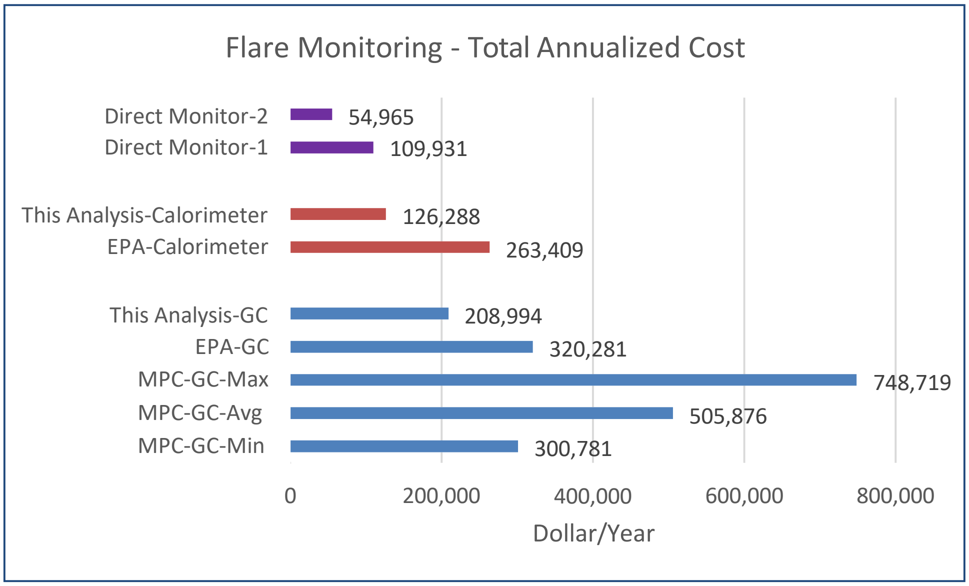

Figure 4. Total annual cost of flare monitoring (annualized capital and annual O&M combined)

Costs That Are Intangible or Difficult to Quantify

There are potential costs that are difficult to quantify. As discussed earlier, the latency associated with the GC based method (and to a lesser degree with the calorimeter-based method) has the potential to increase the risk of deviation from regulatory compliance. If and when compliance deviations occur, the costs to address the issue could be significant.

There is a potential to add more supplemental fuel than necessary. Based on the EPA estimate, the average cost for supplemental fuel is $98,660 per year per flare. This estimate was based on a natural gas price of $5/Mscf. The current natural gas price is in the neighborhood of $2.8/Mscf. Therefore, this fuel cost should be adjusted to $55,250. If the Direct CE Method is used and fuel usage is managed more promptly, there could be some cost savings due to the reduced consumption of supplemental fuel.

If the Direct CE Method is used, the required daily observation of flare visible emissions could be replaced without extra cost. The corresponding cost saving is not quantified.

Conclusion

Unlike most process equipment (such as process heaters, boilers, reactors, etc.), industrial flares have been historically operated with less instrumentation to provide feedback to operators. The indirect monitoring of flare CE through flare tip velocity and combustion zone net heating value is less than ideal and costly. The new method based on a specially designed multi-spectral infrared imager to directly monitor flare CE and simultaneously provide SI can provide the operator with a flare "dashboard" so that flare operation can be modernized and optimized, and emissions can be minimized. This instrument can also be integrated into the process control scheme and achieve a closed loop control for the flare operation. The cost analysis suggests that this new method can be a very cost competitive solution compared to the indirect monitoring methods.

References

Allen, D.T. and V.M. Torres, 2011. TCEQ 2010 Flare Study Final Report, prepared for TCEQ. PGA No. 582-8-862-45-FY09-04 with supplemental support from TCEQ Grant No. 582-10- 94300. http://www.tceq.texas.gov/assets/public/implementation/air/rules/Flare/2010flarestudy/2010- flare-study-final-report.pdf (accessed March 23, 2015).

Coburn, J. 2014. RTI Memorandum. EPA Petroleum Refinery Sector Docket. EPA-HQ-OAR- 2010-0682-0209. https://www.regulations.gov/document?D=EPA-HQ-OAR-2010-0682-0209 (accessed July 21, 2016).

Damodaran, A., 2016. "Cost of Capital by Sector (US)". New York University, Stern School of Business. http://people.stern.nyu.edu/adamodar/New_Home_Page/datafile/wacc.htm (accessed July 26, 2016).

USEPA, 2015a. *Federal Register*, 80 FR 75177, pp. 75177-75354. December 1, 2015.

USEPA, 2015b. Code of Federal Regulation, Title 40, Part 60, Subpart A, Section 60.18. 7-1-15 Edition.

Wikipedia, 2016. "Equivalent Annual Cost." https://en.wikipedia.org/wiki/Equivalent_annual_cost (accessed July 26, 2016).

Zeng, Y., J. Morris, and M. Dombrowski, 2016a. Validation of a new method for measuring and continuously monitoring the efficiency of industrial flare. J. of Air & Waste Mgmt. Assoc., Vol. 66, No. 1, pp. 76-86.

Zeng, Y., J. Morris, and M. Dombrowski, 2016b. Multi-spectral Infrared Imaging System for Flare Combustion Efficiency Monitoring, U.S. Patent No. 9,258,495.

Appendix

Appendix A: Cost Analysis Details - Marathon

Marathon - GC Based Systems
Ref. EPA-HQ-OAR-2010-0682-0209.pdf

MPC Catlettsburg, KY Refinery No. of Flares 4

Stream	Instrument	Qty.	Equipment Purchase	Materials: pi	Installation	Indirect	Start-up, initial	Engineering	Total Capital Cost	Operation (la	Maintenance (l	On-going cer	Utility	Taxes	Total Annual O&M Cost
Vent gas	Flow instrument (flow, temp, and pressure)	8	198,029	1,319,865	1,087,159	1,099,756	52,773	588,003	**4,345,585**	90,244	90,244	0	250,000	0	**430,488**
	GC to measure vent gas composition & heat content	5	1,959,249	251,397	300,217	259,548	52,773	456,664	**3,279,848**	46,496	68,000		200,000		**314,496**
Steam	Flow instrument to measure steam mass flow	4	93,361	699,938	542,735	518,482	52,773	328,103	**2,235,392**	47,882	47,882	0	200,000	0	**295,764**
	Total		2,250,639	2,271,200	1,930,111	1,877,786	158,319	1,372,770	**9,860,825**	184,622	206,126	0	650,000	0	**1,040,748**
	Per-flare		562,660	567,800	482,528	469,447	39,580	343,193	**2,465,206**	46,156	51,532	0	162,500	0	**260,187**

MPC Garyville, LA Refinery No. of Flares 4

Stream	Instrument	Qty.	Equipment Purchase	Materials: p	Installation	Indirect	Start-up, init	Engineering	Total Capital Cost	Operation (la	Maintenance (l	On-going ce	Utility	Taxes	Total Annual O&M Cost
Vent gas	Flow instrument (flow, temp, and pressure)	7	380,000	300,000	1,300,000	350,000	100,000	100,000	**2,530,000**	20,000	15,000				**35,000**
	GC to measure vent gas composition & heat content	4	350,000	850,000	400,000	100,000	500,000	100,000	**2,300,000**	25,000	15,000				**40,000**
Steam	Flow instrument to measure steam mass flow	4	125,000	250,000	1,750,000	400,000	100,000	100,000	**2,725,000**	20,000	15,000				**35,000**
	Total		855,000	1,400,000	3,450,000	850,000	700,000	300,000	**7,555,000**	65,000	45,000				**110,000**
	Per-flare		213,750	350,000	862,500	212,500	175,000	75,000	**1,888,750**	16,250	11,250				**27,500**

MPC Robinson, IL Refinery No. of Flares 6

Stream	Instrument	Qty.	Equipment Purchase	Materials: p	Installation	Indirect	Start-up, init	Engineering	Total Capital Cost	Operation (la	Maintenance (l	On-going ce	Utility	Taxes	Total Annual O&M Cost
Vent gas	Flow instrument (flow, temp, and pressure)	6	720,000	152,500	560,000	171,000	80,000	437,000	**2,120,500**	70,000	70,000	15,000	100,000		**255,000**
	GC to measure vent gas composition & heat content	4	2,078,000	274,000	1,039,000	400,000	46,000	1,272,000	**5,109,000**	70,000	90,000	32,000	70,000		**262,000**
Steam	Flow instrument to measure steam mass flow	4	213,000	212,000	393,000	257,000	12,000	441,000	**1,528,000**	35,000	35,000		75,000		**145,000**
	Total		3,011,000	638,500	1,992,000	828,000	138,000	2,150,000	**8,757,500**	175,000	195,000	47,000	245,000		**662,000**
	Per-flare		501,833	106,417	332,000	138,000	23,000	358,333	**1,459,583**	29,167	32,500	7,833	40,833		**110,333**

MPC Texas City, TX Refinery No. of Flares 2

Stream	Instrument	Qty.	Equipment Purchase	Materials: p	Installation	Indirect	Start-up, init	Engineering	Total Capital Cost	Operation (la	Maintenance (l	On-going ce	Utility	Taxes	Total Annual O&M Cost
Vent gas	Flow instrument (flow, temp, and pressure)	2	50,000	420,000	215,000	91,000		174,600	**950,600**	23,000	20,000	5,000	60,000		**108,000**
	GC to measure vent gas composition & heat content	2	500,000	167,000	180,000	93,000		172,200	**1,112,200**	24,000	24,000		55,000		**103,000**
Steam	Flow instrument to measure steam mass flow	2	100,000	138,000	497,000	136,000		210,000	**1,081,000**	2,000	2,000	5,000	40,000		**49,000**
	Total		650,000	725,000	892,000	320,000	0	556,800	**3,143,800**	49,000	46,000	10,000	155,000		**260,000**
	Per-flare		325,000	362,500	446,000	160,000	0	278,400	**1,571,900**	24,500	23,000	5,000	77,500		**130,000**

MPC Detroit, MI Refinery No. of Flares 4

Stream	Instrument	Qty.	Equipment Purchase	Materials: p	Installation	Indirect	Start-up, init	Engineering	Total Capital Cost	Operation (la	Maintenance (l	On-going ce	Utility	Taxes	Total Annual O&M Cost
Vent gas	Flow instrument (flow, temp, and pressure)	4	173,146	175,500	197,910	57,500	46,650	144,560	**795,266**	45,000	45,000		160,000		**250,000**
	GC to measure vent gas composition & heat content	4	1,450,068	1,421,550	1,603,050	465,750	377,820	1,301,040	**6,619,278**	55,000	55,000		150,000		**260,000**
Steam	Flow instrument to measure steam mass flow	4	89,481	87,750	98,950	28,750	23,320	72,280	**400,531**	45,000	45,000		140,000		**230,000**
	Total		1,712,695	1,684,800	1,899,910	552,000	447,790	1,517,880	**7,815,075**	145,000	145,000		450,000		**740,000**
	Per-flare		428,174	421,200	474,978	138,000	111,948	379,470	**1,953,769**	36,250	36,250		112,500		**185,000**

Per-flare Statistics - Total Cost (in 2010$)

	Capital Cost	Annualized Capital Cost	Annual O&M Cost	Total Annual Cost
Average	1,867,842	306,599	142,604	449,203
Minimum	1,459,583	239,585	27,500	267,085
Maximum	2,465,206	404,654	260,187	664,841

Per-flare Statistics - Total Cost (in 2016$)

Assumed avg. annual inflation rate 2%

	Capital Cost	Annualized Capital Cost	Annual O&M	Total Annual Cost
Average	2,103,493	345,281	160,595	505,876
Minimum	1,643,728	269,812	30,969	300,781
Maximum	2,776,223	455,707	293,013	748,719

GC-Based System

Ref. EPA-HQ-OAR-2010-0682-0209.pdf, Table 7

Per-flare Cost (in 2010$)

Stream	Instrument	Capital Cost	Annualized Capital Cost	Annual O&M Cost	Total Annual Cost
Vent gas	Flow instrument (flow, temp, and pressure)	440,000	41,540	39,210	80,750
	GC to measure vent gas composition & heat content	980,000	92,500	49,000	141,500
Steam	Flow instrument to measure steam mass flow (a)	342,000	32,285	29,865	62,150
	Total	1,762,000	166,325	118,075	284,400

(a) This line item in the EPA report (Table 7) includes both steam control and measurement.
Based on the underlying info, the measurement portion is generally > 50% of the total values used by EPA.
For this analysis, 50% of the values are assigned to measurement.

Per-flare Cost (in 2016$)

Assumed avg. inflation rate	2%

Stream	Instrument	Capital Cost	Annualized Capital Cost	Annual O&M Cost	Total Annual Cost
Vent gas	Flow instrument (flow, temp, and pressure)	495,511	46,781	44,157	90,938
	GC to measure vent gas composition & heat content	1,103,639	104,170	55,182	159,352
Steam	Flow instrument to measure steam mass flow (a)	385,148	36,358	33,633	69,991
	Total	1,984,298	187,309	132,972	320,281

(a) This line item in the EPA report (Table 7) includes both steam control and measurement.
Based on the underlying info, the measurement portion is generally > 50% of the total values used by EPA.
For this analysis, 50% of the values are assigned to measurement.

Calorimeter Based System

Ref. EPA-HQ-OAR-2010-0682-0209.pdf, Table 7

Per-flare Cost - with Hydrogen Analyzer (in 2010 $)

Stream	Instrument	Capital Cost	Annualized Capital Cost	Annual O&M Cost	Total Annual Cost
Vent gas	Flow instrument (flow, temp, and pressure)	440,000	41,540	39,210	80,750
	Calorimeter & H2 analyzer to measure NHVvg	285,000	26,900	64,100	91,000
Steam	Flow instrument to measure steam mass flow (a)	342,000	32,285	29,865	62,150
	Total	1,067,000	100,725	133,175	233,900

(a) This line item in the EPA report (Table 7) includes both steam control and measurement.
Based on the underlying info, the measurement portion is generally > 50% of the total values used by EPA.
For this analysis, 50% of the values are assigned to measurement.

Per-flare Cost - with Hydrogen Analyzer (in 2016 $)

Assumed avg. inflation rate	2%

Stream	Instrument	Capital Cost	Annualized Capital Cost	Annual O&M Cost	Total Annual Cost
Vent gas	Flow instrument (flow, temp, and pressure)	495,511	46,781	44,157	90,938
	Calorimeter & H2 analyzer to measure NHVvg	320,956	30,294	72,187	102,481
Steam	Flow instrument to measure steam mass flow (a)	385,148	36,358	33,633	69,991
	Total	1,201,615	113,433	149,977	263,409

(a) This line item in the EPA report (Table 7) includes both steam control and measurement.
Based on the underlying info, the measurement portion is generally > 50% of the total values used by EPA.
For this analysis, 50% of the values are assigned to measurement.

Appendix D: Cost Analysis Details – This analysis

GC Based System

Stream	Instrument	Capital Cost	Annualized Capital Cost	Annual O&M	Total Annual Cost
Vent gas	Flow meter	150,000	24,622	7,640	32,262
	Temp sensor	16,000	2,626	540	3,166
	Pressure sensor	16,000	2,626	540	3,166
	Online GC	650,000	106,695	42,300	148,995
Steam	Flow meter	24,000	3,940	760	4,700
	Temp sensor	16,000	2,626	540	3,166
	Pressure sensor	16,000	2,626	540	3,166
Suppl. Fuel	Flow meter	24,000	3,940	430	4,370
	Temp sensor	16,000	2,626	375	3,001
	Pressure sensor	16,000	2,626	375	3,001
Total		**944,000**	**154,954**	**54,040**	**208,994**

Calorimeter Based System

Stream	Instrument	Capital Cost	Annualized Capital Cost	Annual O&M	Total Annual Cost
Vent gas	Calorimeter	150,000	24,622	21,160	45,782
	Hydrogen Analyzer	50,000	8,207	12,300	20,507
All other cost items as in GC based system		294,000	48,259	11,740	59,999
Total		**494,000**	**81,088**	**45,200**	**126,288**

Direct Flare CE & SI Monitor

Stream	Instrument	Capital Cost	Annualized Capital Cost	Annual O&M	Total Annual Cost
Flare	Direct Flare Monitor	620,000	101,771	8,160	109,931
Additional Cost Saving - If two flares can be covered by one director monitor					
		310,000	50,885	4,080	54,965

Assumptions for this Analysis – GC Method

Stream	Instrument	Assumptions
Vent Gas	Flow meters	Dual flow meters to cover large turndown ratio For O&M: • Labor: 28 hours @ $55/hr • External calibration of flow meter: $6,100 • Includes regulatory quarterly inspections and other op. expenses
	Temperature sensor	For O&M: • Labor: 2 hour per quarter @ $55/hr
	Pressure sensor	For O&M: • Labor: 2 hour per quarter @ $55/hr
	Online GC	For O&M: • Labor: 5 hours per week @ $55/hr • Supplies: 4 calibration bottles per quarter at $1,500 per bottle • Misc: $4,000 per year for misc. maintenance items
Steam	Flow meter	For O&M: • Labor: 3 hour per quarter @ $55/hr
	Temperature sensor	For O&M: • Labor: 2 hour per quarter @ $55/hr
	Pressure sensor	For O&M: • Labor: 2 hour per quarter @ $55/hr
Supplemental fuel	Flow meter	For O&M: • Labor: 1 hour per quarter @ $55/hr
	Temperature sensor	For O&M: • Labor: 1 hour per quarter @ $55/hr
	Pressure sensor	For O&M: • Labor: 1 hour per quarter @ $55/hr

Assumptions for this Analysis – Calorimeter Method

Stream	Instrument	Assumptions
Vent Gas	Calorimeter	For O&M: • Labor: 2 hours per week @ $55/hr • Supplies: 2 calibration bottles per quarter at $1,500 per bottle • Misc: $3,000 per year for misc. maintenance items
	Hydrogen Analyzer	For O&M: • Labor: 60 hours @ $55/hr • Supplies: 1 calibration bottle per quarter at $1,500 per bottle • Misc: $2,000 per year for misc. maintenance items
Steam	All	Same assumptions as GC method. See previous table.
Supplemental fuel	All	Same assumptions as GC method. See previous table.

Assumptions for This Analysis – Direct Flare CE and SI Monitor

Stream	Instrument	Assumptions
Post combustion gases	Direct flare monitor	Equipment price assumed to be $600,000 Installation costs are minimal, assumed to be $20,000 For O&M: • Labor: 1 hour per month @ $55/hr • Supplies: Assumes cyro-cooler replacement twice during 10 years lifespan of instrument