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Remote Measurement of Flare Gas Flow Rate Using a Video Imaging Spectral Radiometer

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INTRODUCTION

Flares are commonly used at industrial facilities (e.g., oil and gas extraction and production sites, gas processing plants, oil refineries, and petrochemical manufacturing plants) to safely dispose of process gases (i.e. waste gases). Waste gases may be produced due to process upset or because they are unrecoverable for technical or economic reasons. When waste gases are combustible, sending them to a flare is a safe way to dispose of them. Environmental and safety regulations prohibit discharge of such waste gases into the atmosphere without being treated by a flare because of their potential fire hazard and negative effects on human health and the environment. Flares are designed to destroy the waste gases by combusting them into harmless or less harmful gases (e.g., hydrocarbons being combusted into water vapor and carbon dioxide). When waste gases reach the flare tip, a pilot flame positioned at the flare tip ignites the gases. With oxygen from ambient air, the waste gases are combusted and destroyed.

Flares are subject to environmental regulations that requires good combustion efficiency and no visible emissions. Some federal and state regulations also require flare operators to monitor flare gas flow rate for the purpose of calculating combustion zone net heating values, tracking emissions, or determining flaring events. Flare gas flow rate measurement is also needed for flare operation purposes, for example it may be used to determine proper level of steam or air assist. Current methods for flare gas flow measurement include ultrasonic, thermal, and optical flow measurement instruments. There are multiple challenges facing flare gas flow measurement, including low allowance for pressure loss, wide dynamic range, change in gas compositions, etc. Many of these instruments suffer low accuracy in the lower portion of their measurement range.

A method called Video Imaging Spectral Radiometry (VISR) has been developed to monitor flare combustion efficiency and smoke level (Zeng, et. al. 2016a and 2016b). The authors believe that the information captured by a VISR device can also be used to measure flare gas flow rates in addition to the flare combustion efficiency and smoke level. This concept has been tested and the results of the first field test for this method are presented in this paper.

MEASUREMENT PRINCIPLE

The VISR device is a radiometrically calibrated multi-spectral imager. The radiance emitted by the flare is quantitatively measured by the VISR device and expressed in the unit of Watts per solid angle (in radians) per square meter of the surface area of the flare combustion gas volume and per wavelength ($W \cdot sr^{-1} \cdot m^{-2} \cdot \mu^{-1}$). Because the wavelengths are fixed, the measurement can also be expressed in $W \cdot sr^{-1} \cdot m^{-2}$. The VISR device is calibrated using a blackbody designed for Infrared radiance measurement instruments.

The flare radiance can be measured by the VISR device based on the optical properties of the VISR device (which is fixed) and the distance from the VISR device to the flare to derive the flare's spectral power P in Watts (W) or kilowatts (kW). The spectral power P is a fraction of the total energy released per unit of time by the flare combustion in the spectral region covered by the VISR device, and therefore it is proportional to the total energy (or heat) released per unit of time by the flare combustion. It is also proportional to the total net heating value carried by the gases sent to the flare (or total heat input to the flare) due to expected combustion. The flare total heat input, H, in Btu/hr can be calculated by the following equation:

$$H = a \cdot P \qquad \text{Eq. (1)}$$

The term "a" is the proportionate constant, and it represents the fraction of the heat release in the spectral region measured by the VISR device vs. the flare's total heat release across the entire spectral range. It may also reflect other factors affecting the measurement. If the net heating value (NHV) of the flare gas (in Btu/lb) is known, the flare gas flow rate, Q, in bl/hr can be calculated based on the total heat input, H:

$$Q = \frac{1}{NHV} H = \frac{a}{NHV} P \qquad \text{Eq. (2)}$$

To measure flare gas flow rate, the VISR device should be placed at such a distance that the entire flare flame's thermal footprint is captured by the camera's field of view with no objects between the flame and the camera that may block the IR radiance from the flare to the VISR device. The VISR device captures flare images in radiance. Each pixel measures the radiance coming from a column of gases in the flare. Using image processing algorithms, the radiances at the pixel level are tallied to obtain the total spectral power P from the flare. The VISR optical properties and the distance from the VISR device to the flare are used to correctly calculate the spectral power P. The VISR device operates at a frame rate up to 30 Hertz (i.e., about 33 milliseconds per measurement). The results are averaged within 1 second and can be further averaged in other timeframes as needed.

EXPERIMENT SETUP

A series of tests were conducted at the John Zink Company, LLC (John Zink) R&D Test Center in Tulsa, Oklahoma on December 5th, 2018. Figure 1 shows the test setup. The flare used in this test was a steam assisted flare, the same one used in the 2010 flare study commissioned by TCEQ (Allen and Torres, 2011) and in the 2016 flare remote sensing test program sponsored by Petroleum Environmental Research Forum (PERF) (Morris, et. al., 2019). The VISR device was positioned east southeast of the flare at a distance of 410 feet. Wind was blowing from the south.

Figure 1: Site map showing the locations of the flare and the VISR device during the initial flare flow rate test.

During the flare flow rate test, natural gas was used to simulate flare process gases. The natural gas was sent to the flare at different flow rates while the steam flow rate was held constant. The flow rate of the natural gas going to the flare was measured by John Zink using an orifice metering system designed in accordance to ANSI standards. The orifice plate and orifice flanges were certified to meet all applicable procedures and specifications. All flow measurements were fully compensated for pressure and temperature. Although orifice flowmeters are not used in most flares at production facilities due to the significant pressure loss across the orifice, it is more accurate and reliable than other methods such as ultrasonic flow meters, and it is most suitable in this R&D setting.

RESULTS AND DISCUSSIONS

Correlation and Linearity

A series of tests were conducted to confirm the expected correlation and linearity between the flare gas flow rate Q and the flare spectral power P measured by the VISR device as described by Eq. (2). In this set of tests, natural gas was sent to the flare at five different flow rates (1000, 2000, 4000, 6000, and 8,000 lb/hr). The steam flow rate was held constant at approximately 1730 lb/hr. The VISR device, designated as "VISR3", was used to monitor the flare performance and to measure the spectral power of the flare. The relationship between the measured flare spectral power and flare gas flow rate are presented in Figure 2. Figure 2 also includes a plot showing relationship between the measured flare spectral power and the flare total heat input, which will be further discussed later in this paper. Figure 2 shows excellent correlation and linearity, and therefore demonstrates the feasibility of using the VISR to remotely monitor the flare gas flow rate.

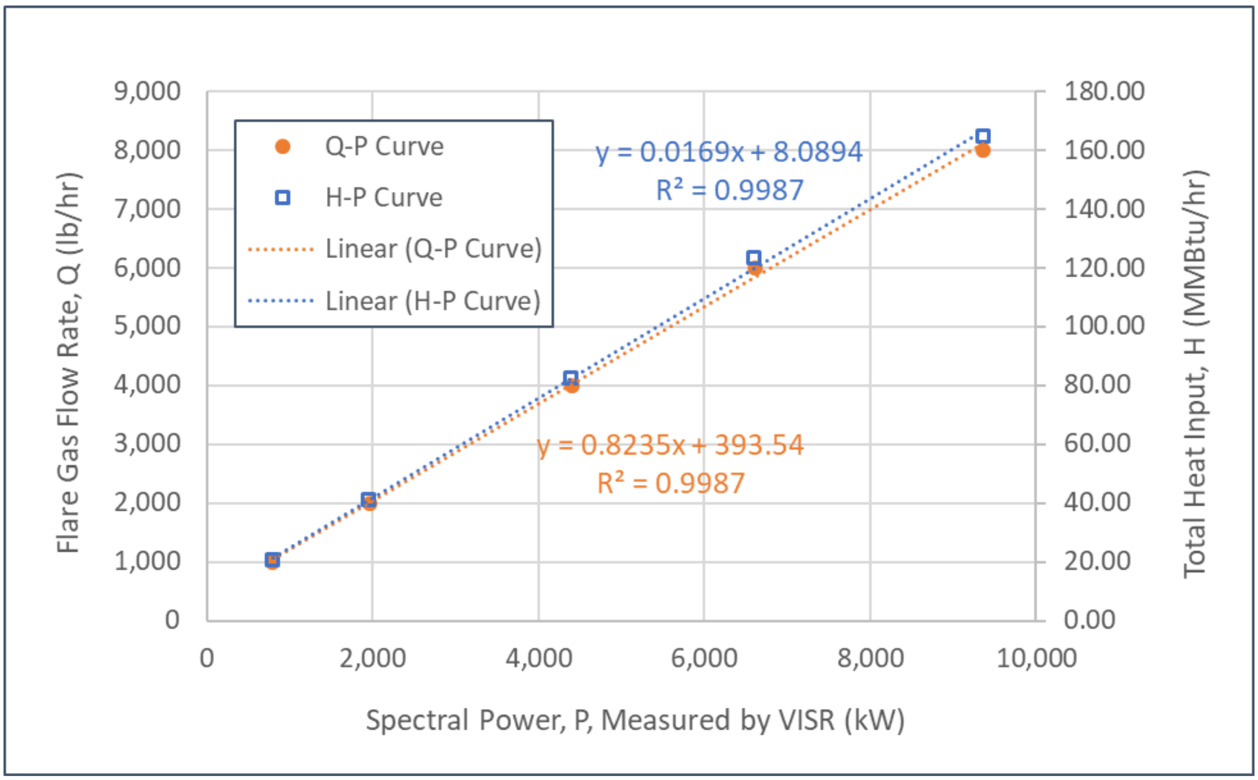

Figure 2: Spectral power (P) measured by VISR vs. flare gas flow rate (Q) measured by the orifice metering system per ANSI standard.

Test Cases

With a strong linear relationship, Figure 2 can be used as a calibration curve for this flow measurement method. There were other tests conducted at this site the day before (12/4/2018) for a different purpose. The data from those tests was used as an assessment of the accuracy and precision of this new flare gas flow measurement method. The results of applying this new method to the test data captured on 12/4/2018 are summarized in Table 1 and Table 2. Table 1 includes tests that were conducted when the flare was operated under design conditions (normal flare operating conditions). Table 2 includes tests that were conducted when the flare was operated under over-steam conditions (low combustion efficiency). The tests were numbered 1 through 15. Tests 2, 5, 8, 11, and 14 were transitions from normal flare operating conditions to over-steam conditions or vice versa, and they were not intended for targeted measurement therefore are not included in the study. Two VISR devices (designated as "VISR2 and VISR3) were used in each of the tests. The two VISR devices were paired to measure the same flare conditions. For Tests 1, 3, and 15, the two VISR devices were co-located at the same position. For other tests, the two VISR devices were located in different positions (different distances or viewing angles, or both). The position of each VISR device is identified by a number listed in Tables 1 and 2 under the column heading of "VISR Position". The position identified by these numbers are shown in the site map in Figure 3.

Table 1: Flare gas flow rate measured by VISR when the flare was operating with normal steam conditions.

Test ID	VISR ID	VISR Position	Distance (ft)	True Flow Rate (lb/hr)	Flow Rate Measured by VISR (lb/hr)	Error (%)	Difference between Paired VISR's (%)	Co-located?
1	VISR2	2	200	1,000	1,014	1.37%	-0.89%	Yes
	VISR3	2	200	1,000	1,023	2.28%		
6	VISR2	3	400	1,000	1,037	3.74%	3.11%	
	VISR3	2	200	1,000	1,006	0.57%		
7	VISR2	4	200	1,000	973	-2.66%	-5.17%	
	VISR3	2	200	1,000	1,025	2.51%		
12	VISR2	5	400	1,001	1,065	6.42%	7.83%	
	VISR3	2	200	1,001	985	-1.60%		
13	VISR2	2	200	1,000	987	-1.27%	0.25%	Yes
	VISR3	2	200	1,001	985	-1.52%		
Average					1,010	0.98%		
SD					29			
RSD					2.83%			

Table 2: Flare gas flow rate measured by VISR when the flare was over-steamed.

Test ID	VISR ID	VISR Position	Distance (ft)	True Flow Rate (lb/hr)	Flow Rate Measured by VISR (lb/hr)	Error (%)	Difference between Paired VISR's (%)	Co-located?
3	VISR2	2	200	1,000	916	-8.39%	-0.62%	Yes
	VISR3	2	200	1,000	922	-7.82%		
4	VISR2	3	400	1,000	1,001	0.10%	3.10%	
	VISR3	2	200	1,000	970	-2.95%		
9	VISR2	4	200	1,002	984	-1.81%	6.82%	
	VISR3	2	200	1,002	919	-8.29%		
10	VISR2	5	400	1,003	1,087	8.36%	4.73%	
	VISR3	2	200	1,003	1,037	3.35%		
15	VISR2	2	200	1,001	1,004	0.26%	1.69%	Yes
	VISR3	2	200	1,001	987	-1.43%		
Average					983	-1.86%		
SD					55			
RSD					5.56%			

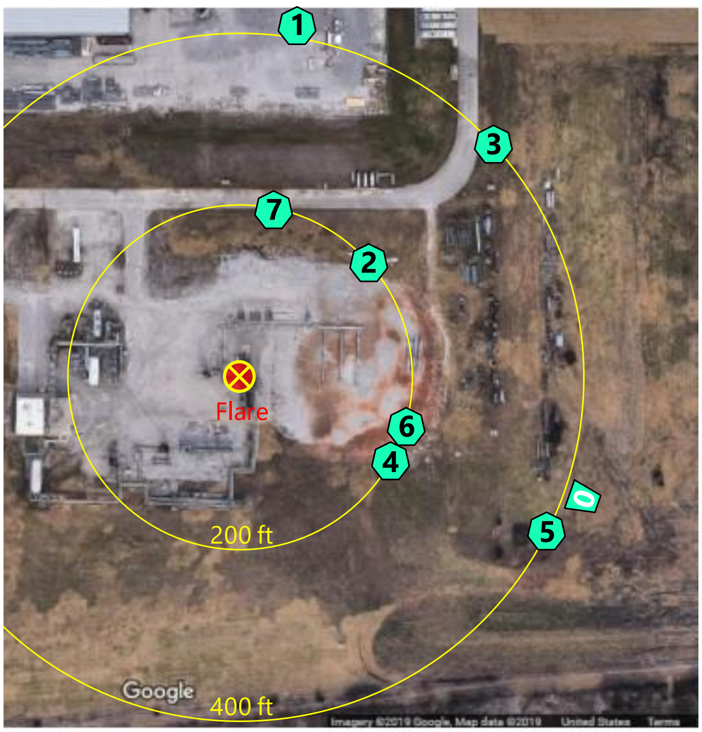

Figure 3: Site map showing the locations of the flare and the VISR devices during additional flare flow rate tests.

In both Tables 1 and 2, the “True Flow Rate (lb/hr)” was the flow rate measured by the orifice metering system. The flow rates measured by the VISR method are compared to the true flow rates and percent errors are calculated and presented in Tables 1 and 2. For the flare operating with normal conditions (Table 1), the errors are in the range of -2.66% to 6.42% with an average of 0.98%. With the exception of Test 12 VISR 2 results, all test errors are within +/- 4%. From the perspective of precision or repeatability, the 10 measurements for the same flow rate in Table 1, the relative standard deviation (RSD) is 2.83%. These 10 measurements include measurements at different distances or viewing angles. When the two VISR devices were co-located at a distance of 200 feet from the flare, the differences between the two measured flow rates are less than 1%.

When the flare was over-steamed, both the errors and the standard deviation are higher (less accurate and lower precision), as shown in Table 2. The errors are in the range of -8.39% to 8.36% with an average error of -1.86%. The relative standard deviation (RSD) of the 10 measurements is 5.56%.

Gas Composition

A plot of flow rate Q vs. spectral power P (or the Q-P curve as shown in Figure 2), which is based on Eq. (2), can be used as a calibration curve for this flow measurement method. Alternatively, a plot of flare total heat input H vs. spectral power (or a H-P curve, also plotted in Figure 2) as described by Eq. (1) can be constructed as a calibration curve, which could be even more versatile. Developing the calibration curve using total heat input H vs. spectral power would mean that the equation does not need to be changed when the gas composition changes. Gas composition changes may cause the gas NHV to change, but that can be adjusted outside of the calibration equation using a simple conversion from H (Btu/hr) to Q (lb/hr) based on the NHV (Btu/lb) of the gas mixture [see Eq. (2)].

It should be noted that the NHV, expressed in Btu/lb, of common hydrocarbons are very close to each other (ranging from 19,300~21,400 Btu/lb for C1-C5 compounds), i.e., the differences between the extreme cases are within +/- 6%. Even a substantial deviation in gas composition (excluding diluents such as nitrogen and water vapor) from an expected composition may cause no significant change (or only a few percentage points) in NHV of the gas mixture excluding diluents. Therefore, a Q-P based calibration like the Q-P curve in Figure 2 may be used as a generic calibration curve without adjusting for composition fluctuation. However, in scenarios where a more accurate method is desired, a H-P based calibration can be used to measure flare total heat input H and the flow rate Q can be calculated from H using a specific NHV.

Notes on the Method

This flow measurement method is different from other commercially available flow measurement methods and instruments. It is based on the Infrared (IR) radiance emitted from the combustion gases. It can be referred to as “radiometric flow measurement method” (the instrument based on this method can be called “radiometric flowmeter”). There are several properties or characteristics about this method that are worth mentioning:

- The method only measures the mass flow rate of the hydrocarbons in the flare gases. The components in the flare gas mixture that do not combust (e.g., nitrogen, water vapor) are irrelevant and are ignored. The flow rate measured by this method could be a fraction of the flow rate measured by conventional methods because conventional methods measure total flow (e.g., nitrogen, water vapor, etc. are included). This feature could be beneficial to the end use of the measured data because in most cases hydrocarbons are the compounds of environmental concern (e.g., for Greenhouse gas reporting). If significant levels of hydrogen are present in the flare gas, it will contribute to the heat release from the flare. Its impact to this method will require further study.
- The method requires combustion. The method performs well when the combustion is good. When the combustion is poor, the method suffers both lower accuracy and lower precision as indicated in Table 2. The results in Table 2 reflect the method performance when combustion efficiency was as low as 90% (compared to the test cases in table 1 where combustion efficiency was above 98%). Further study is planned to gain a deeper understanding of the effect of flare combustion efficiency on the measured spectral power. The outcome of the further study may lead to a better method to compensate for this effect. In the extreme scenario where the flare gas reaches the flare tip without being combusted, the method will only account for the contribution from the pilots if the pilots are lit and occupy at least multiple pixels in the VISR device.
- This is a remote sensing method. The VISR device can be positioned anywhere from 100 to over 1,000 feet away from the flare.
- Unlike most other flowmeters, this method directly measures hydrocarbon mass flow rate. If so desired, the hydrocarbon mass flow rate can be converted to a volumetric flow rate at the standard condition. This means that no additional instruments are needed for the purpose of temperature and pressure compensation when converting a volumetric flow rate to mass flow rate (as required by other methods).
- The VISR method has been developed and validated to monitor flare combustion efficiency and smoke level (Morris, et. al., 2019a and 2019b). Before this flow measurement method was developed, the emission rate from the flare could not be determined by a VISR device alone as there wasn’t an internal way to determine the flow rate. Determining the emission rate required both a VISR device and a flare flow meter. With this flow measurement capability added, a VISR device can now become a comprehensive “all-in-one” flare monitoring instrument that remotely monitors flare combustion efficiency, flare gas flow rate, mass emission rate (calculated from flow rate and combustion efficiency), visible emissions, and the presence of the pilot flame. It could replace a suite of flare monitoring instruments, including online GC/calorimeter/MS, flowmeter/temperature/pressure sensors for flare gas line, flowmeter/temperature/pressure sensors for steam assist line or air assist line, and flowmeter/temperature/pressure sensors for supplemental fuel line.

- The initial work presented in this paper represents the radiometric flow measurement method implemented in the VISR devices. However, the method may be implemented using other radiometrically calibrated Infrared cameras that are less expensive than the VISR system. The development of such a system is underway.

CONCLUSIONS AND FUTURE WORK

A proof of concept has been demonstrated that, in addition to monitoring flare combustion efficiency and smoke level, a Video Imaging Spectral Radiometry (VISR) device can be used to remotely measure flare gas flow rate. Based on ad hoc testing of 10 test cases for a steam assisted flare, the average error comparing to an ANSI standard reference method is 0.98% with a relative standard deviation (RSD) of 2.83% for flares operating at design conditions. When flare is over-steamed (low combustion efficiency), both the average error and RSD are higher, -1.86% and 5.56%, respectively.

This new method (referred to as “radiometric flowmeter” method) measures hydrocarbon mass flow rate to the flare. It excludes inert gas components such as nitrogen, water vapor, etc. Adding this radiometric flowmeter method to a VISR device means that a single device can calculate the mass emission rate of hydrocarbons and greenhouse gases from the flare.

More comprehensive testing is needed to assess this new radiometric flowmeter method. Future testing will evaluate a wider dynamic range, a wider range of distance between the flare and the VISR device, different gas compositions (including effect of dilluents), different flare types (steam assisted, air assisted, pressure assisted and non-assisted flares), and the impact of hydrogen in the flare gases. Repeated testing will also be done to further assess the accuracy and precision of the method.

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