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Title

PERF Project 2014-10 Results and Analysis of the VISR Method for Remote Flare Monitoring

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Abstract

The Petroleum Environmental Research Forum (PERF) is a non-profit organization created to provide a stimulus to and a forum for the collection, exchange, and analysis of research information relating to the development of technology for health, environment and safety; waste reduction; and system security in the petroleum industry. PERF project 2014-10 (Test) was created by participating PERF companies to provide a test platform for various developers/vendors of flare remote sensing technologies (Invitees) to participate in a blind test to evaluate the effectiveness of each technology. A total of 45 test points were evaluated over 10 days of testing. Extractive sampling was performed on each test point to provide a measurement for comparison with the various technologies brought by Invitees. This paper will examine the results of the Video Imaging Spectral Radiometry (VISR) portion of those tests and previous testing of the VISR method.

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 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 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% and above for CE and 98% and above 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).

On December 1, 2015, the U.S. EPA promulgated a rule for petroleum refineries following a lengthy Risk and Technology Review (RTR) process as required by the 1990 Clean Air Act Amendment; that rule will hereafter be referred to as the Refinery RTR Rule (USEPA, 2015a). The rule imposes new requirements for continuously monitoring flares 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 more strict definitions of the surrogate parameters, i.e., changing NHV_{vg} to Combustion Zone Net Heating Value (NHV_{CZ}). To comply with the new rule, an on-line gas chromatograph (GC) or calorimeter is needed to monitor NHV_{vg} (at least one data point in 15 minutes). 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), also 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 are to continuously monitor (having at least one data point every 15 minutes) and react to these online analyzers to keep the flare in compliance. In addition to the high cost of these continuous monitors, recent studies have found that using NHV_{CZ} as a surrogate compliance parameter has the potential to over-regulate (i.e., surrogate parameters are not meeting the regulatory requirements but the CE is above the intended level), creating unmerited deviations from the regulation and unnecessary use of supplemental fuel gas (Zeng and Morris, 2017). The petroleum industry has expressed the desire to use a method that directly measures flare CE without using these expensive and potentially erroneous indirect monitoring technologies.

Recognizing a Need to Determine Actual CE

The Petroleum Environmental Research Forum (PERF) is a non-profit organization created to provide a stimulus to and a forum for the collection, exchange, and analysis of research information relating to the development of technology for health, environment and safety; waste reduction; and system security in the petroleum industry. Recognizing the need for a more efficient method to determine the actual CE, PERF project 2014-10 (Test) was created by participating PERF companies to provide a test platform for various developers/vendors of flare remote sensing technologies (Invitees) to participate in a blind test to evaluate the effectiveness of each technology.

The Test was administered by John Zink Hamworthy Combustion and was conducted at their research and test facility in Tulsa, OK. Testing began on October 17th, 2016 and continued for 10 days. A test protocol was developed which identified a series of test conditions to evaluate various factors. Some logistical and environmental factors were shared with the Invitees (such as distance from the flare, sun in field of view, daytime/nighttime testing) but the specific flare conditions were not shared. Invitees were not provided with any information regarding the fuel gas used, firing rates, steam rates, or any other flare operating parameters. A total of 45 test points were evaluated over the 10 days of testing. Extractive sampling was performed on each test point to provide a measurement for comparison with the various technologies brought by the Invitees. A method based on Video Imaging Spectral Radiometry (VISR) which has been developed for testing or continuously monitoring combustion efficiency (CE) of industrial flares was included in the PERF tests.

Similar testing was conducted at Zeeco, Inc in September of 2016. The results of those tests are included in the analysis.

TEST FACILITY AND TESTING PROTOCOL

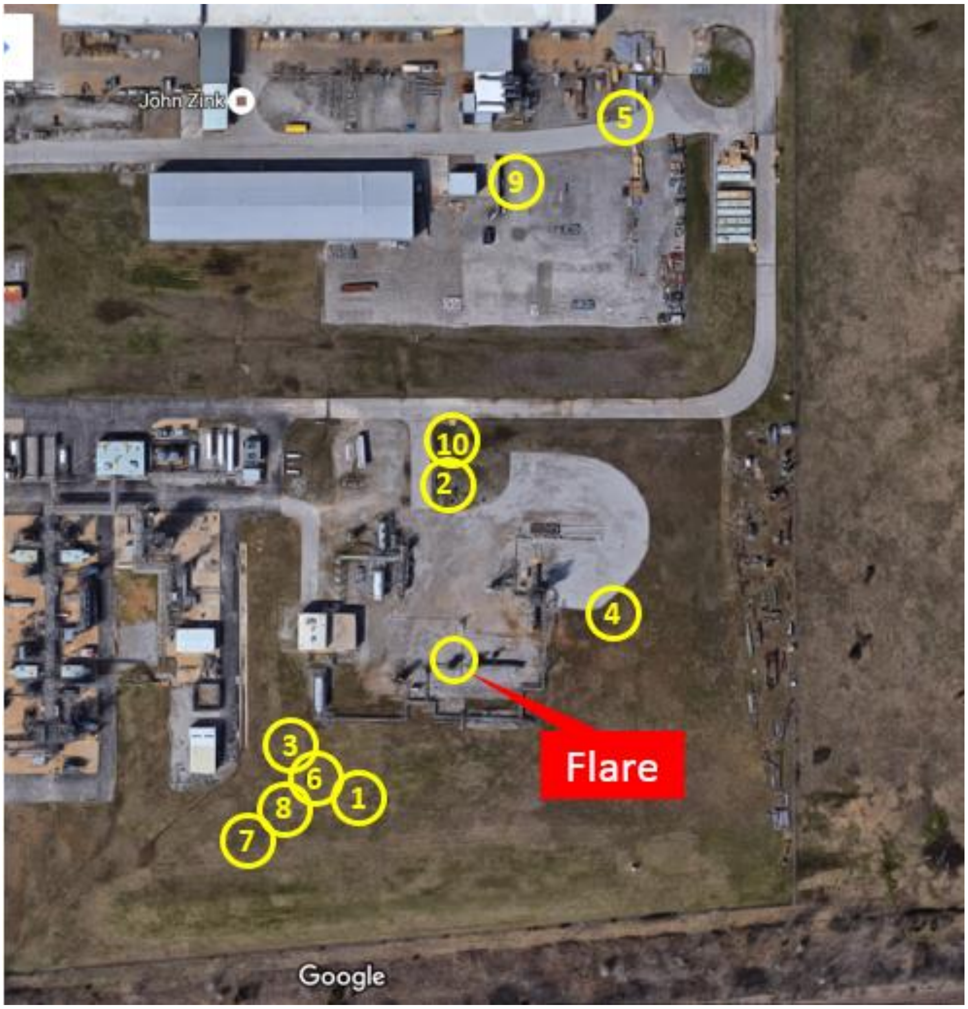


Figure 1: *Test facility with VISR positions used throughout the Test.*

Except for Test Points 31 and 45, each test point consisted of seven 10-minute segments:

- Extractive sampling 1 (E1), 10 minutes
- Remote measurement 1 (R1), 10 minutes
- Extractive sampling 2 (E2), 10 minutes
- Remote measurement 2 (R2), 10 minutes
- Extractive sampling 3 (E3), 10 minutes
- Remote measurement 3 (R3), 10 minutes
- Extractive sampling 4 (E4), 10 minutes

VISR METHOD AND EXPERIMENTAL SETUP

The VISR flare monitor is a remote monitoring device that can be positioned at any distance provided the flare to be monitored is in the line of sight and there are a sufficient number of pixels of the flare flame image in the VISR monitor. The distances from flare to the VISR monitor in the experiments reported here ranged from 174 feet to 650 feet. To evaluate the performance of the VISR method, an extractive sampling system was used as a reference method. A sample extraction apparatus was suspended by a crane over the flare plume to extract combustion product gases. The sample was transported through a heated sampling line to a sample manifold in a testing trailer. The sample manifold was connected to analyzers for oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), and hydrocarbon (HC). The methods for measuring O_2, CO_2, CO, and HC were EPA Method 3A, 3A, 10, and 25A, respectively. The level of O_2 was used to confirm that the sampling probe was in the flare plume.

The VISR method is designed for continuous and unattended operation, so setting up the system for a short term test was quite straightforward. The imager was placed on a tripod with a clear line of sight to the flare tip. The distance from VISR to the flare tip was adjusted per the test protocol, but the system can operate within a wide range of distances. There were no specific concerns regarding the background conditions which affected the placement of the VISR, although two of the test points specifically required that the sun be in the field of view for the imager. A laptop computer was connected to the VISR during the test to capture and archive raw data from the imager. Setting up the VISR system took approximately ten minutes.

Figure 2: *Typical VISR setup during the Test.*

These test campaigns covered a wide range of process conditions: multiple vent gas compositions (natural gas, propane, propylene, hydrogen, in pure form or mixed with nitrogen); vent gas flow range from 10 lb/hr to 10,000 lb/hr; various steam and air assist levels resulting in combustion zone net heating value (NHVcz) in a range of 120 to 1,250 Btu/scf.

The test campaigns also covered a wide range of environmental conditions: distance ranging from 174 ft. to 650 ft.; different wind speed and direction (crosswind, wind oriented towards VISR device, and wind oriented away from VISR device); daytime vs. nighttime; various sky conditions (blue sky, cloudy, moving clouds); the sun in or out of field of view; rain, and fog.

BLIND TEST RESULTS

The blind test results of the PERF test are summarized in **Table 1** below. The columns under the Extractive Method in **Table 1** are minimum, maximum, and average of the four CE values measured by the Extractive Method in four extractive segments. The column labeled as “Difference” is the difference between the average CE of the VISR Method and the Extractive Method.

The average difference across all Test Nos. in **Table 1** is -1.2%. Upon further review of the flare images, it has been observed that the largest differences between the two methods were caused by reflections from equipment located less than 10-20 feet from the test flare. The configuration of the test facility is unique in that the flare tip is located close to the ground and there were other stacks in the background which were taller. It is unlikely that this condition would be encountered in a real-world installation of an elevated flare, though it could be a consideration for a ground flare. The effect of the reflected energy was an overall negative bias in the VISR CE calculation which varied from test point to test point based on the degree of reflection.

__Table 1__. Original blind test results (reflection bias has not been corrected)

		Extractive Method			VISR Method				Remark
Test No.	Date	CE Min (%)	CE Max (%)	CE Avg (%)	CE Min (%)	CE Max (%)	CE Avg (%)	Diffe-rence	(More discussion in text)
1	10/18	98.8	99.4	99.0	91.7	96.9	94.8	-4.2	Severe reflection
2	10/18	92.8	95.8	94.2	91.6	94.8	93.1	-1.1	
3	10/21	98.9	99.5	99.3	95.9	100.0	98.1	-1.1	Sun in the field of view
4	10/22	92.9	97.0	94.3	93.0	97.5	95.0	0.7	Sun in the field of view
5	10/21	99.8	99.8	99.8	98.6	98.8	98.7	-1.1	
6	10/21	96.1	97.3	96.8	93.3	96.2	95.0	-1.8	
7	10/22	99.4	99.5	99.5	97.2	98.1	97.7	-1.7	
8	10/22	92.3	94.4	92.8	87.2	89.4	88.2	-4.6	
9	10/27	95.5	99.8	98.4	96.3	97.7	97.1	-1.3	
10	10/27	93.2	96.8	95.4	93.3	95.8	94.7	-0.7	
11	10/18	97.1	98.3	97.7	95.8	97.2	96.3	-1.3	
12	10/19	92.4	96.3	94.3	91.0	94.4	92.9	-1.4	Rain during part of test
13	10/20	93.4	95.1	94.2	N/A	N/A	N/A		VISR not available
14	10/20	96.2	99.2	97.9	94.2	97.8	96.9	-1.0	
15	10/19	98.5	99.8	99.4	95.8	98.4	97.1	-2.3	
16	10/19	88.1	91.6	90.1	90.8	92.7	91.5	1.4	
17	10/22	98.4	98.8	98.6	98.3	98.9	98.6	0.0	
18	10/22	89.2	93.9	91.6	85.9	91.2	89.2	-2.4	
19	10/19	98.6	99.6	99.2	97.5	98.7	98.0	-1.2	Rain during part of test
20	10/21	93.7	94.7	94.3	90.0	95.0	91.9	-2.4	
21	10/20	97.3	98.3	97.8	97.8	98.5	98.1	0.3	
22	10/20	93.0	95.5	94.2	94.8	96.7	95.8	1.6	
23	10/18	98.2	99.0	98.6	96.9	98.6	97.9	-0.7	
24	10/18	94.9	98.2	96.6	95.9	97.3	96.6	0.1	
25	10/27	99.6	99.7	99.7	92.0	95.9	93.7	-6.0	Fog
26	10/26	92.6	98.7	96.0	96.2	97.7	97.0	1.0	
29	10/27	99.0	99.8	99.5	94.1	98.7	96.5	-3.0	Fog
30	10/27	92.3	94.9	93.6	90.7	93.1	91.9	-1.7	Fog
31	10/21	Varying CE			See subsection on Test No. 31				Varying flare conditions
32	10/24	99.6	99.6	99.6	97.7	98.7	98.3	-1.3	
33	10/24	95.1	97.2	96.1	94.5	97.5	95.9	-0.2	
34	10/24	90.3	91.6	91.2	88.2	92.0	90.4	-0.8	
35	10/24	99.3	99.6	99.5	93.3	97.5	95.5	-3.9	Visible emission
36	10/26	98.4	98.9	98.7	96.1	97.5	96.7	-2.0	
37	10/26	93.8	96.2	94.9	95.4	97.1	96.2	1.3	
38	10/25	98.8	99.7	99.2	96.3	98.7	97.9	-1.3	
39	10/25	94.8	95.9	95.3	90.9	95.4	93.1	-2.2	
40	10/26	88.7	92.2	90.2	90.5	92.0	91.5	1.3	
42	10/27	93.7	95.2	94.3	96.6	99.2	97.3	3.0	
43	10/25	99.1	99.6	99.4	95.3	97.7	96.9	-2.5	
44	10/25	98.7	99.6	99.1	97.7	98.5	98.1	-1.0	
45	10/25	N/A			Smoke test				No extractive sampling
A1	10/24	99.9	99.9	99.9	95.1	97.4	96.6	-3.3	Very large flame
A3	10/20	81.7	86.7	83.5	80.9	85.9	82.4	-1.1	
A4	10/26	100.0	100.0	100.0	98.5	99.0	98.7	-1.3	
Average								-1.2	

TEST RESULTS AND DISCUSSIONS

Precision

Precision is a measure of how the results of multiple measurements by the same method scatter while the target of the measurement holds steady. This is difficult to assess for flare measurements because even when the flare operating conditions are held steady (as they were in each test point of the PERF Test), the flare CE may change due to changes in environmental conditions. Analyte spiking or quadruplet sampling described in EPA Method 301 would help to isolate the measurement method precision from the fluctuation of the target itself. However, these methods are not feasible for flare measurement. Nevertheless, the measurement precision can still be evaluated using the data from the PERF test. For each PERF test condition, 4 segments of measurement were made by the extractive method and 3 segments of measurement were made by VISR while the flare operating conditions were held constant (although flare CE did fluctuate due to changes in environmental conditions). The standard deviation (SD) and relative standard deviation (RSD) can be calculated based on these replicate measurements. **Table 2** is a summary of the SD and RSD for both the VISR method and the extractive method used in the PERF Test. As shown in **Table 2**, the RSD for the VISR method is in a range of 0.07% to 1.98% with an average of 0.62%. The variation of the VISR method appears to be slightly better than the extractive method from the perspective of both the average and the range of the RSD values, suggesting that the precision of VISR is at least as good as the extractive method. Note that in both cases, the variation due to changing environmental conditions is included in the RSD as there is no practical method to separate it. Despite the inclusion of environmental changes, the RSD is more than an order of magnitude smaller than 20% as required in EPA Method 301 (Section 9.0). If a more stringent criteria is used in which the 20% limit on RSD is applied to the most relevant range of 90-100 % CE measurement (i.e., in the span of 10 % CE measurement), the criteria would be SD < 2 % CE (20% of 10% = 2 % CE). As shown in **Table 2**, the highest SD is 1.84 measured as % CE, which is lower than the SD of 2 % CE measurement and therefore satisfies the more stringent criteria.

Table 2. *Relative Standard Deviation (RSD) of VISR and extractive method per PERF Test*

Method	CE Avg.	CE Range	SD Avg.	SD Range	RSD Avg.	RSD Range
VISR	96.47	80.61-99.91	0.59	0.07-1.84	0.62%	0.07-1.98%
Extractive	96.41	83.50-100.00	0.83	0.00-2.61	0.88%	0.00-2.72%

The Zeeco test did not include multiple replicated measurements under each test condition. Therefore, a precision analysis has not been performed on that data.

Accuracy

The accuracy of the VISR method is evaluated based on the Zeeco test and the PERF Test. In the two tests, the flare CE was measured by both the VISR method and the extractive method. The extractive method was used as the control (reference) method. Strictly speaking, what can be assessed is the agreement between the two methods, not the accuracy of either method because the true flare CE is unknown. The agreement between the two methods can be evaluated using a statistical method. One such method is to use a t-test on the differences between the paired CE measurements by VISR and extractive methods. This method is the same as the method used in EPA Method 301 to determine if there is a difference caused by different sample storage time (it should be noted that the methods for bias described in Method 301 are not directly applicable because they are specifically designed for analyte/isotopic spiking or quadruplet sampling systems, which are not feasible for flare measurement). The value of the t-statistic is calculated using the following equation.

$$t = \frac{|d_m|}{\frac{SD_d}{\sqrt{n}}}$$

Where d_m and SD_d are the mean and the standard deviation of the difference between the paired samples (VISR and extractive sample), and n is the total number of samples. The resulted t-statistic value is compared to the critical value of the t-statistic with a 95 percent confidence level and n-1 degree of freedom. If the resulted t-statistic value is less than the critical value, the difference between the VISR method and the extractive method is not statistically significant, i.e., the two methods are statistically the same. The results of the t-statistical analysis for both Zeeco and PERF tests are summarized in **Table 3**. The number of samples (tests) in **Table 3** is less than the number of tests actually conducted because some tests were designed for other purposes (e.g., smoke test) and they are not included in the evaluation of the agreement between VISR and extractive methods.

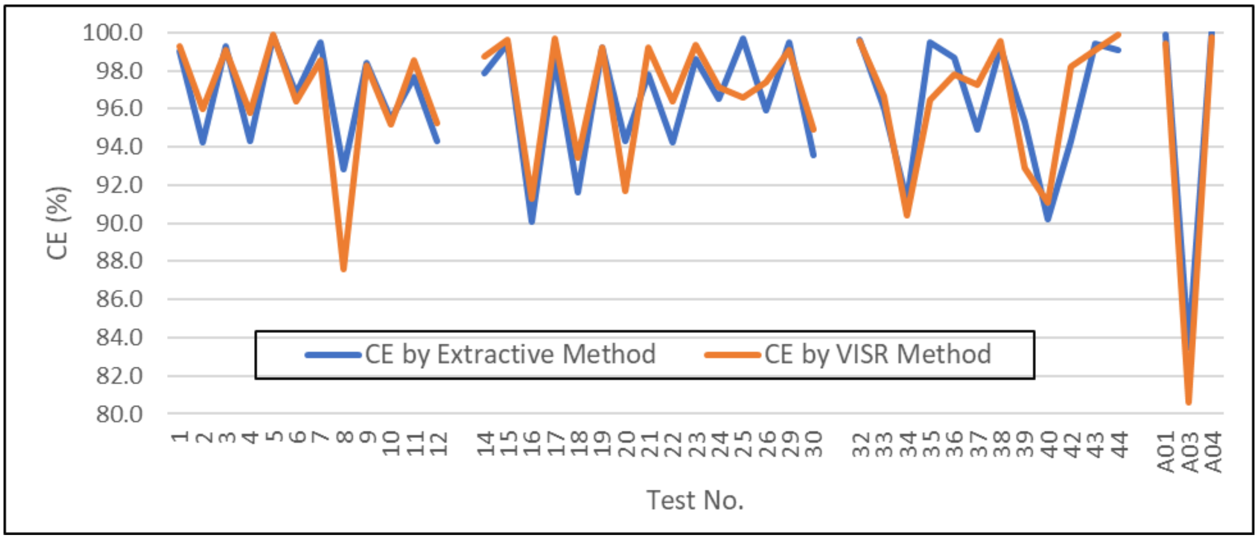
Table 3. *t-Test to determine if the VISR method is statistically different from the extractive method*

	Zeeco Test (Steam Flare)	**Zeeco Test (Air Flare)**	**PERF Test**
No. of Samples, n	11	9	42
Mean Difference, d_m (% CE)	0.30	-0.21	0.07

Standard Deviation, SD_d (% CE)	1.32	0.65	1.69
t-Statistic Value	0.756	0.967	0.254
Degree of Freedom	10	8	41
t_95 Critical Value	2.228	2.306	2.020
Statistically Different?	No	No	No

As demonstrated in **Table 3**, statistically there is no difference between the flare CE measured by the VISR method and by the extractive method. The agreement between the two measurement methods can also be illustrated in **Figure 3** using the results from the PERF Test.

Figure 3. *Flare CE measured by VISR method and extractive method – PERF Test results*



Sun in the Field of View

The PERF test protocol included two test points when the sun is in the field of view (FOV), Test Points 3 and 4. During this test, the sun entered the FOV, then passed behind another flare stack, then re-entered the FOV. The presence of the sun did cause more fluctuation in the CE measurement; however, the average CE values during the time the sun is in and out of FOV are essentially the same for both Test Points 3 and 4. The two test points have shown that the VISR flare monitor can perform well even when the sun is in the Field of View.

Smoke Index

One of the important features of the VISR flare monitor is its ability to monitor the level of the smoke in the flame. This measurement is called Smoke Index (SI). During PERF Test No. 45, steam was gradually reduced and the flare gradually showed visible emissions. SI has a range from 0 to 10 with 0 indicating absolutely no smoke, and 10 indicating the max level of smoke. Generally speaking, when SI reaches approximately 1 to 1.5, visible smoke is observed. The SI responded to the smoke level in test No. 45. End users of the VISR flare monitor can determine what SI threshold they would like to establish to avoid visible flare emissions as defined by EPA Method 22. The user-defined SI threshold, along with CE measured by the VISR flare monitor, can be integrated into the flare control system for a closed-loop operation to achieve optimum flare performance (i.e. an automated system to achieve incipient smoke point).

Results after Correction for Reflection

Prior to the test, interference due to fog had not been encountered during the development of the VISR Method. Similarly, significant interference due to IR reflections from nearby structures had not been encountered. Based in part on the PERF test results, further development has taken place for the VISR Method to recognize and account for these conditions and minimize their effect. The average difference in CE measurement across all test points is reduced from -1.2% to -0.1%. The correlation between the Extractive Method and the VISR Method was 0.87. After the correction for the reflection, the correlation between the two methods is improved to 0.90.

Effect of Fog

Fog was present during Test Nos. 25, 29, and 30. Due to the small size of the water droplets that form fog, some scattering/reflection of Infrared (IR) light is observed in the VISR images.

The water droplets reflected the strong IR rays from the flare and formed a circular hollow IR light ring around the flame. The result was that some of these reflected pixels were included as part of the flare plume and the net effect was similar to the reflection by nearby structures discussed in the previous subsection. The effect was more severe during the early morning (Test No. 25) when the fog was very dense where the VISR bias in CE measurement was as high as -6.0%.

CONCLUSION

This comprehensive testing has demonstrated that the VISR Method is a valid flare monitoring technology, which is consistent with earlier studies of this method (Zeng, et. al., 2016a). On average, the VISR Method has achieved an accuracy within less than 1% in CE measurement when compared to the Extractive Method. The VISR Method has outperformed the Passive Fourier Transform Infrared (PFTIR) Method in a 2010 TCEQ flare study. The results have shown that the accuracy of the VISR Method does not depend upon the fuel composition and process conditions tested. The VISR Method is also immune to nearly all environmental conditions tested in this PERF program. The only small impact observed was under very dense fog conditions, under which the VISR result appears to be biased low by approximately -3% points in comparison to the Extractive Method (approximately -1~2% incremental bias in comparison to other individual test results). Moderate to light fog conditions do not appear to have an impact on VISR performance, i.e., their differences compared to the Extractive results are comparable to other non-fog conditions.

In addition to accuracy, there are many other benefits that the VISR Method can provide (Zeng, et. al., 2016a; Zeng, et. al., 2016b; Zeng and Morris, 2017). Due to its capability of directly and autonomously monitoring flare CE with high data availability, high temporal resolution, and low latency, it is ideally suited as a continuous flare monitor. Many end users wanting to ensure they are within EPA compliance are installing a first stage oxidizer for the continuous waste gas flow cases along with a quick response gas chromatograph or a quick response on line calorimeter and expensive flow meters. The low cost and minimal maintenance requirements of VISR make it an ideal candidate to replace these items and the other required indirect monitoring equipment specified by regulations (USEPA, 2015a; USEPA, 2015b). Finally, the data provided by a continuous VISR flare monitor could be used to make closed-loop flare control, achieving optimal flare performance without human intervention.

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