Flare Combustion Index in Lieu of Combustion Zone Net Heating Value

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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 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 the potential fire hazard and the 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 provided from ambient air, the waste gases are combusted and destroyed.

Flares are subject to environmental regulations to ensure good combustion efficiency (CE) and no visible emissions. In recent years, the U.S. Environmental Protection Agency (EPA) has promulgated new regulations that require flares at oil refineries and ethylene production facilities to be continuously monitored to ensure a high CE (USEPA, 2015; USEPA, 2020) without any visible emissions. At the time of rulemaking, there was no commercially available technology to directly monitor flare CE. As a result, the regulations promulgated by the EPA uses an indirect monitoring method based on combustion zone net heating value (NHVcz) as a surrogate parameter for flare CE. The regulations require that facilities must operate steam assisted flares with NHVcz above 270 British Thermal Units per standard cubic foot (BTU/scf) to be in compliance with the regulations. For flares with perimeter assist air, the regulatory threshold is 22 BTU/ft^2 measured as NHV Dilution parameter (NHVdil).

Demonstrating compliance with the flare NHVcz monitoring requirement typically requires ten measurement devices which must be installed on the process lines leading to each flare. These devices can include an online a gas chromatograph (GC) or calorimeter, high and low range flow meters, as well as multiple temperature and pressure measurement instruments. The measured results from these devices must be synchronized and used to derive the value of NHVcz. The cost for installing and maintaining a NHVcz monitoring system is very high.

A new technology using the Video Imaging Spectral Radiometry (VISR) method has been developed to directly and remotely monitor flare CE (Zeng, et. al., 2016a and 2016b). The VISR method has been validated through blind testing, including a comprehensive test organized by an industry group (Morris, et. al., 2019a). The EPA uses the VISR method as an enforcement tool to remotely inspect flares (Morris, et. al., 2019b). In addition to CE, the VISR method is also used to monitor the presence of smoke in the flare through a parameter called Smoke Index (SI). These two parameters are provided simultaneously and without latency, enabling flare operators (or a closed loop flare control system) to keep the flare in the optimum operating condition, i.e., high CE with no smoke. For continuous flare monitoring, one VISR instrument can monitor one or more flares in real time at distances up to 1500 feet away from flare. The VISR method costs significantly less than the NHVcz method.

This paper introduces an expansion of the VISR method in the form of a new parameter called Combustion Index (CI). The CI method is evaluated and compared to the NHVcz method as a means to demonstrate high combustion efficiency and compliance with existing regulations. Similar to the CE parameter, CI can be used (along with the SI parameter) to continuously and remotely monitor flare performance and provide for closed loop control. One important distinction between the two VISR parameters (CI and CE) is that CI can be measured with a much simpler and less expensive VISR instrument.

MEASUREMENT PRINCIPLE

The indirect method of using NHVcz as an indicator for flare performance, more specifically flare CE, is based on multiple flare studies, including a comprehensive flare study commissioned by Texas Commission on Environmental Quality (TCEQ) in 2010 (Allen and Torres, 2011). A summary review of these studies and the basis for using a NHVcz threshold value to ensure flare performance can be found in an EPA report (USEPA, 2012). **Figure 1** is representative of these studies and an illustration of how NHVcz can be used as an indicator for flare CE. As NHVcz increases, the flare CE increases. When NHVcz is above the regulatory threshold of 270 BTU/scf, flare CE is generally above the regulatory expectation of 96.5% (corresponding to a destruction efficiency of 98%). **Figure 1** can be segmented into four quadrants divided by the vertical line representing NHVcz=270 BTU/scf and the horizontal line representing CE=96.5%.

- Upper right quadrant: NHVcz≥270 and CE≥96.5%, flare is deemed compliant.
- Lower left quadrant: NHVcz<270 and CE<96.5%, flare is deemed non-compliant.
- Upper left quadrant: NHVcz<270 but CE≥96.5%, flare is deemed non-compliant but CE is above the regulatory target of 96.5% (over-regulated).
- Lower right quadrant: NHVcz≥270 but CE<96.5%, flare is deemed compliant but CE is below the regulatory target of 96.5% (under-regulated).

Ideally the NHVcz method works when all data points fall in the upper right or the lower left quadrants. As shown in **Figure 1**, there are some exceptions - the data points in the lower right and upper left quadrants. Those data points show the potential shortcomings of the indirect NHVcz method (over regulation or under regulation). Despite these shortcomings, the indirect NHVcz method generally provides a good indicator of combustion efficiency and has been accepted by the regulator and implement by industry.

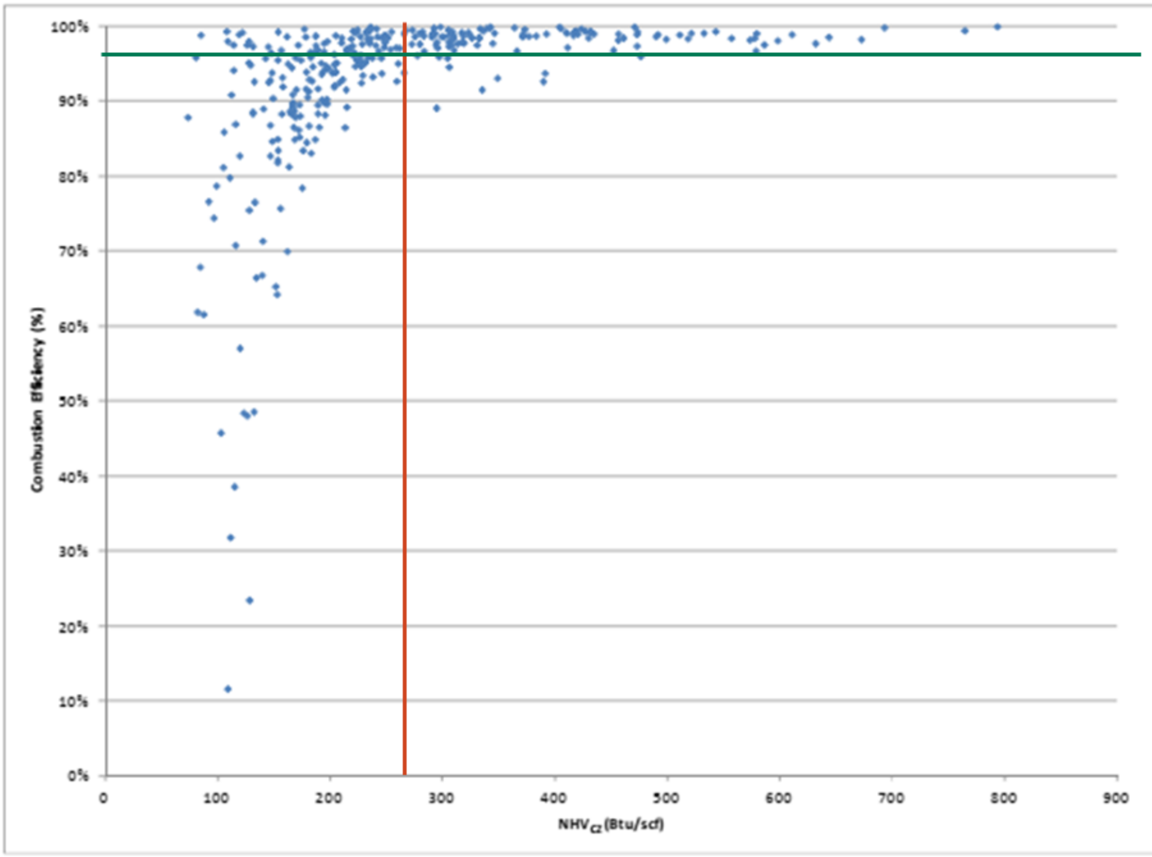


Figure 1: Relationship between flare CE and NHVcz as well as regulatory target for CE (>96.5%) and compliance threshold for NHVcz (>270 BTU/scf). Source: Ref. USEPA, 2012, p. 3-33. The red vertical line (NHVcz=270 BTU/scf) and green horizontal line (CE=96.5%) are added by author.

The new CI method introduced in this paper is based on the measurement of Infrared (IR) radiances emitted by the flare in multiple IR spectral bands. The relationship between these spectral radiances reveals how hot the flare is for a unit of combustion gas volume in the flame, which correlates with the NHVcz, i.e., the higher the net heat released in the combustion zone, the hotter the flame volume (or combustion zone) will be. Consequentially a high CI value will indicate a high combustion efficiency (high CE) in the same way that a high NHVcz does. The CI parameter is a unitless metric which can be used for continuous flare monitoring, similar to NHVcz as shown in the table below:

	NHVcz (BTU/scf)	CI (unitless)
Flare performs well (CE≥96.5%)	≥ 270	≥ 1
Flare performs poorly (CE<96.5%)	< 270	< 1

The CI parameter can be derived using a Video Imaging Spectral Radiometer (VISR), a radiometrically calibrated multi-spectral IR imager coupled with a computer running an image processing algorithm to derive the CI value at a frame rates. This CI value can then be tabulated and reported on a 1-second interval along with other VISR parameters, such as SI.

While the indirect NHVcz method provides a mechanism to ensure a minimum level for good combustion, it does not address the other end of the spectrum when NHVcz is very high. When the flare is fuel rich it can lead to visible emissions (e.g., smoke), which will not be detected by the NHVcz method. The regulatory approach to address this limitation is to require additional methods (such as visual inspection) to ensure that there are no visible emissions. The VISR instrument used to monitor CI can also provide a Smoke Index (SI) which indicates the presence of visible emissions. This offers the possibility of directly monitoring both the combustion efficiency and the presence of visible emissions from a single VISR instrument positioned at some distance from flare (e.g., 100-1500 feet).

EXPERIMENT SETUP

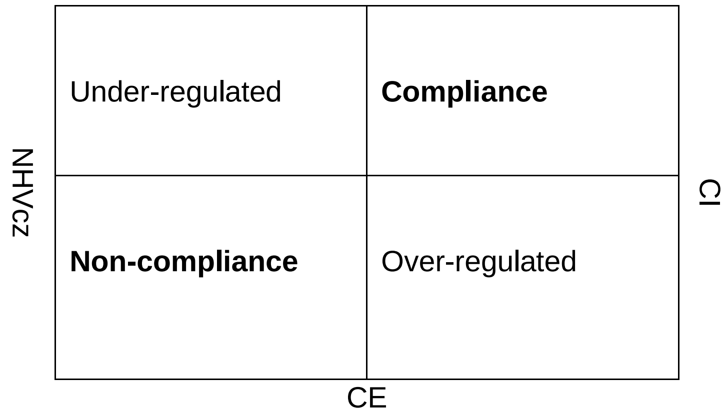
To test the efficacy of this new VISR parameter (CI) for flare monitoring, a radiometrically calibrated multi-spectral IR imager is positioned at a distance from a test flare. The test flare is operated under different process conditions which cover a range of flare CE. Meanwhile, conventional online instruments (online GC or calorimeter, flow meters, temperature transmitters, pressure transmitters) are installed on the flare header, steam assist and air assist lines to measure the physical/chemical properties of these streams and derive NHVcz. In addition to NHVcz, flare CE is also measured by established methods – the extractive method, the VISR method, or both. In the extractive sampling method, post-combustion gas samples from the tail portion of the flare flame are extracted by a hood suspended over the flare. The extracted samples are conveyed through a heated line to the instruments for composition analysis of the post-combustion gases using EPA reference methods. The results of the post-combustion gas composition analysis are used to determine flare CE (see Allen and Torres, 2011, for the extractive sampling method for flare CE measurement). Description of the VISR method for flare CE measurement can be found in other publications (Zeng, et. al., 2016a and 2016b; Morris, et. al., 2019a and 2019b).

While the CI parameter is newly developed, it is derived from the radiances measured by a VISR imager. As a result, it can be retroactively derived from VISR data sets collected during previous flare studies. The VISR data sets from the following flare studies are used to examine this new CI parameter:

- EPA Precision Study. In 2018, EPA funded a study to evaluate the precision of the CE parameter derived by the VISR method. Two VISR instruments were used in the study, which was performed at the John Zink Hamworthy Combustion (John Zink) test facility in Tulsa, Oklahoma. The flare CE was measured by the VISR method and the flare NHVcz was provided by John Zink using conventional instruments. The measurements of CI and CE were derived from the VISR instruments located at distances of 200 ft. and 400 ft from the flare.
- PERF Study. In 2016, a flare study was sponsored by the Petroleum Environmental Research Forum (PERF), an industry consortium, to evaluate remote flare monitoring technologies. The study was done at the John Zink test facility in Tulsa, Oklahoma. It was organized as a blind test, meaning the flare performance was not shared with the technology vendors who participated in the study. Flare CE was measured using the extractive sampling method by a contractor retained by PERF. Flare CE was also independently measured by Providence Photonics using the VISR method. The flare NHVcz was calculated and provided by John Zink. More information on this test can be found in Morris, et. al. (2019a). The VISR instrument used to derive CE and CI was located at various distances from about 170 ft. to 650 ft.
- Refinery Study. A flare at an operating refinery in the U.S. was monitored by a VISR instrument for a 9-day study period. The refinery was also equipped with the instrumentation to measure NHVcz per EPA regulations. Multiple flaring events were monitored during the 9-day study period. The VISR instrument for CE and CI was located 1100 ft. from the flare.

RESULTS AND DISCUSSIONS

The CI method is assessed for each of these flare studies by plotting CE vs. CI in four quadrants, similar to the CE vs. NHVcz plot in **Figure 1**. If the data points from the CI method follow the same trend as the data points from the NHVcz method, then CI can be used as a flare performance indicator in the same way that NHVcz is used. To facilitate the comparison, both CI and NHVcz from each test are plotted on the same chart. NHVcz is plotted on the primary y-axis, CI is plotted on the secondary y-axis and flare CE is on the x-axis. As a result, the quadrants for results are oriented slightly different from **Figure 1**. The quadrants are reassigned as shown below:



EPA Precision Study

Eighteen tests were conducted under different flare and measurement conditions. Flare conditions included high CE (target CE ~99%), low CE (target CE ~91%) and medium CE (target CE ~96%). There was one test when flare was smoking, and five tests when the flare was transitioning between high CE and low CE.

The results of CI vs. NHVcz under stable flare conditions (i.e., excluding the smoke test and transition between flare conditions) are summarized and presented in **Figure 2**. As shown in **Figure 2**, the pattern observed between the NHVcz method and the CI method (with respect to CE) are very comparable, i.e., the same compliance conclusions will be derived if CI is used in lieu of NHVcz. There are two data points in **Figure 2** that are borderline – Test 17 and Test 18. However, the CE for these two tests are also borderline with CE very close to the 96.5% threshold.

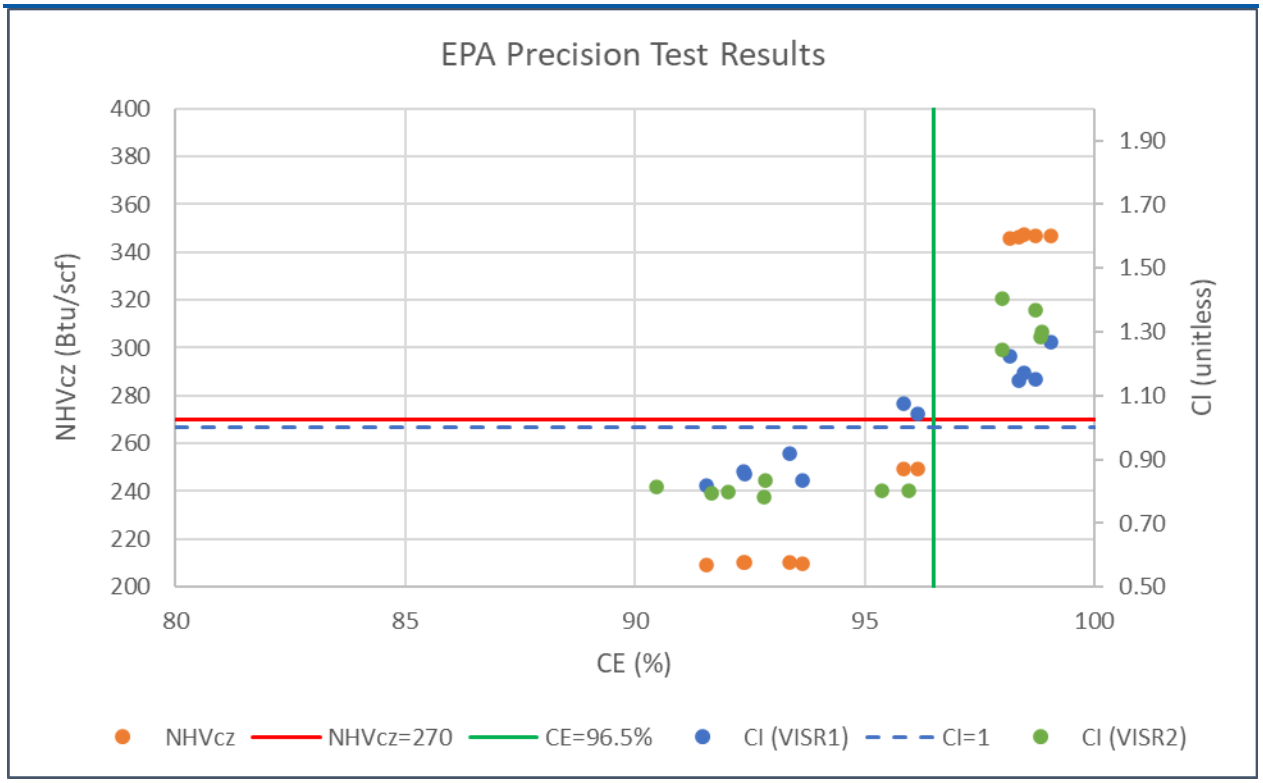
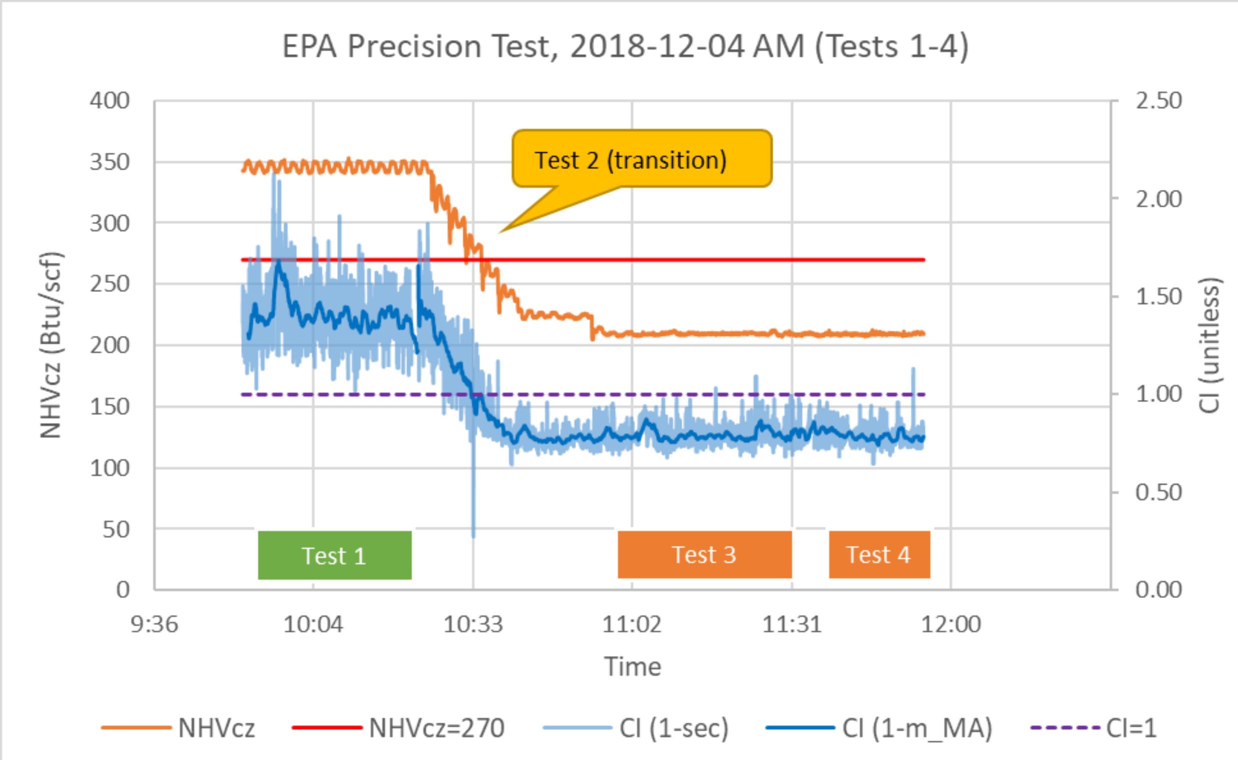


Figure 2: Using NHVcz and CI for compliance monitoring – Results based on EPA precision test in 2018.

Figure 3 provides two time series plots of NHVcz and CI measured by one of the two VISR instruments during Day 1 of the EPA precision study. The test number and transitions are described in the time series plot. In both time series plots, the flare is transitioning between high CE (compliance) and low CE (non-compliance). The horizontal red line and purple dotted line are the compliance thresholds for NHVcz and CI respectively. The two parameters track each other very well and result in the same compliance determination.



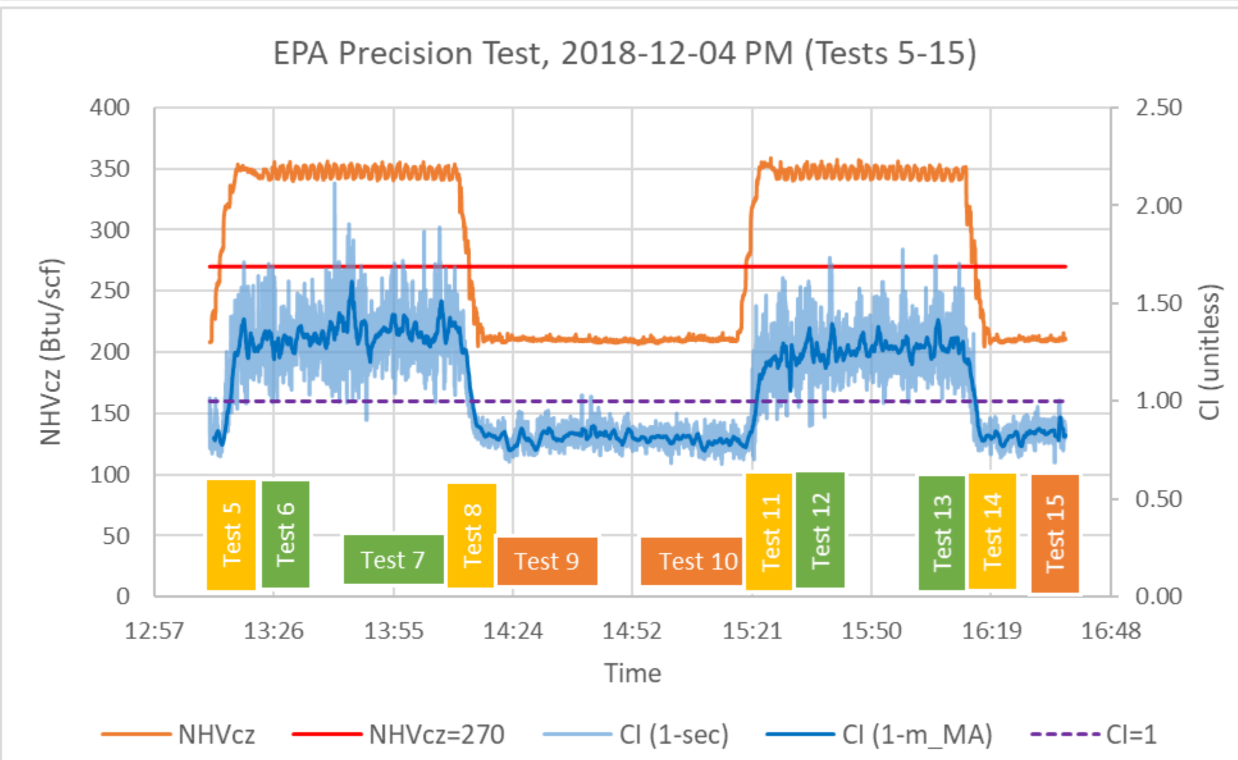


Figure 3: Continuous monitoring of the test flare at John Zink test facility using NHVcz and CI during Day 1 of the EPA precision test in 2018.

Correlation between NHVcz and CI can be examined during the transitions in Tests 2, 5, 8, 11, and 14 when the flare condition was changing (refer to **Figure 3**). The correlation between NHVcz and CI during these transitions is shown in **Figure 4.** The data points in **Figure 4** are 1-minute averages. The correlation is stronger when the flare transitioned from high CE to low CE (i.e., Tests 2, 8, and 14 when steam was being added) than when the flare transitioned from low CE to high CE (i.e., Tests 5 and 11 when steam was being reduced).

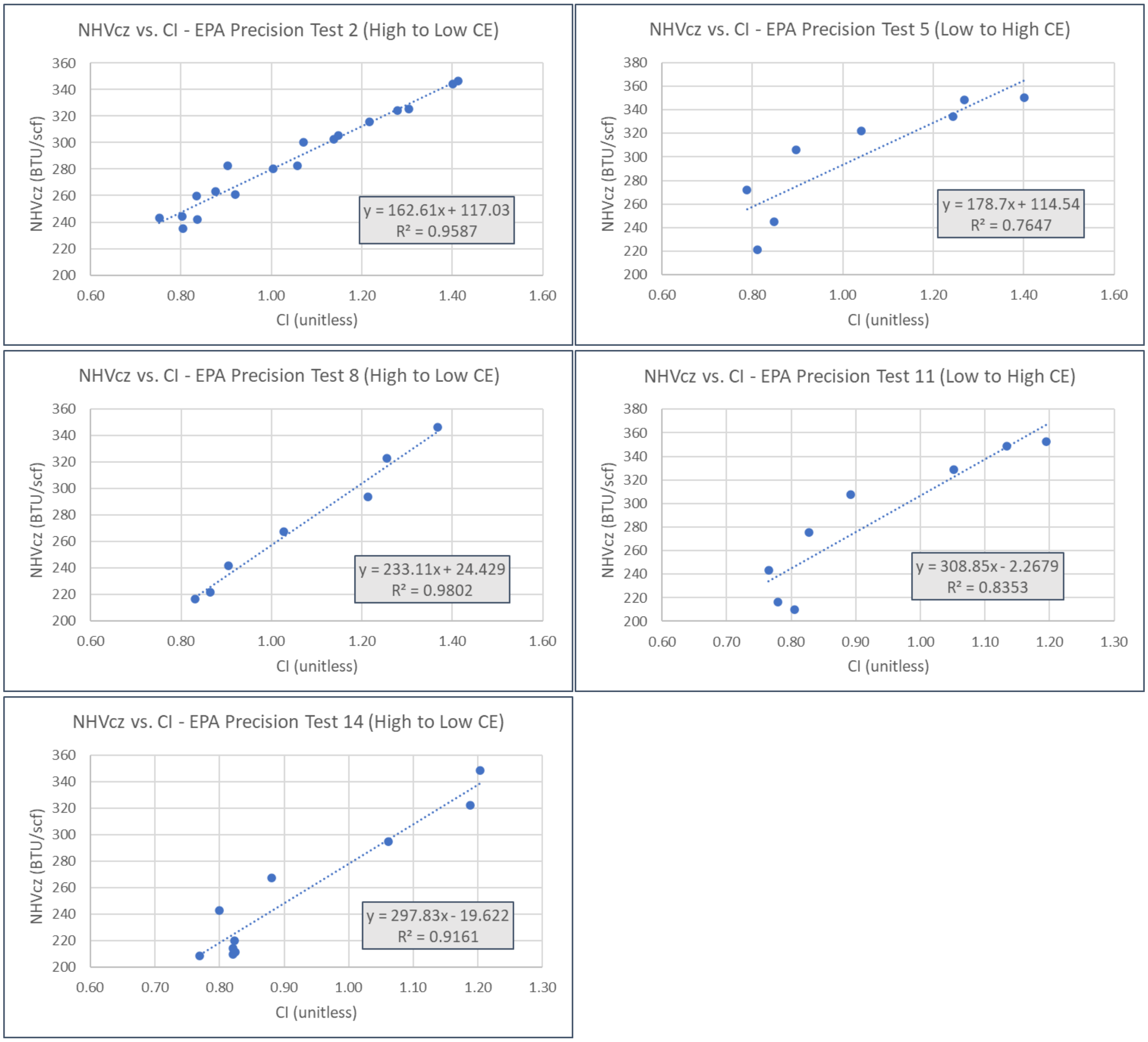
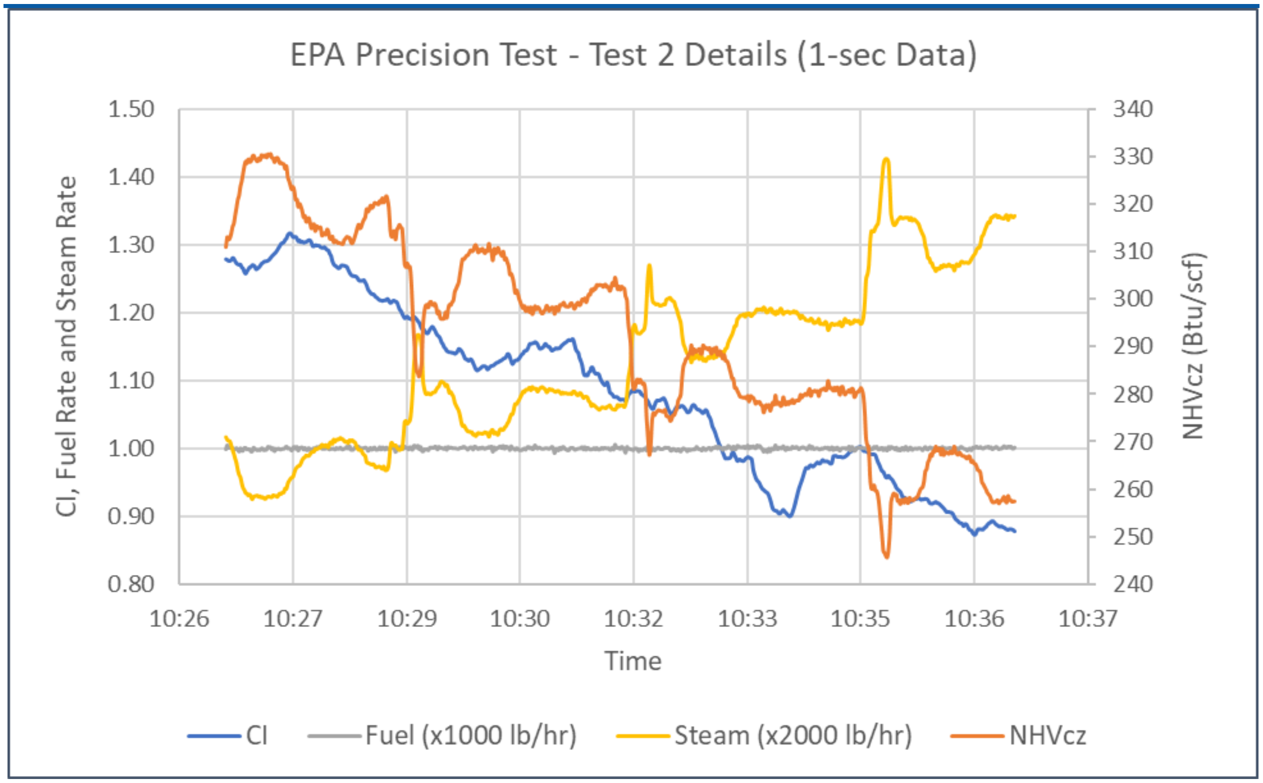


Figure 4: Correlation between NHVcz and CI when flare condition was changing.

To investigate this disparity, a comparison is made using 1-second data for Test 2 (high to low CE transition) and Test 5 (low to high CE transition) in **Figure 5**. In both cases, the fuel was held constant at 1000 lb/hr and steam was changed to transition to a different CE condition.



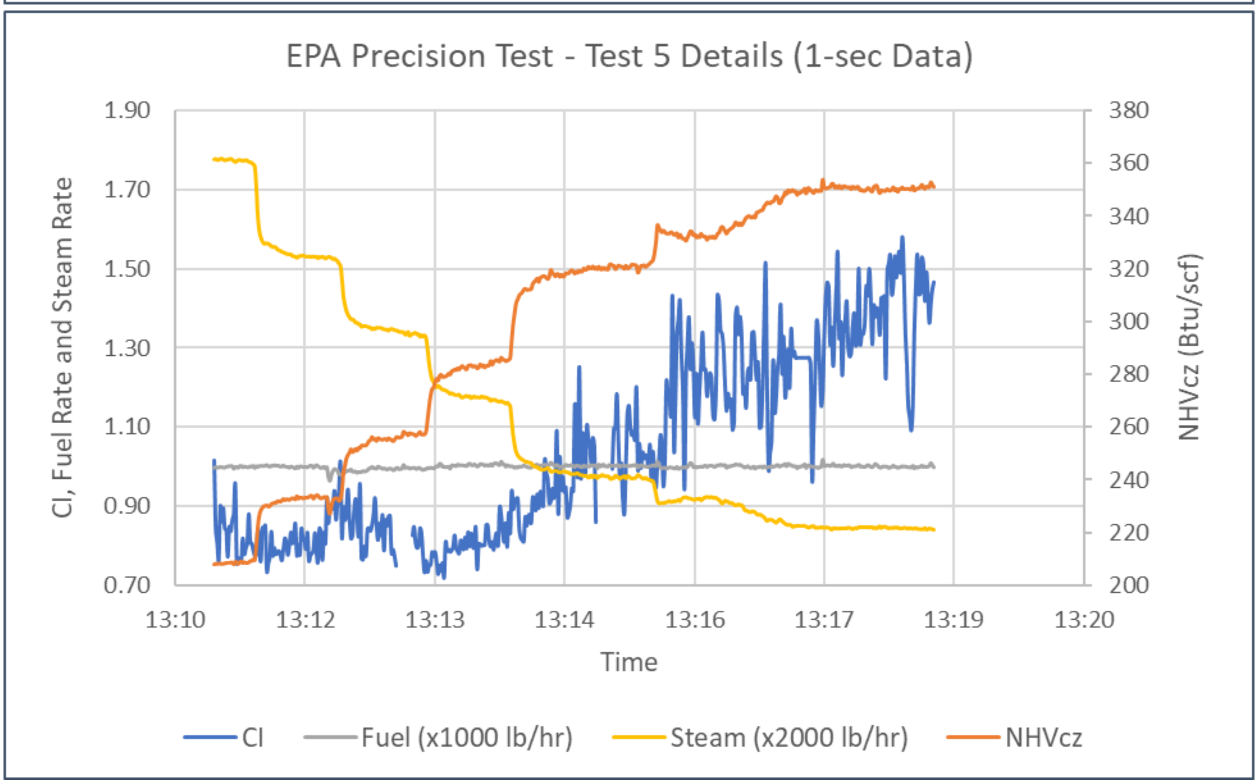


Figure 5: Time series plot at 1-secend interval for CI, fuel rate, steam rate, and NHVcz for EPA Precision Test 2 (transition from high CE to low CE and Test 5 (transition from low CE to high CE).

Two observations can be made based on **Figure 5** which highlight the advantage of a direct measurement method (VISR CI parameter) verses an indirect method (NHVcz). The first observation is that the change in steam flow rate is reflected immediately in the steam flowmeter (and consequently in the calculation for NHVcz) but the effect at the flare tip has some smoothing. We believe that this smoothing is due to the buffering in the steam pipe between the steam flowmeter and the flare tip. The sharp spikes in steam flow rate (and NHVcz) near 10:29 AM, 10:32 AM, and 10:35 AM do not result in sharp spikes at the flare tip, but instead are smoothed as the increased steam flow reaches the flare tip. This is also demonstrated by the CI curve, which is a direct measurement of the combustion zone and does not show these sharp spikes.

The second observation is that when steam is reduced during Test 5, there is a noticeable delay in its effect at the flare tip. This is demonstrated by the CI curve (blue line), which does not respond to the decrease in steam flow rate (and corresponding increase in NHVcz) until approximately 1.5 minutes later (refer to the lower chart in **Figure 5**). Such a delay is not as pronounced when the steam rate is increasing during Test 2 (refer to the upper chart in **Figure 5**). Our hypophysis is that when adding steam, the steam is forcefully pushed to the flare tip and the effect is more immediate. When reducing steam, it takes some time for the steam already in the pipe between the steam flowmeter and the flare tip to dissipate toward the flare tip. As a result, the effect is more gradual when reducing steam rates and the correlation between NHVcz (which is based on the flowmeter measurement) and CI (which is based on a direct measurement of the combustion zone) is weaker in Test 5 (r^2 = 0.7647) than in Test 2 (r^2 = 0.9587) - see **Figure 4**. The lower correlation in Test 5 is not an indictment of the efficacy of the CI method, rather it illustrates the inherent latencies found in indirect monitoring methods such as NHVcz. The CI parameter reflects the effect of the fluid dynamic properties of the gases after they have passed their respective flowmeters.

PERF Study

There were a total of 46 test cases in this study. Thirty-four of the test cases used natural gas as flare gas, six of them used a propylene-nitrogen blend at different ratios, and six of them used natural gas-hydrogen blend at different ratios. The results of the NHVcz method and the CI method are shown in **Figure 6**. Each orange dot represents a test result using the regulatory NHVcz method under a specific flare test condition, and each blue dot represents a test result by the CI method under the same flare test condition. Similar to the results of the EPA precision study discussed above, the NHVcz method and the CI method are in a good agreement in determining compliance/non-compliance, with two notable outliers.

The two outliers in the CI method were Test Point 42 and Test Point 37. The flow rate for these two test points were the two lowest rates of the entire study (125 lb/hr for TP42 and 320 lb/hr for TP37). In both cases, the flame was very small relative to the diameter of the flare tip (36 inches) and the size of the extraction hood used to measure CE. It is reasonable to consider that the extractive CE measurement might be less accurate for these low flow test points due to a high degree of sample dilution by ambient air and the CE measured by the VISR method may be more accurate under these test conditions. In fact, the CE measured by the VISR method for these two test points was above 96.5%. If we the CE measured by the VISR method, the two data points in question would not be outliers as they would fall in the upper right quadrant (i.e., the flare should be in compliance). In other words, the cause for the two outliers may not be attributable to the CI method. Instead, it could be caused by inaccuracy in the extractive CE measurement due to a low flow rate, a relatively small flare footprint, and high degree of ambient air dilution. The remaining 44 test cases show expected results, CI is an effective method to predict combustion efficiency and demonstrate compliance with a regulatory target of CE>96.5%.

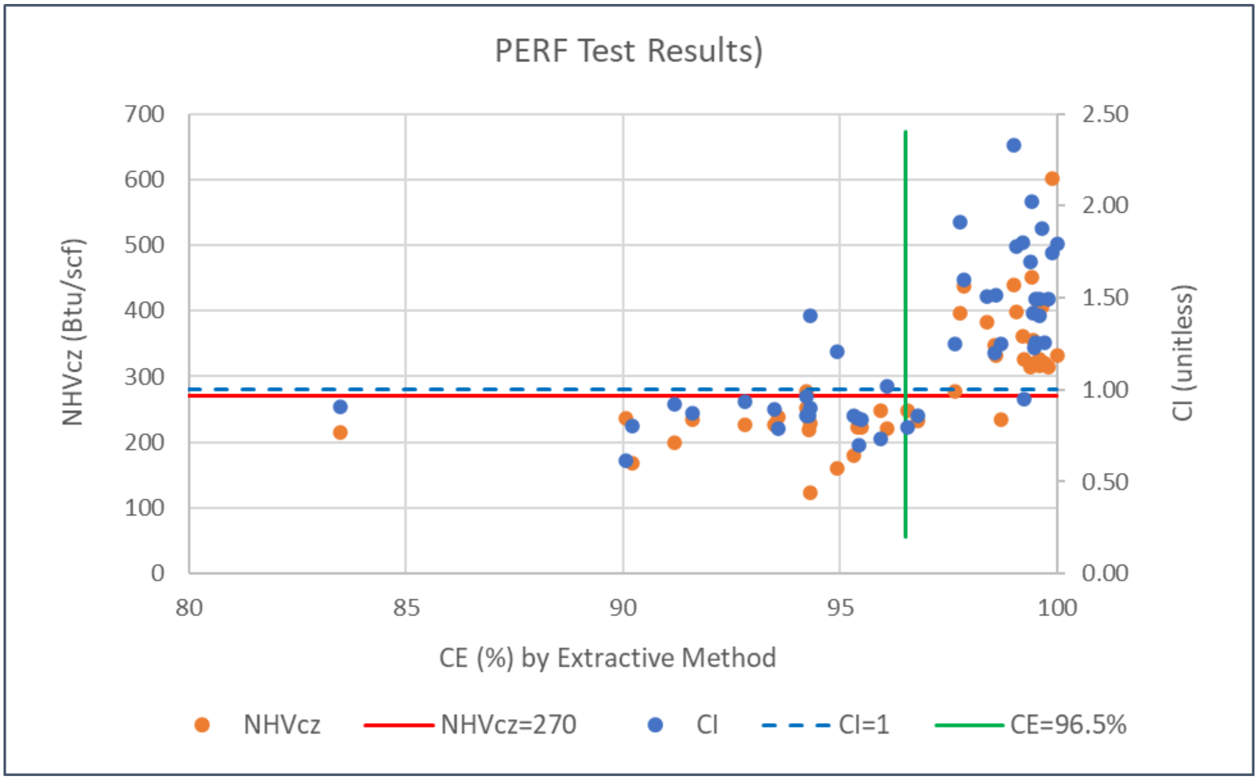


Figure 6: Comparison of the NHVcz method and the CI method based on the PERF flare study.

If we accept that the extractive CE measurement is accurate for Test points 42 and 37, then the CI method produced only two outliers out of 46 test conditions in this study. For 95% of the test cases, the CI method correctly determined whether the flare was in compliance. Comparing these results with the NHVcz results used as the basis of the current regulations (see **Figure 1**, Source: Ref. USEPA, 2012, p. 3-33.), the CI method produced significantly fewer outliers. This is observed by examining the NHVcz outliers in the upper left quadrant of **Figure 1** (over-regulating) and the lower right quadrant of **Figure 1** (under-regulating)**.** Keep in mind that the quadrant assignment in **Figure 1** are different from other NHVcz vs. CE figures in this paper due to a change in x- and y-axis assignment.

Refinery Study

During this 9-day flare study period, multiple flaring events occurred. Both the NHVcz method and the CI method are applied and results are presented in **Figure 7.** The charts on the left are time series plots of NHVcz and CI with a 1-minute time resolution. The charts on the right are NHVcz and CI vs. CE with 1-minute time resolution. The time series plots show that NHVcz and CI generally track each other very well. As discussed in the above EPA Precision Study section, the indirect NHVcz method tends to have more spikes (both high and low). As the flare gases and assist steam reach the flare tip, the effect of these sharp changes in the calculated NHVcz tend to be muted. Some misalignments between the NHVcz data and the CI data can be seen due to the time difference in the two methods (e.g., the time delay for the online instruments and inherent latencies due to the time it takes to see the effects at the flare tip). Which method is more accurate or representative is a subject which could be debated, but both methods demonstrate that the flare is operating in a good combustion condition during these flaring events and is in compliance with the regulation (e.g., the results are generally above the "NHVcz=270" line and the "CI=1" line respectively), especially when the results are averaged into 15-minute blocks as specified by the regulation.

If the flare CE is directly used as the compliance method (which is not required in the current regulations), this flare will still be in compliance. With a few exceptions in the 1-minute time domain, the vast majority of the data points are on the right side of the vertical green line, indicating a CE > 96.5%. For flaring events 1 and 2, most of the data points are in the upper right quadrant indicating agreement between the NHVcz method, CI method and the actual CE. Flaring event 3 has a significant number of orange dots in the lower right quadrant, suggesting "over-regulating" or falsely classified as non-compliance due to the NHVcz falling below the 270 BTU/scf regulatory threshold, but the flare CE is actually above the target CE of 96.5%. In this case, the CI method does a better job of predicting flare performance (vs. NHVcz) and avoids over regulation.

Figure 7: Comparison of the NHVcz method and the CI method based on a flare study at an anonymous refinery in the U.S.

CONCLUSIONS AND FUTURE WORK

A new direct monitoring method called Combustion Index (CI) has been proposed for measuring flare performance. CI is derived from the VISR method, which is an established method utilizing a multi-spectral Infrared (IR) imaging device to measure radiances emitted by the flare in different spectral bands. Three flare studies are used to validate this new flare monitoring method and compare it to the indirect method (NHVcz) currently used in flare regulations. The results from these three flare studies show that the CI method can be used to monitor flare performance in the same way as the NHVcz method. Since the CI method is also highly correlated to NHVcz, it should readily fit into the current regulatory framework as an alternative method to measure NHVcz.

The VISR based CI method has multiple advantages over the indirect NHVcz method. The CI method is a remote sensing method and can be performed at distances up to 1500 feet away from the flare. Unlike the online instruments necessary to monitor flare NHVcz, the VISR instrument can be installed without a process shutdown. The maintenance for the VISR instrument is dramatically less than the instruments required for the NHVcz method, yielding better data availability for the CI method. The CI method directly monitors what is happening at the flare tip, eliminating any biases caused by inherent latencies of the indirect NHVcz method. As illustrated in this study, there can be a disconnect between what is measured at the flow meter and what is actually happening at the flare tip.

The VISR based Combustion Efficiency (CE) method has already been established as an effective way to remotely measure flare combustion efficiency. The VISR instrument needed to measure CI is much less sophisticated than the VISR instrument needed to measure CE and, as a result, the cost is significantly lower. Provided that a direct measurement of Combustion Efficiency is not needed, a single inexpensive VISR instrument can be installed to directly measure Combustion Index (CI), Smoke Index (SI), flare footprint (FF), fractional heat release (FR), and flame stability (FS) in a 1-second temporal resolution with no latency. This device will be well suited to closed loop control and will be able to demonstrate compliance with the current flare monitoring regulations (including both the NHVcz requirement and the visible emissions requirement) at a fraction of the cost. The capital and operating costs for this VISR based method will be an order of magnitude lower than cost of the current NHVcz method.

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