Remotely Monitoring Flare 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 regulations 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.

The authors of this paper presented the concept of Combustion Index at the AFRC 2020 Industrial Combustion Symposium (Zeng and Morris, 2020) and envisioned a lower cost remote sensing device that can be used to monitor Combustion Index. Since then, the team has developed a device (see **Figure 1**) that utilizes similar VISR methodology and can directly and remotely monitor flare NHVcz and other flare performance metrics at a much lower cost. A prototype of this new device was tested in December 2020 at the John Zink Hamworthy Combustion (John Zink) test facility in Tulsa, Oklahoma. The results of the test are presented in this paper.

Figure 1: Newly developed flare monitoring device that can remotely and directly measure flare NHVcz, Smoke Index, and other flare performance metrics.

MEASUREMENT PRINCIPLE

The new method is an extension of the Combustion Index (CI) concept (Zeng and Morris, 2020). The CI is a metric 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 relative to the expected adiabatic combustion condition for a given volume of combustion gas in the flame, which correlates with the NHVcz in BTU/scf, i.e., the higher the net heat released in a given volume of gases, the hotter the flame volume (or combustion zone) will be. The CI can be used as the measurement signal. When properly calibrated, the correlation between CI and NHVcz can be established and used to remotely measure NHVcz.

While any NHVcz based regulations provide a safeguard to ensure a minimum level of fuel 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 may 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. In addition to measuring NHVcz, the new device can also provide a Smoke Index (SI) which indicates the presence of visible emissions. In other words, the new device can directly and remotely monitor both the combustion efficiency and the presence of visible emissions at distances up to 1500 feet from the flare tip.

EXPERIMENT SETUP

To test the efficacy of this new method of remotely and directly measuring flare NHVcz, a radiometrically calibrated multi-spectral IR imager was positioned at various distances from a test flare at the John Zink test facility in Tulsa, Oklahoma (see **Figure 2**). The test flare was operated under different process conditions which cover a range of flare NHVcz. Meanwhile, conventional online instruments (online GC/calorimeter or equivalent method, flow meters, temperature transmitters, pressure transmitters) installed on the flare header, steam assist and air assist lines were used to measure the physical/chemical properties of these streams and derive NHVcz. The flare NHVcz measured by the conventional method was used as the control method (or reference method) to evaluate the measurement of NHVcz by the new method.

A total of 22 tests were conducted. Because this was the first time this new method was applied and the calibration had not been established, the first 4 tests were used to establish the calibration. The calibration curve is presented in **Figure 3**. The calibration equation is then used for the rest of the tests to measure flare NHVcz. Based on the measurement principle, this calibration is intended to establish the method and site-specific calibration is not required. This will be further evaluated in future tests planned for 4Q 2021. Tests 5-22 were designed to evaluate different flare operating conditions and measurement conditions as summarized in **Table 1**.

Figure 2: Location of test flare and new device locations: 1: Test 1-7; 2: Test 8-11; 3: Test 12-21; 4-8: Test 22.

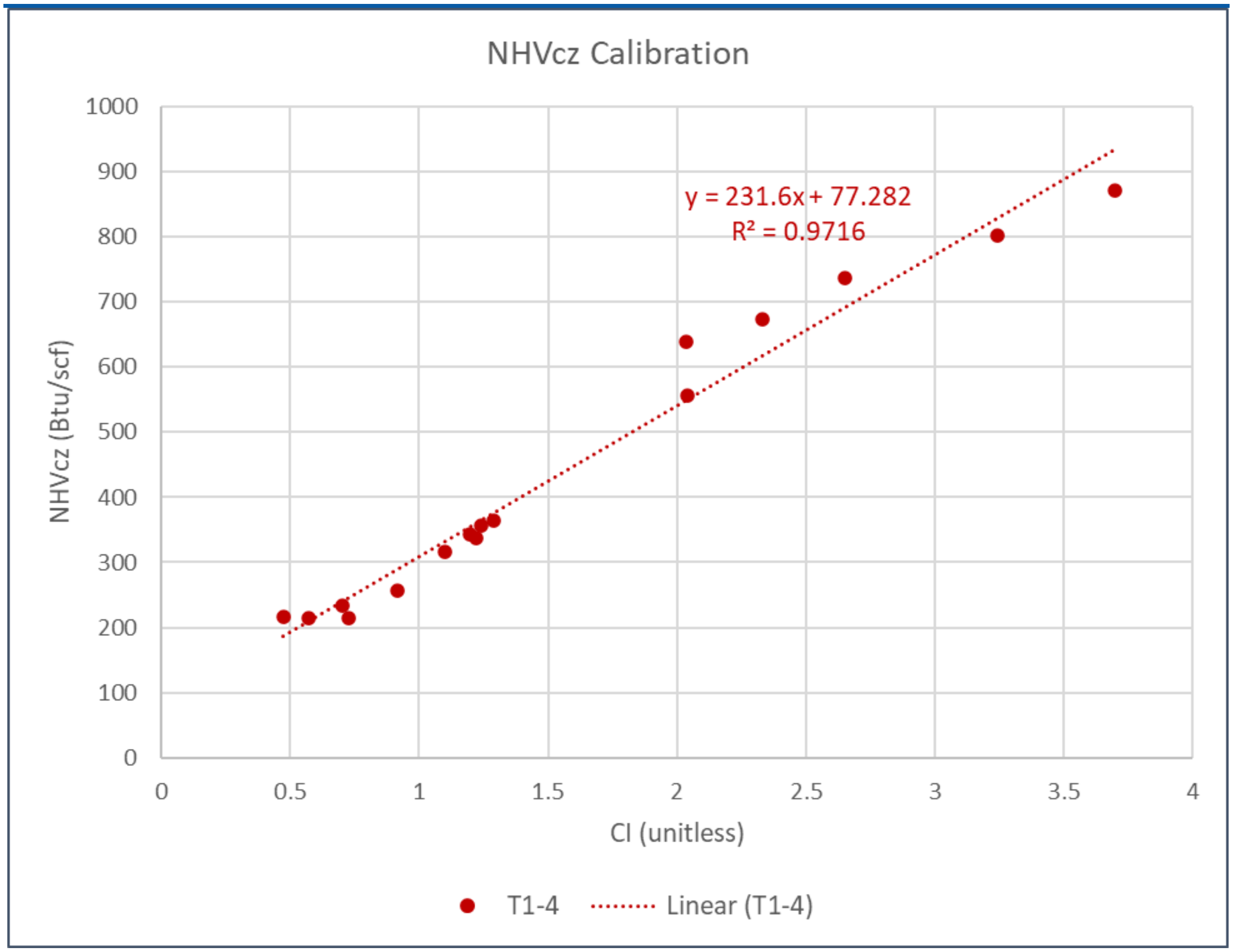

Figure 3: Instrument calibration using Tests 1-4.

Table 1: Test Matrix

Test No.	NHVcz Range (Btu/scf)	Fuel Type	Fuel Rate (lb/hr)	Steam Rate (lb/hr)	Sensor Distance (ft.)	Sensor View Angle
1-3	360 → 210	NG	1000	1600 → 3600	200	Crosswind
4	1400 → 360	Propane	2000 → 1500	500 → 3400	200	Crosswind
5-7	380 → 210	NG	1000	1600 → 3600	200	Crosswind
8-10	220 → 620	NG	1000 → 2100	3500 → 1100	400	Crosswind
11	580 → 130	NG	1900 → 300	1200 → 2000	400	Crosswind
12	400 → 1360	Propane	1300 → 2000	3200 → 550	400	Downwind
13-15	320 → 210	Propane	1000	2500 → 4000	400	Downwind
16-18	350 → 150	50:50 NG:N2	740 → 420	500 → 1200	400	Downwind
19-21	360 → 150	50:50 NG:H2	900 → 810	1300 → 5000	400	Downwind
22	370	NG	1000	1600	258→618	Downwind

RESULTS AND DISCUSSIONS

The results of this new remote-sensing device for measurement of flare NHVcz are presented in **Figures 4-7**. In these figures, the NHVcz measured in the conventional method using inline instruments are continuous (represented by the blue line in these figures). At the time of these tests, the new device was still at the prototype stage and the measurements were taken as discrete intervals rather than continuous measurements. The measurements from the new method are plotted as red squares in these figures. The fact that the new method results are discrete (rather than continuous) should be factored in when reviewing these results. The final product will take continuous measurements at a 1-second interval and the correlation to the conventional method should improve. At that time, any differences observed could be attributed to the fact that the conventional method measures what goes into the flare and the new method measures what is actually happening at the flare tip, including the effect of environmental conditions (such as wind) and flare tip design. The wind speed averaged over the period of the new method measurement is also plotted (green diamonds in the plots).

As shown in **Figure 4**, the NHVcz values measured by the two methods are very consistent. One outlier occurs when the flare is smoking during Test 4 (very high NHVcz), the new method tends to underestimate the NHVcz (the first 3 red squares in the upper right plot of **Figure 4**). From a compliance standpoint, this condition would be flagged by the smoke index and the facility would take some action to remove the visible emissions.

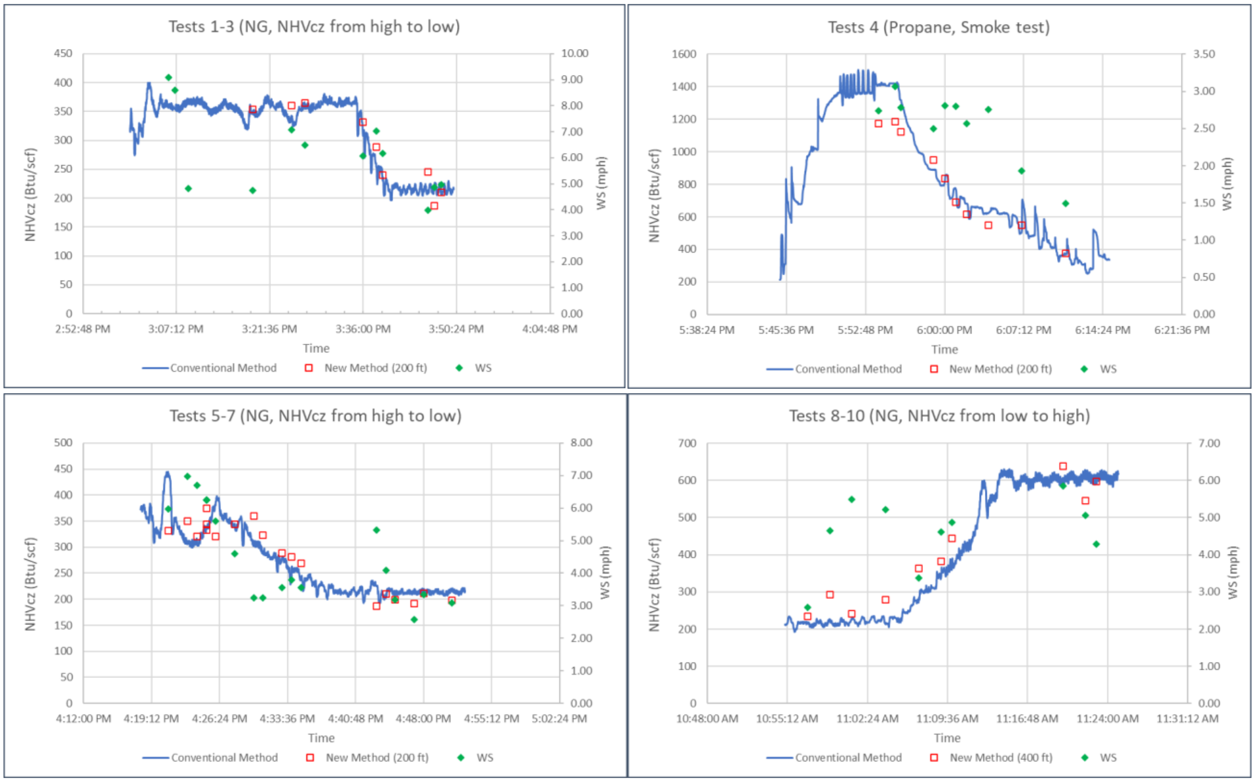

Figure 4: Flare NHVcz measured by the conventional method and the new method. Tests 1-10.

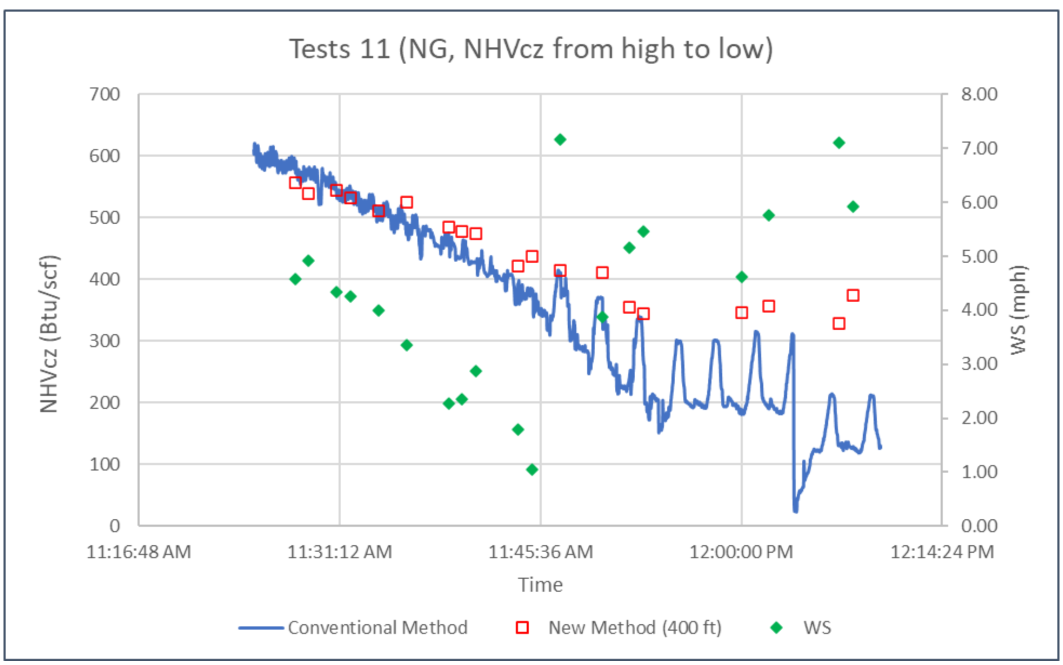

Figure 5: Flare NHVcz measured by the conventional method and the new method. Test 11.

The case of Test 11 is an interesting one to examine. During Test 11 (see **Figure 5**), the fuel was gradually reduced from nearly 2,000 lb/hr to about 300 lb/hr. During the second half of the test, the NHVcz measured by the new method is generally higher than the average of the results from the conventional method. However, the NHVcz measured by the conventional method (inline instruments) shows a dramatic variation (up and down pattern), making it less reliable to compare to the short (few seconds) discrete measurements by the new method, i.e., it is difficult to pin down the time of the discrete measurement – is it coinciding with the peak or the valley of the conventional method. It is also observed that the wind is noticeably higher in this period than the first half of the test. It is our speculation that the wind may play a larger role under this condition. When the fuel flow drops to about 500 to 300 lb/hr, the flare tip exit velocity is several times lower than the early part of this test (in fact lower than any other tests in this study, see fuel rate in **Table 1**). When the flare tip exit velocity is low, the mixing in the combustion zone would presumably be low. Under such a condition, a high wind speed (WS) could create better mixing at the flare tip, promoting a better combustion. Such wind effects are not accounted for in the conventional method. In the new method, however, it could be reflected because if the wind promotes a better mixing in the combustion zone and the combustion temperature is higher, the higher radiance will be measured by the new method and will cause the NHVcz to be higher. When the fuel rate is high and flare tip exit velocity is much higher than the wind speed, the effect of wind speed may become negligible. The observation made here supports our theory. However, the fluctuation in the flare operation during this test complicates this analysis. Hopefully more similar phenomenon will be observed in future tests or deployments with this new device which can further support or debunk this theory.

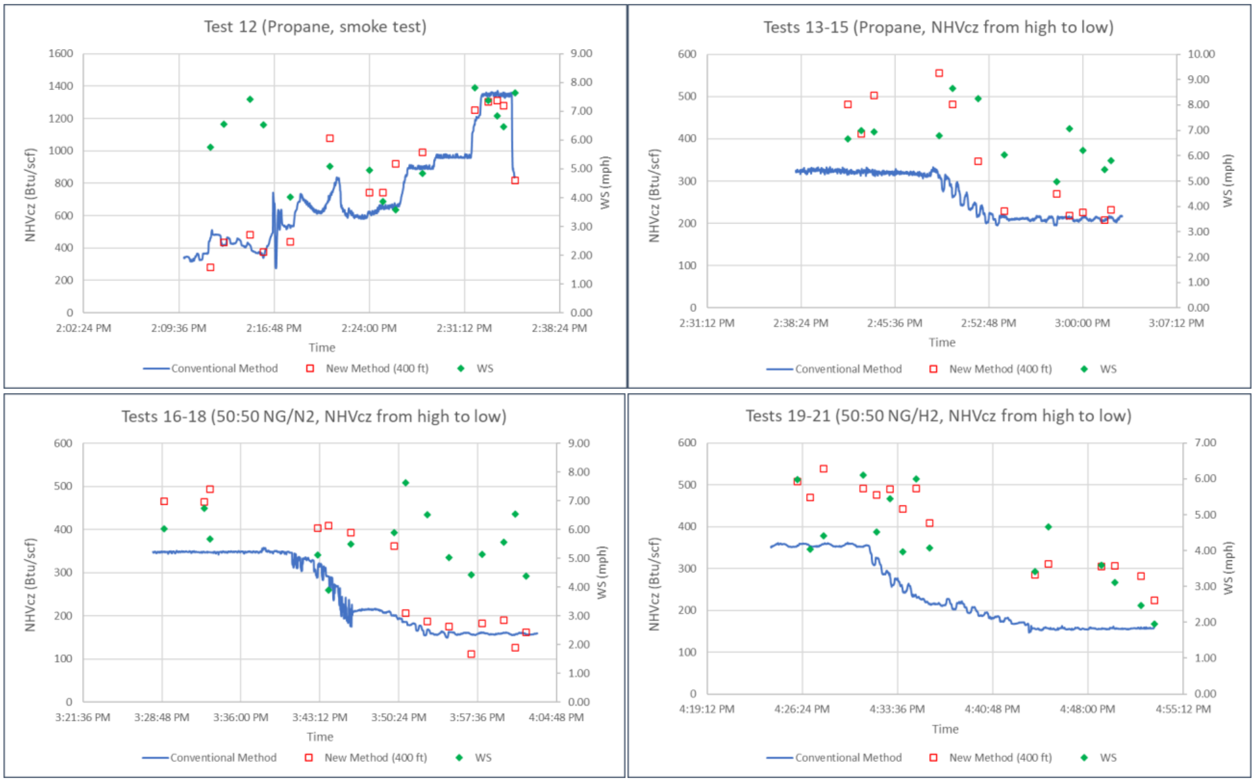

Figure 6: Flare NHVcz measured by the conventional method and the new method. Tests 12-21.

In **Figure 6**, with the exception of the smoke test (Test 12 in the upper left plot), the NHVcz measured by the new method is generally higher than that of the conventional method. More study may be needed to fully understand the divergence of the two methods. Some observations or speculations are offered here. The wind probably does not play a significant role in these Tests due to the high fuel rates and high exit velocities. It should be noted that in Tests 16-18 (the 50:50 natural gas and nitrogen mixture), the fuel rate in **Table 1** appears to be low, but it only accounts for natural gas and does not include nitrogen. When the mass of nitrogen is added, the combined mass flow rate is about 4 times higher than the flow rate of natural gas component of the mixture (due to the higher molecular weight of nitrogen and the target 50:50 being based on volume ratio). As a result, the effective exit velocity is much higher than what is indicated in **Table 1**. The conventional method does factor in the contribution of the nitrogen to the denominator of the NHVcz equation, making the NHVcz lower when more nitrogen is present. Does it over-compensate the effect of diluent nitrogen (resulting in a lower NHVcz), especially when the NHVcz is on the higher side of the EPA threshold of 270 BTU/scf (see the lower left chart in **Figure 6**)? Or does the new method produce a biased high result under such a condition. It is hard to draw a conclusion on which of the two methods is closer to the "true" value with this limited test data without another way to assess the true condition. In practice, this only matters when the value is very close to the EPA compliance threshold of 270 BTU/scf. In the conditions represented in Test 16-18, the two methods will yield the same compliance conclusion.

In the case of Tests 13-15 (upper right chart in **Figure 6**), the NHVcz measured by the new method is higher than that of the conventional method when the NHVcz is higher (the left half of the chart). Further test may help to see if this phenomenon is reproduceable and if so, what might cause the divergence.

In the case of Tests 19-21 for 50:50 mixture of natural gas and hydrogen (lower right chart in **Figure 6**), the NHVcz measured by the new method is consistently higher than that of the conventional method across the low and high NHVcz range. Again, it is difficult to judge which method is "correct" (or more appropriate to meet the intended purpose of this compliance parameter). Considering the extremely high heating value of hydrogen on a mass basis, we speculate that the new method is more reliable for the intended purpose of using the NHVcz as a compliance parameter. The fact that EPA has granted exceptions for flares with high hydrogen content would support our view. If the NHVcz is measured by the new method, there may be no need for a special exception from EPA. More study on this subject will be beneficial to stakeholders.

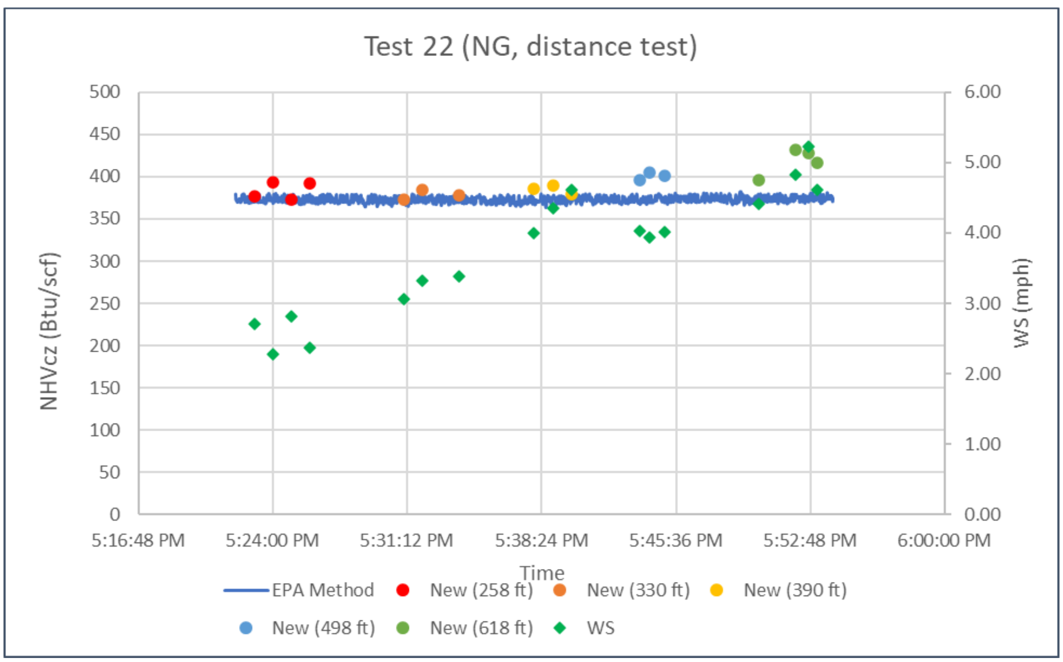

Figure 7: Flare NHVcz measured by the conventional method and the new method. Test 22.

Figure 7 summarizes the results of Test 22 designed to evaluate the performance of the new device with varying distances from the flare while the flare was held at near constant condition. As shown in **Figure 7**, the results are very consistent with the EPA method in the first three distances (~250 to 400 ft.). At the 4th distance (~500 ft.), the value begins to drift higher, and it continues to drift higher at the 5th distance (~620 ft.). We believe that the bias is introduced when the distance is too far and the pixels in the imager are not completely “filled” (i.e., some pixels cover a portion of the flare gas and a portion of the background or different parts of the flame that represent different phases of combustion). We expect this issue being addressed optically by using an appropriate field of view (FOV) for expected flame size. Based on this study (and future study), we intend to develop a deployment chart to help specify the proper combination of optics for the imager, distance from the flare, and expected flame size.

The fuel rate for Test 22 is high enough and the wind speed is not a noticeable factor. This is consistent with what is shown in **Figure 7**, especially the first three distances.

CONCLUSIONS AND FUTURE WORK

A new device/new method has been developed for remotely measuring or monitoring a key flare performance and compliance parameter, combustion zone net heating value (NHVcz). An initial test based on a prototype of the new device has shown very close agreement with the method specified by the EPA flare regulations, which relies on 7-10 inline instruments (depending on whether a supplemental fuel line is part of the flare system) to derive NHVcz. In this study, there are cases of divergence between the two methods. The divergence could be reflective of the fact that the conventional method specified in the EPA regulations only measures the process conditions, and it does not account for the effect of the environmental conditions (such as wind) on the combustion. The new method, by contrast, directly measures the flare condition so environmental effects will be included. Further study will provide a deeper understanding of the advantages and disadvantages of both methods, especially with the final design of the device which will provide continuous measurements at a 1-second data rate to match the data rate of the conventional method.

The new device is capable of simultaneously monitoring NHVcz, smoke index (SI) and other useful flare performance metrics such as flare thermal footprint, flame stability, and fractional heat release. The results of these additional metrics are beyond the scope of this paper and will be discussed in a separate publication.

This new method presents a great opportunity for streamlining flare monitoring. While the conventional method requires multiple inline instruments to derive a single compliance parameter (NHVcz), this method utilizes a single device to remotely monitor NHVcz along with other flare performance parameters. This device can demonstrate compliance with NHVcz regulations as well as EPA Method 22 opacity regulations. It is non-contact, extremely low maintenance, and has no latency. It is well suited for close-loop flare control for optimum operation at all times.

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