EPA United States Environmental Protection Agency

Region 6 - Enforcement & Compliance Assurance Division

INSPECTION REPORT

Inspection Date(s):	08/01-02/2022	
Media Program:	Air	
Regulatory Program(s)	SIP, Title V	
Company Name:	**BASF Corporation**	
Facility Name:	**Geismar Site**	
Facility Physical Location:	8404 River Road (Highway 75)	
(city, state, zip code)	Geismar, LA 70734	
County/Parish:	Ascension	
Facility Coordinates (Entrance):	30.188210, -91.012321	
Facility Phone Number	225-339-2231	
Facility Contact:	David Mihalik	EHSMS Director
	david.mihalik@basf.com	
FRS Number:	110000597364	
Identification/Permit Number:	LDEQ Agency Interest Number 2049	
Media Identifier Number:	AFS # 22-005-00013	
NAICS:	325199 - All Other Basic Organic Chemical Manufacturing	
SIC:	2869 - Industrial Organic Chemicals	
Personnel participating in inspection:		
James Haynes	EPA Region 6, Air Toxics Enforcement	Physical Scientist
Colleen McCarthy	EPA Region 6, Air Toxics Enforcement	Life Scientist
Dan Hoyt	EPA OECA, Air Enforcement Division	Environmental Engineer
Jon Morris	Providence Photonics	EPA Contractor
Michael Morris	Providence Photonics	EPA Contractor
Daniel Wolf	BASF Corporation	Environmental Team Leader
David Mihalik	BASF Corporation	EHSMS Director
EPA Lead Inspector Signature/Date	JAMES HAYNES Digitally signed by JAMES HAYNES Date: 2023.01.27 13:12:21 -06'00'	
	James Haynes	Date
Supervisor Signature/Date	JAMES LEATHERS Digitally signed by JAMES LEATHERS Date: 2023.01.27 14:02:44 -06'00'	
	James Leathers	Date

6ENFORM-019-R8.2 (02/12/2020)

Section I – INTRODUCTION

PURPOSE OF THE INSPECTION

I, James Haynes, U.S. Environmental Protection Agency ("EPA") Region 6 inspector, arrived at the BASF Corporation ("BASF") Geismar Site in Geismar, LA on August 1 and 2, 2022, to conduct an unannounced Clean Air Act ("CAA") inspection. I arrived with Ms. Colleen McCarthy, EPA Region 6 inspector, Mr. Dan Hoyt, EPA OECA-AED inspector, and two EPA contractors with Providence Photonics – Mr. Jon Morris and Mr. Michael Morris. We met with BASF representatives Mr. Daniel Wolf, Environmental Team Leader, and Mr. David Mihalik, EHSMS Director. I presented my inspector credentials to Mr. Mihalik and notified him of my intent to conduct a CAA Partial Compliance Evaluation ("PCE"). EPA contracted Providence Photonics to conduct flare observations using the Video Imaging Spectral Radiometry ("VISR") method. VISR uses a cooled, multi-spectral mid-wave infrared imager to measure relative concentrations of combustion gases to calculate a flare's combustion efficiency ("CE").

FACILITY DESCRIPTION

The Geismar Site is an integrated chemical manufacturing facility that manufacturers acetylene, amine compounds, aniline, 1,4-butanediol, ethylene oxide, formic acid, MDI, TDI, polyols, and other chemicals.

Section II – OBSERVATIONS

On August 1, 2022, Mr. Wolf and Mr. Mihalik provided me with an overview of the site operations and current conditions. Providence Photonics set up the imaging device outside the process area and began collecting CE data at the EO flare at 03:45 PM. We also collected CE data at the TDI, Acetylene Synthesis, Polyol, MDI-1, and Specialty Amines flares. Providence Photonics stopped collecting data at 06:54 PM.

On August 2, 2022, we continued evaluating other BASF flares. Providence Photonics set up the imaging device outside the process area and began collecting CE data at the Diols flare at 03:31 PM. We continued to the Aniline, Aniline I, and Aniline II flares. Providence Photonics stopped collecting CE data at 05:11 PM. See Appendix 1. We conducted a closing conference with BASF and exited the facility.

Section III – AREAS OF CONCERN

During the closing conference, I noted that the Diols and Aniline flares' CE was lower than expected. In general, achieving 96.5% CE correlates to approximately 98% destruction efficiency and good flare performance.

Section IV – FOLLOW UP

After EPA exited the facility, BASF provided additional information on August 19 and November 3, 2022.

Section V – LIST OF APPENDICES

Appendix 1 – VISR Flare Measurement Report

Appendix 1

VISR Flare Measurement Report

PROVIDENCE PHOTONICS

VISR Flare Measurement Report

Facility: BASF Corp – Geismar Site

8404 River Road

Geismar, LA 70734

Ascension Parish, Louisiana

Prepared for

US Environmental Protection Agency

Region 6

1201 Elm Street, Suite 500

Dallas, TX 75270

PROJECT NO. 0010-004-002

PREPARED BY

Providence Photonics, LLC | 1201 Main Street, Baton Rouge, LA 70802

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Introduction

Through its contract 68HERC21D0007/Task Order 68HERC21F0185 with Eastern Research Group, Inc. (ERG), EPA Office of Enforcement and Compliance (OECA) and Region 6 retained Providence Photonics, LLC (Providence) to assist the inspection of the BASF Corp facility (BASF) located at 8404 River Road, Geismar Louisiana, 70734. Providence measured the combustion efficiency (CE) and other performance metrics of several BASF flares using the Video Imaging Spectral Radiometry (VISR) method.

Background

The VISR method utilizes a multi-spectral mid-wave infrared imager to remotely and continuously measure relative concentrations of combustion gases. Based on these relative concentrations, flare CE is calculated. The VISR method provides continuous measurement of the following five flare performance metrics at 1-second data rate.

1. **Combustion Efficiency (0 to 100%):** Combustion efficiency (**CE**) is a measure of the relative concentration of hydrocarbon vs. carbon dioxide in the post combustion gas plume. If there is no hydrocarbon present in the post combustion gas plume, then CE is 100%.
2. **Smoke Index (0 to 10):** Smoke index (**SI**) is a unit-less number which indicates the degree of visible emissions within the combustion envelope. A SI of 0 means no visible emissions are present while a SI of 10 means the flare has heavy black smoke. While SI only represents the degree of visible emissions within the combustion envelope, it is generally correlated to opacity and a SI above 3 generally indicates that some visible emissions are likely present outside of the combustion envelope.
3. **Flame Footprint (m^2):** Flame footprint (**FF**) is a measure of the flame size in square meters. It is not necessarily correlated to the visible flame size as the FF is determined by the Infrared radiance, not the visible flame. Note that the orientation of the flame will impact the FF as the depth of the flame will change with viewing angle.
4. **Fractional Heat Release (MMBtu/Hr):** Fractional Heat Release (**FH**) is a measure of the heat released from flare combustion in the spectral bands monitored by the Mantis flare monitor. Although it is not a measure of the total heat release across the entire energy spectrum, FH is expected to be correlated to the total heat release.
5. **Flame Stability (0 to 100%):** Flame stability (**FS**) is a measure of the change in radiance measured by the Mantis flare monitor in a 1-second interval. A FS of 100% indicates a flame that has a constant radiance. A low FS value (generally lower than 80%) indicates a flame with significant radiance fluctuation within 1 second interval, suggesting a less stable flame. Variability on a longer time scale will not be described by the flame stability metric.

Appendix B provides additional information on the accuracy and precision of the VISR method. More information about the VISR method and its validation is provided at https://www.providencephotonics.com/flare-monitoring.

Summary of Inspection

Inspection Date: August 1st – 2nd, 2022

Personnel:

James Haynes (EPA Region 6)

Colleen McCarthy (EPA Region 6)

Daniel Hoyt (EPA OECA)

Jon Morris (Providence)

Michael Morris (Providence)

Facility:

BASF Corp

8404 River Road, Geismar, LA 70734

Results: ***Table 1*** below provides a summary of the VISR results. Complete results can be found in ***Appendix A***.

Date	Start Time (Local)	End Time (Local)	Site Description	Distance (m)	Temp (°C)	RH (%)	Avg Wind Speed (mph)	CE Avg (%)	SI Avg	FF Avg (m2)	FH Avg (MMBTU/HR)	FS Avg (%)
8/1/2022	3:45 PM	4:00 PM	EOEG	196	32	83	2 - 4	97.25	0.88	18.77	0.29	96.19
8/1/2022	4:35 PM	4:37 PM	TDI	120	32	75	2 - 4	98.04	0.28	6.06	0.07	94.97
8/1/2022	5:22 PM	5:37 PM	399	246	29	67	2 - 4	98.77	0.45	25.38	0.41	95.63
8/1/2022	5:45 PM	6:00 PM	Polyol	65	29	67	2 - 4	97.84	0.19	4.05	0.05	94.56
8/1/2022	6:16 PM	6:31 PM	MDI1	110	27	67	2 - 4	97.85	0.15	6.56	0.07	94.19
8/1/2022	6:39 PM	6:54 PM	Amines	103	27	78	2 - 4	97.57	0.76	22.58	0.38	94.98
8/2/2022	3:31 PM	3:46 PM	DIOLS	128	32	70	2 - 4	96.85	0.65	13.03	0.19	96.19
8/2/2022	4:21 PM	4:43 PM	Aniline 501	145	31	63	2 - 4	94.43	0.61	5.45	0.04	93.99
8/2/2022	4:53 PM	4:58 PM	Aniine 503	56	31	63	2 - 4	99.15	0.83	0.12	0.00	93.15
8/2/2022	5:00 PM	5:11 PM	Aniline 501 (repeat)	132	31	63	2 - 4	93.81	0.37	4.62	0.05	94.16

Table 1: Summary VISR Results.

Observations

The following sections describe field observations and comparisons derived from the dataset.

Field Conditions

The inspections were conducted on August 1st and August 2nd, 2022. Each measurement with the VISR instrument was within the method limits for distance, as determined by the minimum plume pixels required by the QAPP. The ambient temperature ranged from 27°C to 32°C and winds were generally light, from 2 – 4 mph. On the evening of August 1st, a strong thunderstorm moved through the facility. The rain coincided with the measurement of the DIOLS flare and impacted the quality of the VISR data. The DIOLS flare measurement was repeated on August 2nd.

On August 1st, a temporary equipment malfunction prevented continuous recording of the VISR data. The malfunction impacted only the TDI flare measurement. As a result, only 2 minutes of VISR data was recorded for the TDI flare measurement.

EOEG Flare

The EOEG flare performance data is plotted in ***Figures 1 and 2*** below. ***Figure 1*** shows Combustion Efficiency vs. Fractional Heat Release and ***Figure 2*** shows Combustion Efficiency vs. Smoke Index. There were no visible emissions from this flare, as indicated by the Smoke Index values < 3. Average Combustion Efficiency for this measurement was 97.25% and the average Smoke Index was 0.88.

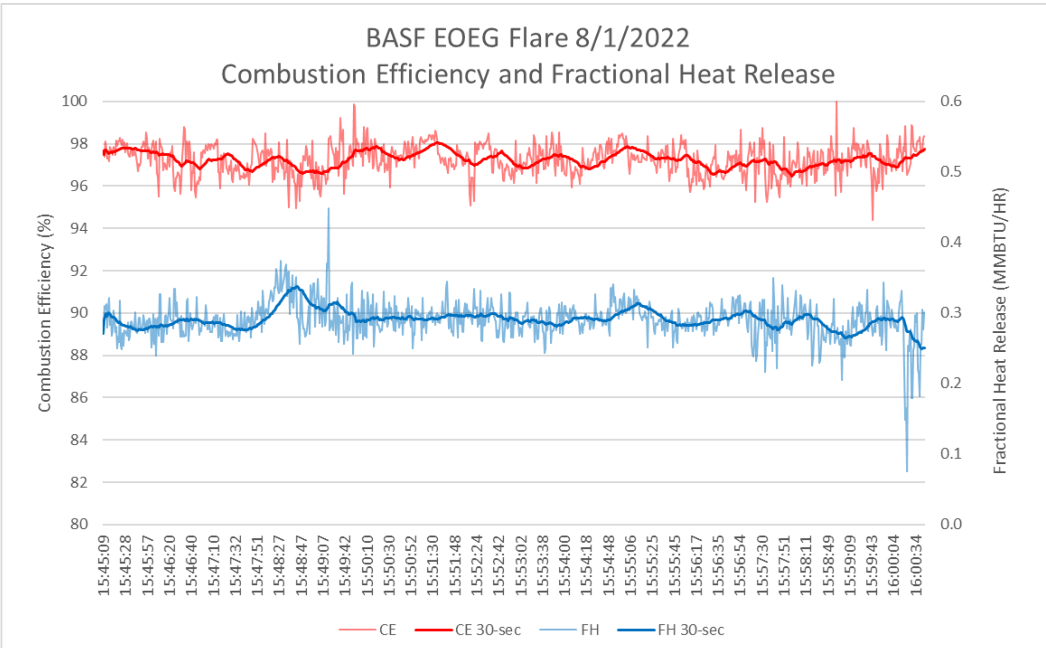


Figure 1: Combustion Efficiency and Fractional Heat Release for BASF EOEG flare on 8/1/2022.

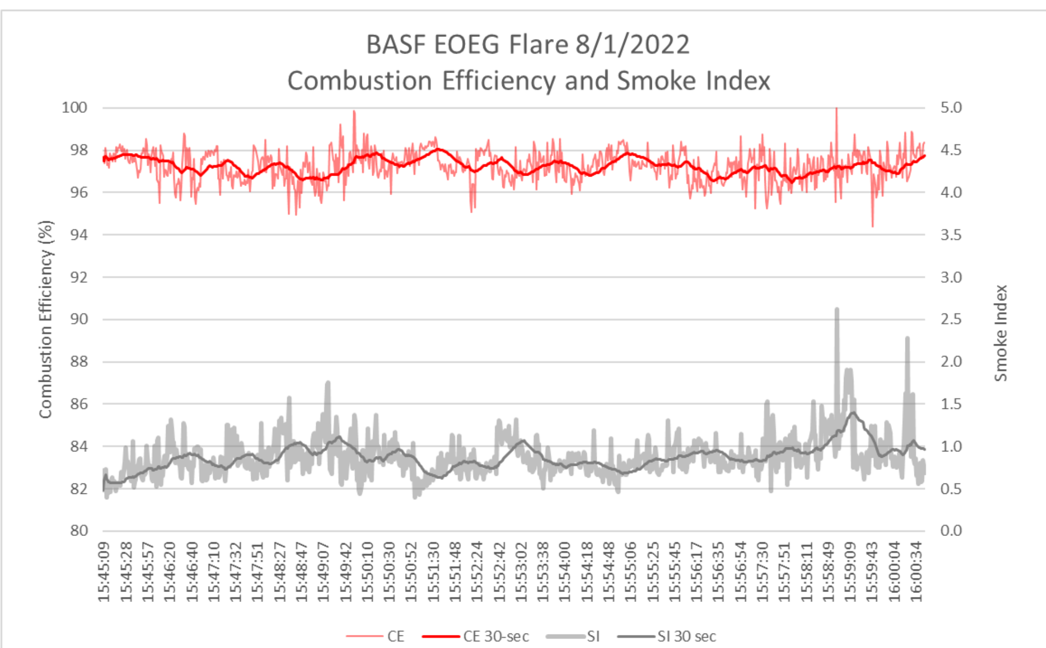


Figure 2: Combustion Efficiency and Smoke Index for BASF EOEG flare on 8/1/2022.

399 Flare

Figure 3 shows Combustion Efficiency vs. Fractional Heat Release for the 399 flare and ***Figure 4*** shows Combustion Efficiency vs. Smoke Index.   There were no visible emissions from this flare, as indicated by the Smoke Index values < 3. Average Combustion Efficiency for this measurement was 98.77% and the average Smoke Index was 0.45.

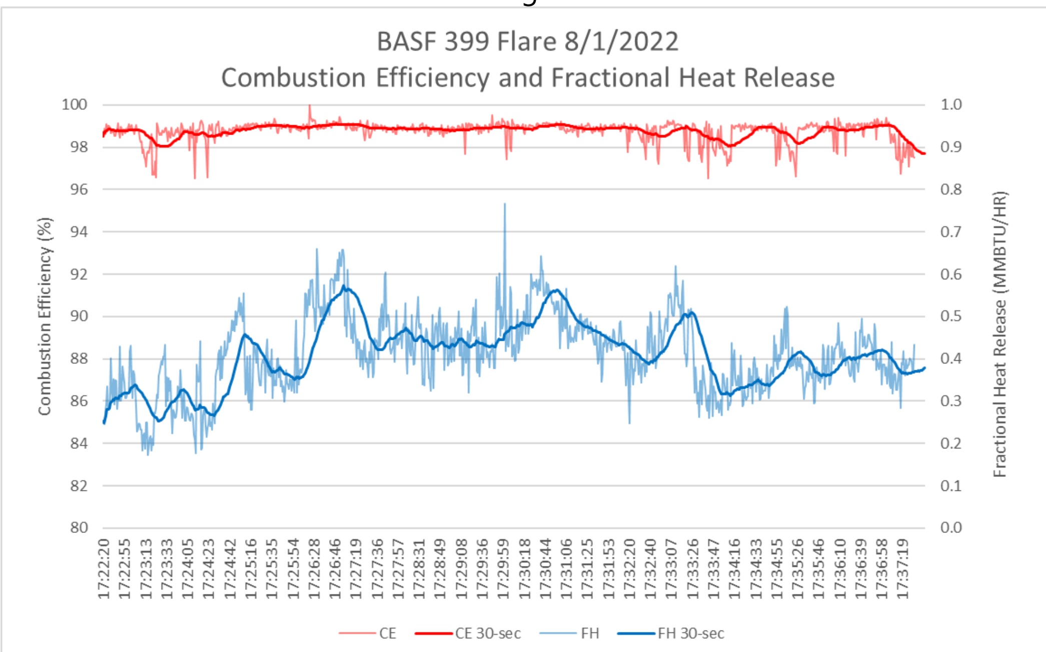


Figure 3: Combustion Efficiency and Fractional Heat Release for BASF 399 flare on 8/1/2022.

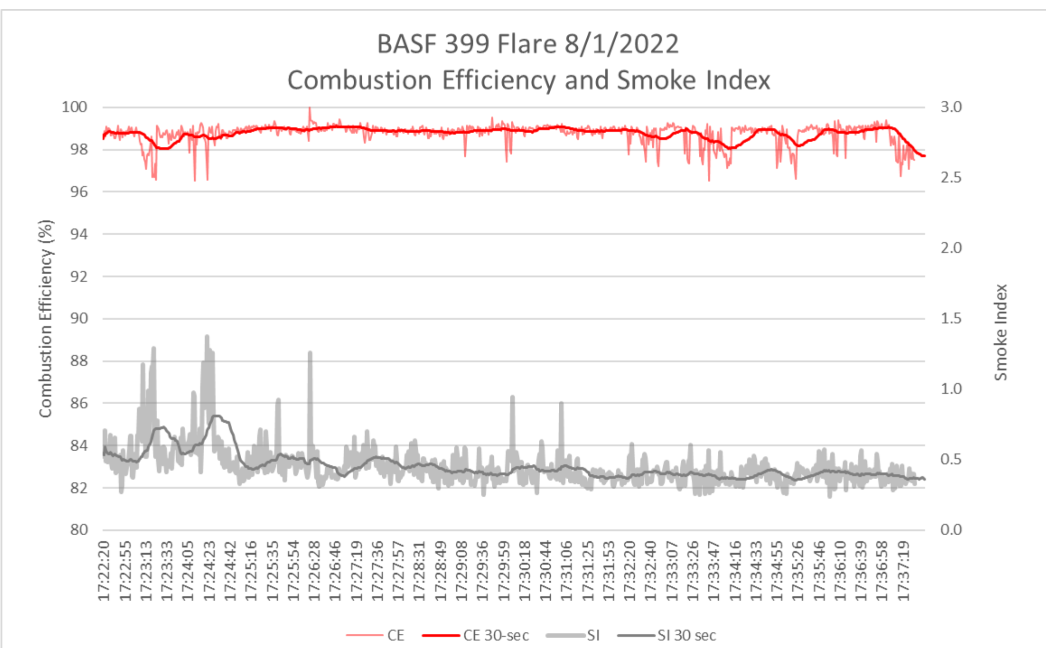


Figure 4: Combustion Efficiency and Smoke Index for BASF 399 flare on 8/1/2022.

Polyol Flare

Figure 5 shows Combustion Efficiency vs. Fractional Heat Release for the Polyol flare and ***Figure 6*** shows Combustion Efficiency vs. Smoke Index. There were no visible emissions from this flare, as indicated by the Smoke Index values < 3. Average Combustion Efficiency for this measurement was 97.84% and the average Smoke Index was 0.19.

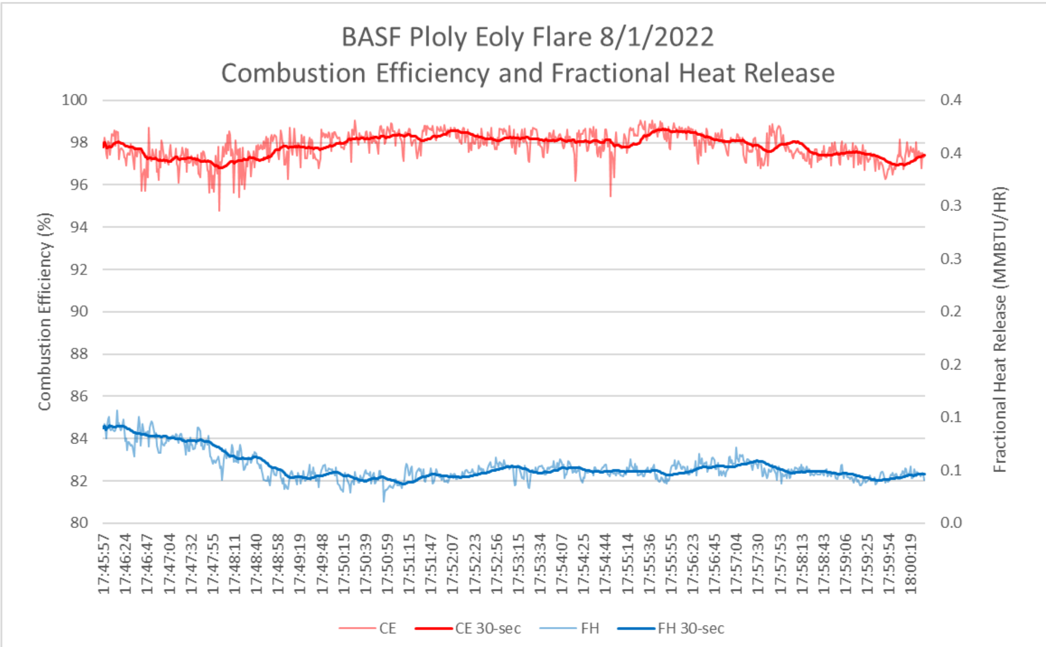


Figure 5: Combustion Efficiency and Fractional Heat Release for BASF Polyol flare on 8/1/2022.

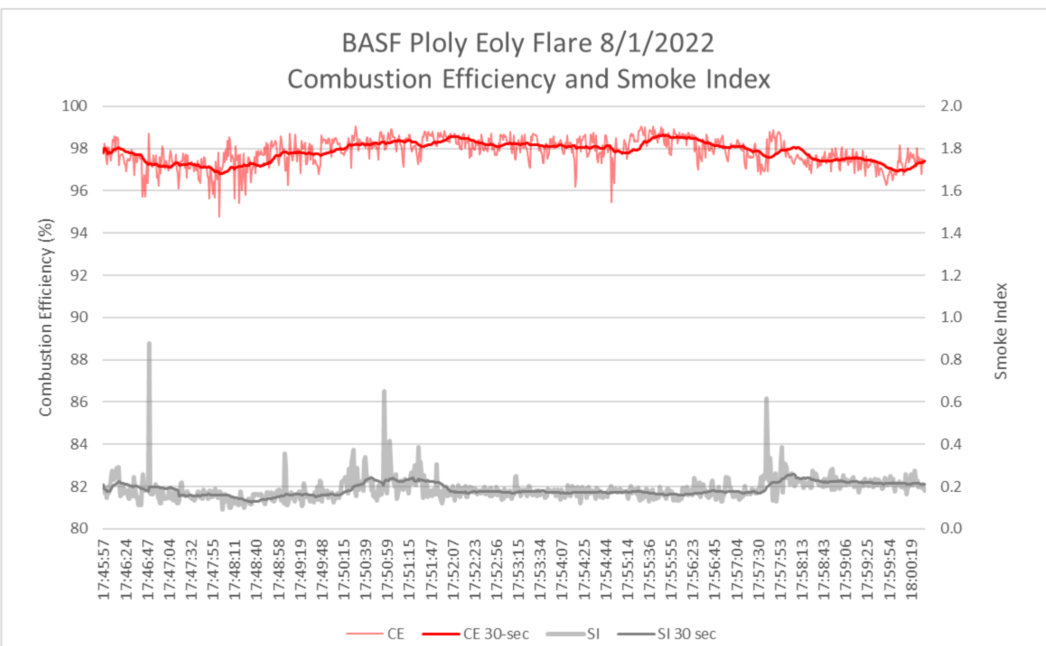


Figure 6: Combustion Efficiency and Smoke Index for BASF Polyol flare on 8/1/2022.

MDI1 Flare

Figure 7 shows Combustion Efficiency vs. Fractional Heat Release for the MDI1 flare and ***Figure 8*** shows Combustion Efficiency vs. Smoke Index. There were no visible emissions from this flare, as indicated by the Smoke Index values < 3. Average Combustion Efficiency for this measurement was 97.85% and the average Smoke Index was 0.15.

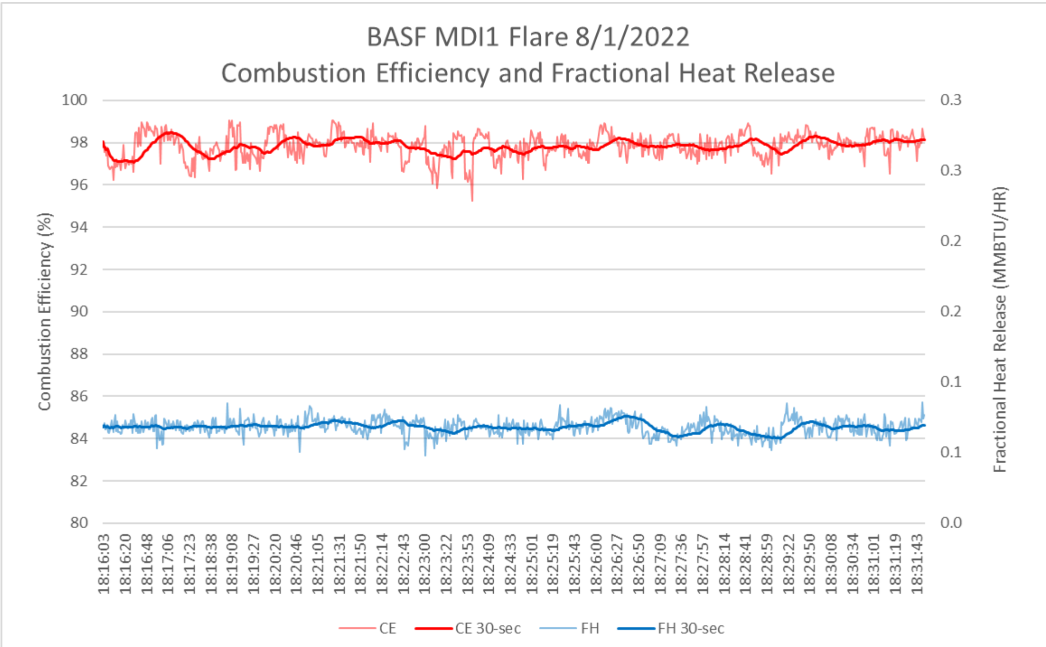


Figure 7: Combustion Efficiency and Fractional Heat Release for BASF MDI1 flare on 8/1/2022.

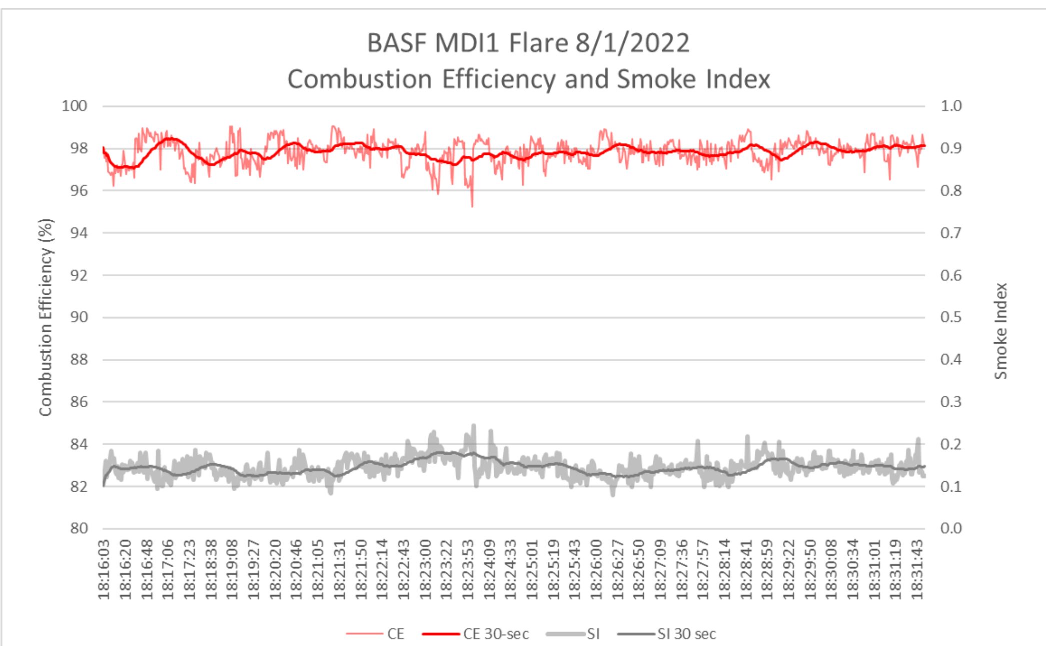


Figure 8: Combustion Efficiency and Smoke Index for BASF MDI1 flare on 8/1/2022.

Amines Flare

Figure 9 shows Combustion Efficiency vs. Fractional Heat Release for the Amines flare and ***Figure 10*** shows Combustion Efficiency vs. Smoke Index. There were no visible emissions from this flare, as indicated by the Smoke Index values < 3. Average Combustion Efficiency for this measurement was 97.57% and the average Smoke Index was 0.76.

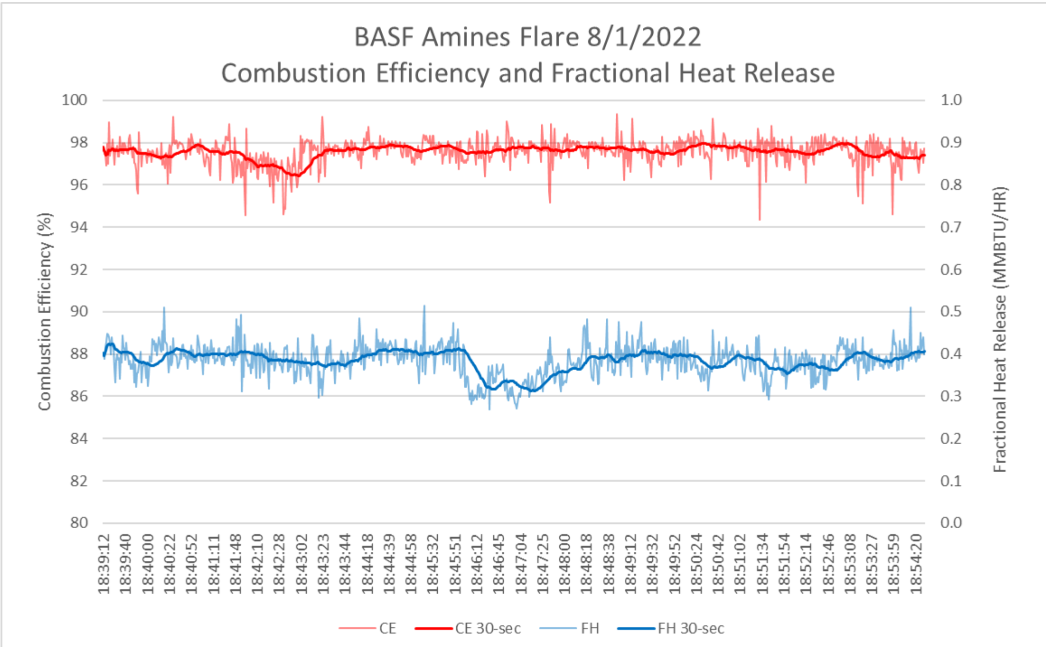


Figure 9: Combustion Efficiency and Fractional Heat Release for BASF Amines flare on 8/1/2022.

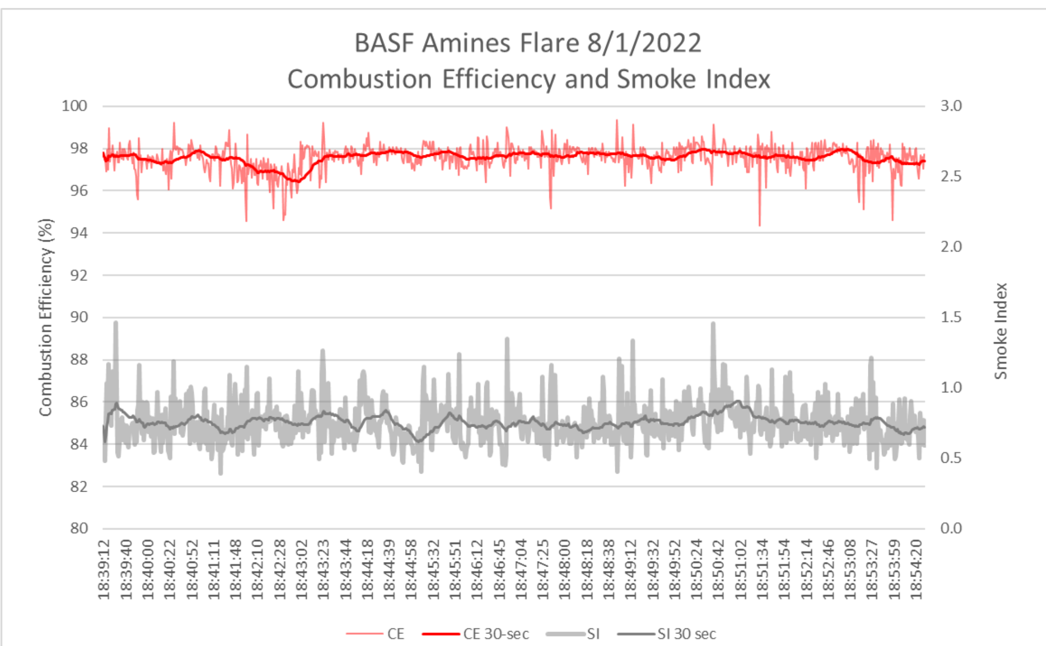


Figure 10: Combustion Efficiency and Smoke Index for BASF Amines flare on 8/1/2022.

DIOLS Flare

Figure 11 shows Combustion Efficiency vs. Fractional Heat Release for the DIOLS flare and ***Figure 12*** shows Combustion Efficiency vs. Smoke Index. This chart depicts the second measurement of the DIOLS flare conducted on 8-2-2022 as the first measurement was impacted by heavy rain. There were no visible emissions from this flare, as indicated by the Smoke Index values < 3. Average Combustion Efficiency for this measurement was 96.85% and the average Smoke Index was 0.65.

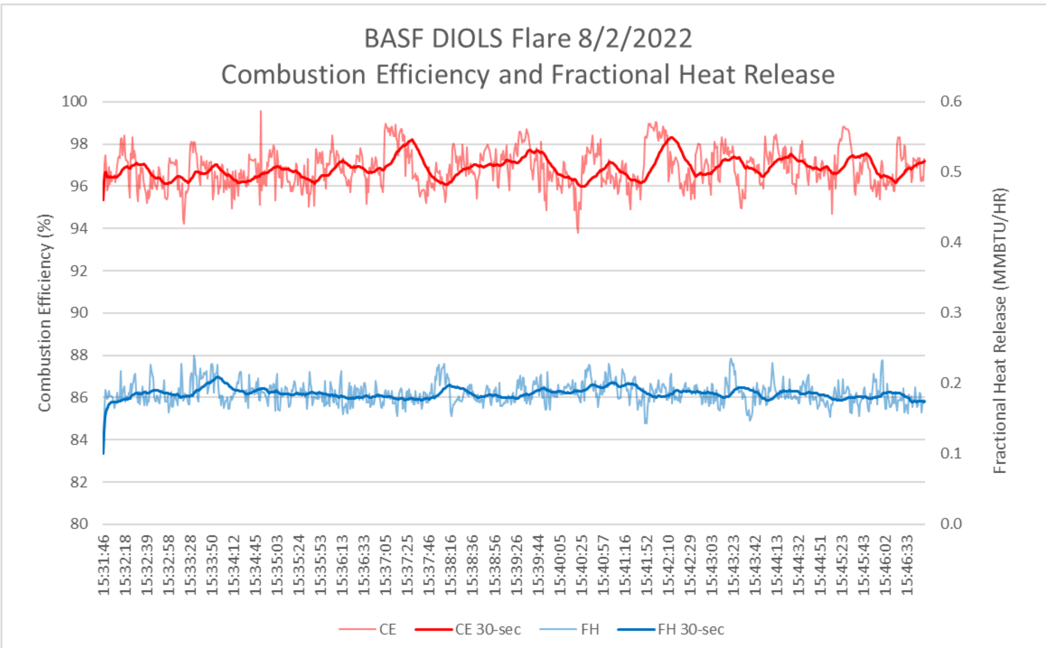


Figure 11: Combustion Efficiency and Fractional Heat Release for BASF DIOLS flare on 8/2/2022.

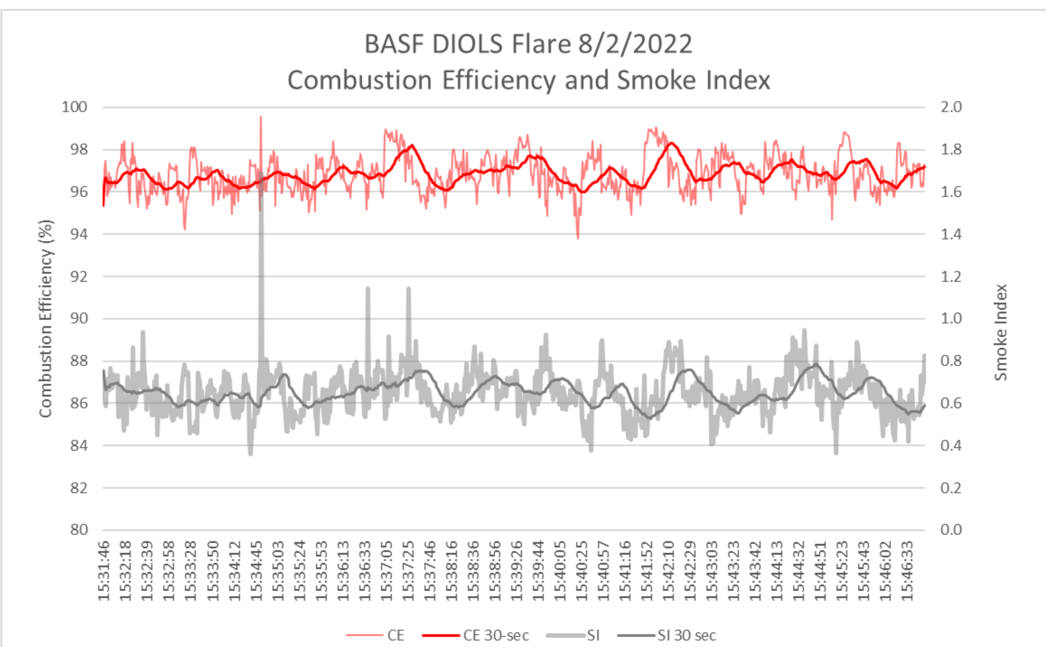


Figure 12: Combustion Efficiency and Smoke Index for BASF DIOLS flare on 8/2/2022.

Aniline 501 Flare

Figure 13 shows Combustion Efficiency vs. Fractional Heat Release for the Aniline 501 flare and ***Figure 14*** shows Combustion Efficiency vs. Smoke Index. There were no visible emissions from this flare, as indicated by the Smoke Index values < 3. Average Combustion Efficiency for this measurement was 94.43% and the average Smoke Index was 0.61.

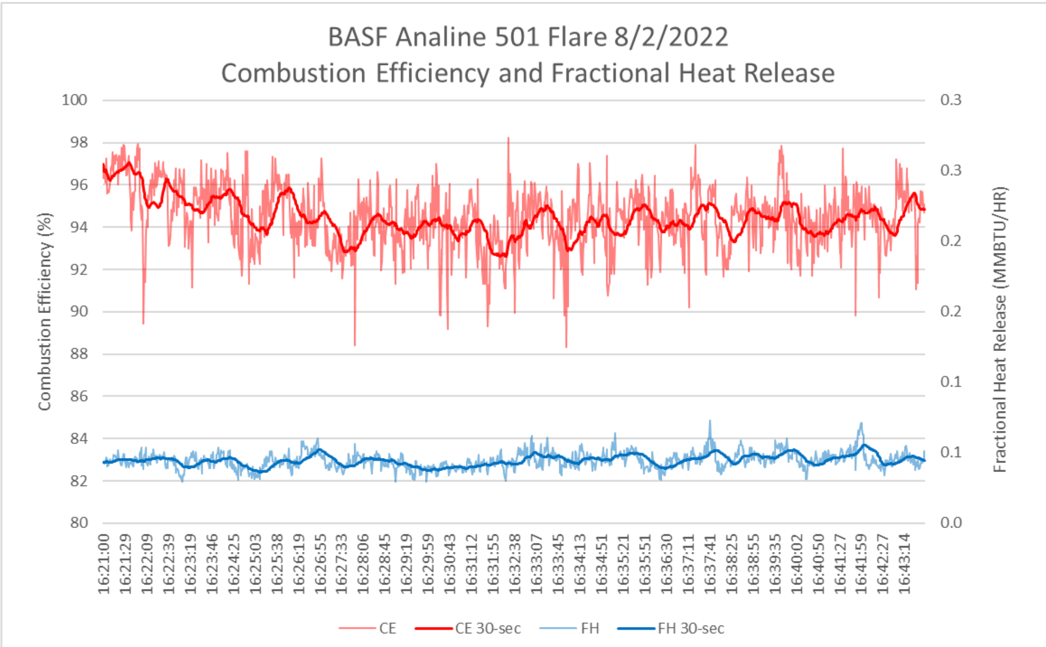


Figure 13: Combustion Efficiency and Fractional Heat Release for BASF Aniline 501 flare on 8/2/2022.

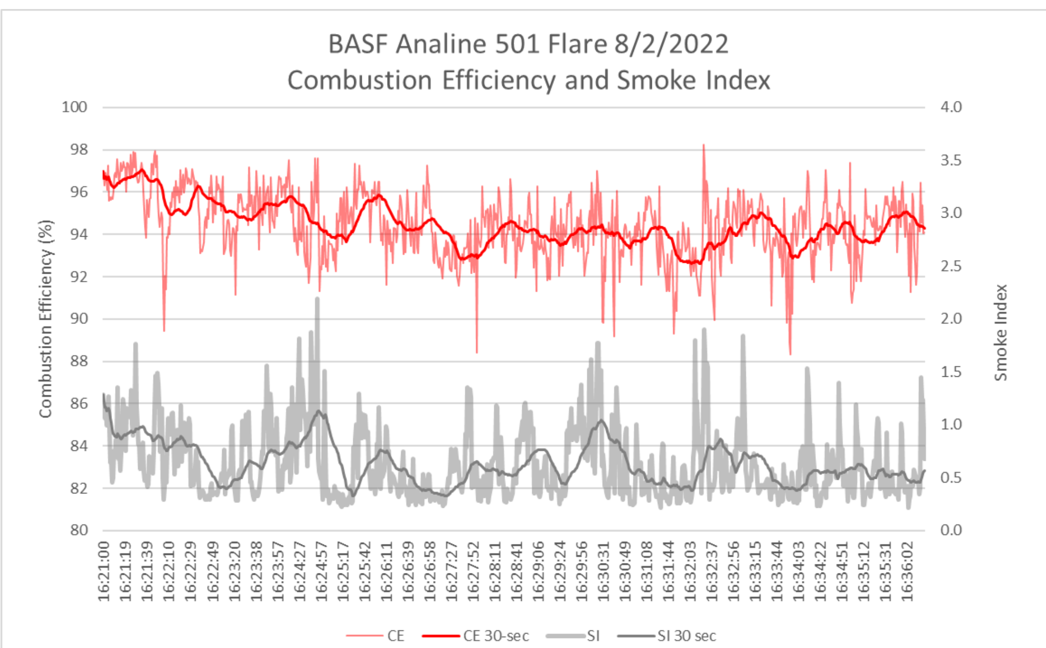


Figure 14: Combustion Efficiency and Smoke Index for BASF Aniline 501 flare on 8/2/2022.

Aniline 503 Flare

Figure 15 shows Combustion Efficiency vs. Fractional Heat Release for the Aniline 503 flare and ***Figure 16*** shows Combustion Efficiency vs. Smoke Index. There were no visible emissions from this flare, as indicated by the Smoke Index values < 3. Average Combustion Efficiency for this measurement was 99.15% and the average Smoke Index was 0.83.

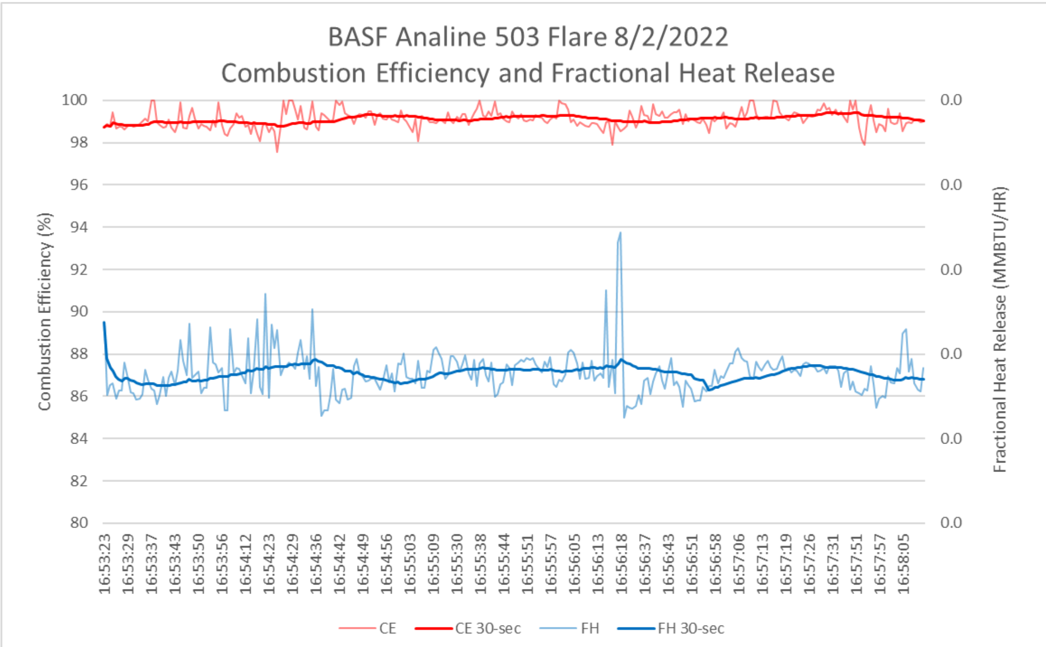


Figure 15: Combustion Efficiency and Fractional Heat Release for BASF Aniline 503 flare on 8/2/2022.

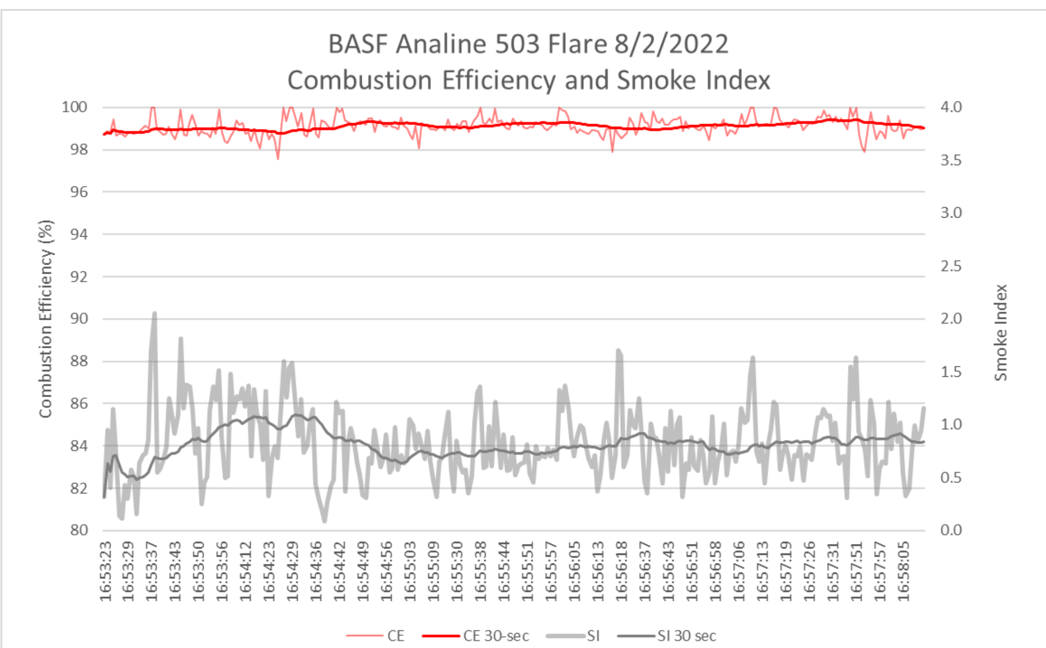


Figure 16: Combustion Efficiency and Smoke Index for BASF Aniline 503 flare on 8/2/2022.

Aniline 501 Flare (2nd location)

Figure 17 shows Combustion Efficiency vs. Fractional Heat Release for the Aniline 501 flare and ***Figure 18*** shows Combustion Efficiency vs. Smoke Index. This data depicts a second measurement of the Aniline 501 flare from a different location. There were no visible emissions from this flare, as indicated by the Smoke Index values < 3. Average Combustion Efficiency for this measurement was 93.81% and the average Smoke Index was 0.37.

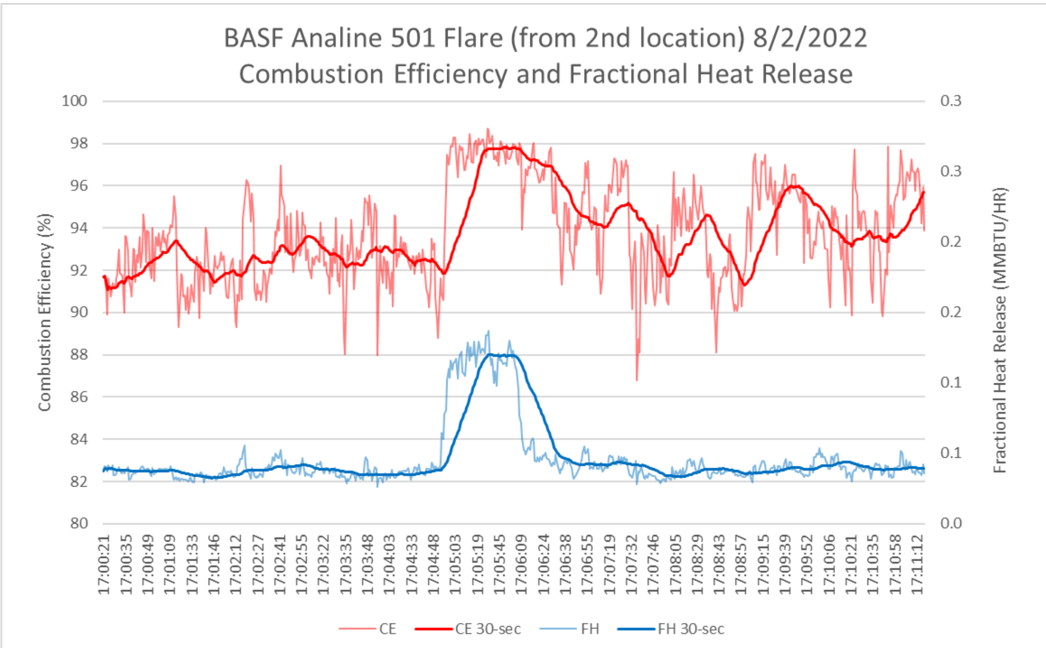


Figure 17: Combustion Efficiency and Fractional Heat Release for BASF Aniline 501 (2nd Location) flare on 8/2/2022.

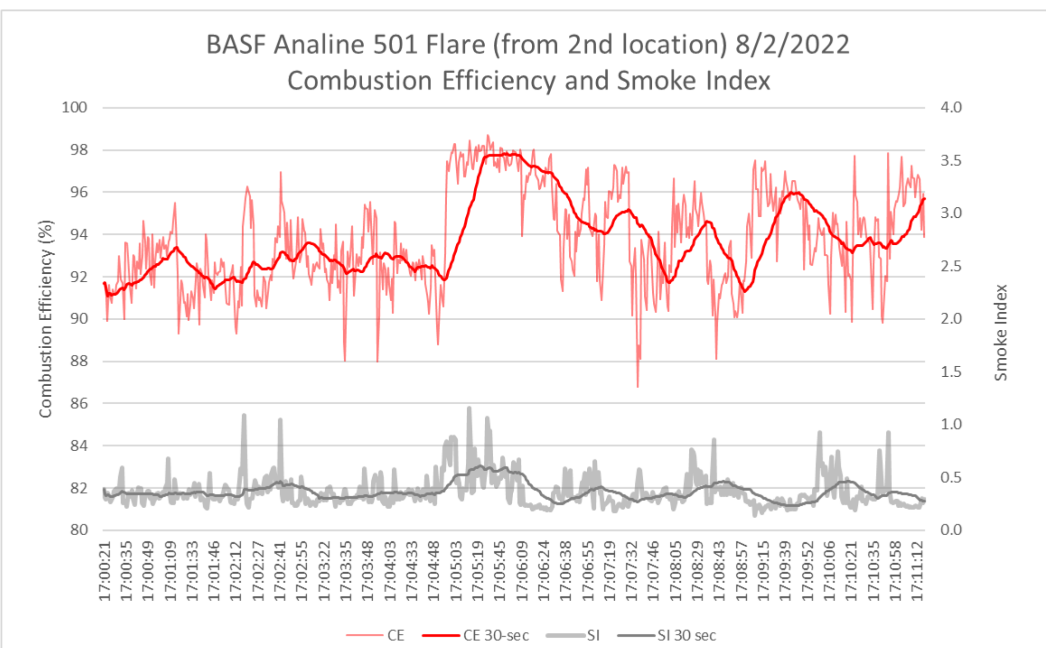


Figure 18: Combustion Efficiency and Smoke Index for BASF Aniline 501 (2nd location) flare on 8/2/2022.

Electronic Data Generated from the Test

The following electronic data are submitted to the US EPA Region 6 as part of this report:

- A Microsoft Excel file containing second-by-second results from the VISR instrument and averages for each measurement period.
- FLIR video recording of each flare during the inspection.

References

1. Yousheng Zeng, Jon Morris & Mark Dombrowski (2015) Validation of a new method for measuring and continuously monitoring the efficiency of industrial flares, Journal of the Air & Waste Management Association, 66:1, 76-86, DOI: 10.1080/10962247.2015.1114045
2. Yousheng Zeng, Jon Morris. (2019, April 2nd). *Precision and Accuracy of the VISR Method for Flare Monitoring*. Air Quality Measurement Methods and Technology, Durham, North Carolina, United States.

Appendix A: Results

Date	Start Time (CST)	End Time (CST)	Site	Description	Distance (m)	Temp (°C)	RH (%)	Wind Speed (mph)	CE Avg	CE Min	CE Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD
8/1/2022	3:45 PM	4:00 PM	BASF Geismer	EOEG	196	32	83	2 - 4	97.25	94.42	99.99	0.73	0.9	0.4	2.6	0.2	18.8	12.6	26.1	1.8	0.291	0.075	0.448	0.026	96.2	69.9	100.0	3.1
8/1/2022	4:35 PM	4:37 PM	BASF Geismer	TDI	120	32	75	2 - 4	98.04	96.87	98.73	0.40	0.3	0.2	0.5	0.1	6.1	3.8	7.1	0.8	0.071	0.042	0.088	0.011	95.0	78.3	99.6	4.8
8/1/2022	5:22 PM	5:37 PM	BASF Geismer	399	246	29	67	2 - 4	98.77	96.53	99.99	0.48	0.5	0.2	1.4	0.1	25.4	14.3	37.9	4.7	0.410	0.173	0.766	0.090	95.6	70.6	100.0	3.6
8/1/2022	5:45 PM	6:00 PM	BASF Geismer	Polyol	65	29	67	2 - 4	97.84	94.76	99.07	0.66	0.2	0.1	0.9	0.1	4.0	1.8	7.9	1.0	0.053	0.020	0.107	0.014	94.6	75.9	100.0	3.5
8/1/2022	6:16 PM	6:31 PM	BASF Geismer	MDI1	110	27	67	2 - 4	97.85	95.25	99.07	0.58	0.1	0.1	0.2	0.0	6.6	5.0	8.3	0.6	0.068	0.048	0.086	0.006	94.2	85.3	100.0	2.8
8/1/2022	6:39 PM	6:54 PM	BASF Geismer	Amines	103	27	78	2 - 4	97.57	94.35	99.34	0.60	0.8	0.4	1.5	0.1	22.6	16.3	29.9	2.1	0.384	0.269	0.515	0.037	95.0	81.3	100.0	3.3
8/2/2022	3:31 PM	3:46 PM	BASF Geismer	DIOLS	128	32	70	2 - 4	96.85	93.78	99.56	0.89	0.6	0.4	1.7	0.1	13.0	10.2	16.8	1.1	0.186	0.101	0.239	0.016	96.2	88.5	100.0	2.1
8/2/2022	4:21 PM	4:43 PM	BASF Geismer	Aniline 501	145	31	63	2 - 4	94.43	88.35	98.23	1.48	0.6	0.2	2.2	0.3	5.5	3.6	8.4	0.7	0.045	0.029	0.073	0.006	94.0	42.9	100.0	3.6
8/2/2022	4:53 PM	4:58 PM	BASF Geismer	Aniline 503	56	31	63	2 - 4	99.15	97.54	99.99	0.41	0.8	0.1	2.1	0.3	0.1	0.1	0.2	0.0	0.000	0.000	0.001	0.000	93.2	60.2	99.7	5.3
8/2/2022	5:00 PM	5:11 PM	BASF Geismer	Aniline 501 (repeat)	132	31	63	2 - 4	93.81	86.80	98.70	2.34	0.4	0.1	1.2	0.1	4.6	3.4	10.4	1.4	0.046	0.026	0.137	0.023	94.2	80.1	99.9	2.9

Table 2: Complete VISR Results.

Appendix B: Validation of the VISR method

Precision and Accuracy of the VISR Method for Flare Monitoring

Extended Abstract: ME92
Presented at the conference:
Air Quality Measurement Methods and Technology
April 2-4, 2019
Durham, NC

Jon Morris, Yousheng Zeng, and Srikanth Mutyala
Providence Photonics, Baton Rouge, Louisiana

Introduction

Industrial flares represent a large category of air emission sources for Volatile Organic Compounds (VOC), air toxics, and greenhouse gases (GHG)[1-4]. Depending on their combustion efficiency (CE), the emissions of these air pollutants can be significantly different. Despite the large contribution of flares to air emission inventories, flares are the only source category for which no EPA test or monitoring methods can be applied to directly measure their efficiency or emission rates. As a result, flare emissions in air emission inventories may carry significant uncertainties.

A method based on Video Imaging Spectral Radiometry (VISR) has been developed for testing or continuously monitoring combustion efficiency (CE) of industrial flares[5]. To validate the VISR method, tests were conducted at flare test facilities of Zeeco, Inc. (Zeeco) and John Zink Hamworthy Combustion (John Zink), both located in Tulsa, Oklahoma, in September and October 2016, respectively. The test at Zeeco included both an air assisted flare and a steam assisted flare. Twenty-eight flare conditions were tested, 14 for the air flare and 14 for the steam flare. This test is referred to as the "Zeeco Test" in this paper.

The test at John Zink was part of a program sponsored and organized by the Petroleum Environmental Research Forum (PERF), an industry consortium. PERF project 2014-10 Direct Monitoring of Flare Combustion Efficiency was created and funded 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 blind test was administered by John Zink. Testing began on October 17th, 2016 and continued for 10 days, concluding on October 27th, 2016. The flare tip used was the John Zink model EEF-QSC-36, which was the same flare tip used during the 2010 TCEQ Flare Study[4]. A test protocol was developed which identified a series of test conditions to evaluate various factors that could affect flare CE measurement. Only limited logistical and environmental factors were shared with the Invitees (i.e., distance from the flare, view angle with respect to flame orientation due to wind, sun in/out of the field of view, daytime/nighttime testing). Information regarding flare operations such as the type of fuel gas used, firing rates, steam rates or any other flare operating parameters was concealed from Invitees. A total of 45 test points was evaluated over the 10 days of testing. Extractive sampling was performed on each test point as the control method for flare CE measurement. The results of the extractive sampling were not provided to Invitees until Invitees submitted their won results based on their respective measurement technology. This test is referred to as the "PERF Test" in this paper.

In this paper, the precision and accuracy of the VISR method are evaluated based on the test campaigns described above.

Methods and experimental setup

The VISR flare monitor is a remote monitoring device that can be positioned at any distance as long as 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 were in the range of 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 concentrations of CO_2, CO, and HC were used to calculate flare CE per method used in the 2010 TCEQ flare study[3].

These test campaigns covered a wide range of process conditions: two steam flares and one air flare; 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 for the steam flares and net heating value dilution parameter (NHVdil) in a range of 6.7 to 244 Btu/ft^2 for the air flare.

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.

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[6]. 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 1** 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 1**, 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)[6]. 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 1**, 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 1. 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 is not performed on that data.

Accuracy

The accuracy of the VISR method is evaluated based on the Zeeco Test and PERF Test. In these 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 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[6] (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 of 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 2**. The number of samples (tests) in **Table 2** 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.

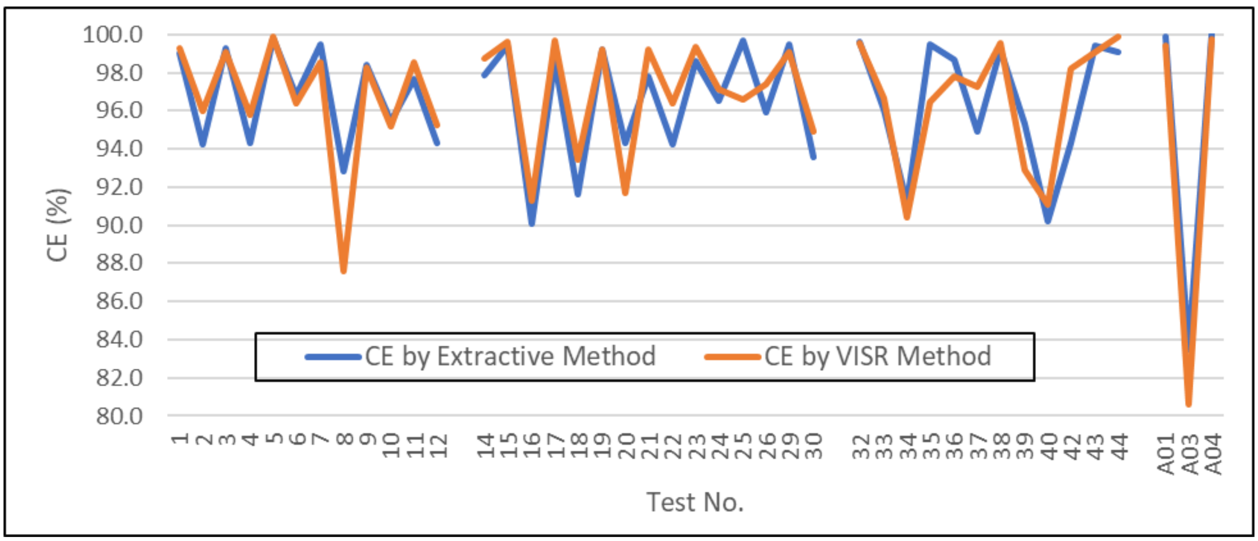
Table 2. t-Test to determine if the VISR method is different from the extractive method

	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 2**, 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 1** using the results from the PERF Test.

Figure 1. Flare CE measured by VISR method and extractive method – PERF Test results



Conclusion

Industrial flares can now be measured or continuously monitored by the VISR method for their performance, i.e., combustion efficiency (CE). The VISR method is a remote sensing method and can be deployed easily and practically. The VISR method transforms flare testing/monitoring from most difficult task (impossible in many cases) to a task that is easier than most conventional air emission testing methods. With the significant potential benefits that the VISR method can bring, it is important to characterize and understand the precision and accuracy of this method.

Through a large number of tests under various process and environmental conditions, a high precision and accuracy have been demonstrated for the VISR method. The relative standard deviation (RSD) is in the range of 0.07-1.98% with an average RSD of 0.62% for flare CE in the range from 80 to 100%. The average RSD of 0.62% is more than an order of magnitude smaller than the minimum precision target of 20% RSD set in EPA Method 301. The highest SD is only 1.84 measured as % CE.

The flare CE measured by the VISR method is in excellent agreement with the flare CE measured by the extractive method. The mean difference between the two methods is in the range of -0.21 to 0.30 measured in % CE. The t-statistic value in each of the three test groups are well below its corresponding t-test critical value, passing the t-test with a substantial margin. Keep in mind that the extractive method is suitable only in research. It is virtually impossible to deploy the extractive method to elevated flares at industrial production facilities. Having a method that can be easily deployed to industrial sites and produce highly time-resolved and accurate flare measurement results is a significant advancement.

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