Measurement of Oil and Natural Gas Well Pad Enclosed Combustor Emissions Using Optical Remote Sensing Technologies

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Mark Modrak
ARCADIS Inc., 4915 Prospectus Drive, Suite F, Research Triangle Park, NC 27713, USA

Eben D. Thoma
U.S. EPA, Office of Research and Development, National Risk Management Research Laboratory, 109 TW Alexander Drive, E343-02, Research Triangle Park , NC 27711, USA

Adam Eisele, Rebecca Matichuk, Gail Tonnesen
U.S. EPA, Region 8, 1595 Wynkoop Avenue, Denver, CO, 80202, USA

ABSTRACT

The U.S. Environmental Protection Agency (EPA), Office of Research and Development (ORD) and EPA Region 8 are collaborating under the EPA's Regional Applied Research Effort (RARE) program to evaluate ground-based remote sensing technologies that could be used to characterize emissions from enclosed combustion devices (ECD) at upstream oil and natural gas well pads. This paper describes a 5-day pilot study executed by ARCADIS in September 2014 to remotely observe emissions from ECDs at multiple well pads in Weld County Colorado using a passive Fourier transform infrared radiometer, and a mid-wave infrared hyper-spectral imager. The goals of the study were to evaluate the measurement technologies, provide speciated emissions information, and to assess the combustion efficiency (CE) of the ECDs. A total of 10 well pads were surveyed during the campaign. This paper describes the measurement systems, field deployment methods, and select results from the study. In general, the remote sensing approaches were found to be potentially useful as a research tool for offsite observation of ECD operation if more direct onsite measures are not available. Limitations were found in ease of execution, data analysis throughput, and observable ECD temperature ranges. Of the 10 sites observed, two sites had ECDs that could not be measured due to insufficient infrared signal caused by overall low combustion throughput (resulting in low temperature of the ECD). With uncertainties in CE accuracy noted, seven of the 8 measurable sites showed ECD CEs generally close to, or exceeding 98%. One site showed higher emissions of several alkanes and alkenes, with CE values calculated to be as low as 60%.

INTRODUCTION

As U.S. domestic energy production has increased dramatically in recent years, effective control of air emissions of greenhouse gases (GHGs) and volatile organic compounds (VOCs) has become increasingly important. Previous EPA field studies have shown that methane and VOCs can be emitted from well pad sources that are improperly maintained or controlled.[1-4] In some areas, well pad sources have the potential to emit ozone precursor VOCs, hazardous air pollutants such as benzene, and GHGs. ECDs are commonly used as control devices to control VOC emissions from well pad sources such as atmospheric storage tanks. To support energy development practices with minimal environmental impacts, it is important to develop easy-to - use measurement techniques that can verify the effectiveness of ECD operation in the field. Remote sensing systems may provide a means to improve understanding of ECD operation without direct onsite sampling of the combustion plume.

As part of the overall EPA research program on this topic, EPA ORD and Region 8, with contract support from ARCADIS, conducted a pilot study to investigate two currently available remote sensing technologies that could be utilized to characterize ECD performance on well pads from remote vantage points. The goals of this research study were to demonstrate and evaluate the systems for characterization of ECD operation, provide speciated emissions information if possible, and assess the CE of the ECDs. The pilot field study was conducted from September 8-12, 2014 in Weld County, Colorado and observed emissions from 10 oil and natural gas well pads. Data were collected using two remote sensing systems; a passive Fourier Transform Infrared (PFTIR) radiometer (IMACC, LLC, Round Rock, TX, USA), and a mid-wave infrared hyper-spectral imaging (HSI) camera (Telops, Quebec City, QC, CANADA). Data were collected with the PFTIR during each day of the study, and with the mid-wave infrared hyper-spectral imager on September 10-11. The two technologies were utilized in a previous study to characterize emissions from industrial flares[5]. An optical gas imaging (OGI) camera (GF-320, FLIR Systems, Inc., Boston, MA, USA) was also deployed during the current study to provide complimentary qualitative data on the ECD emissions. Additionally, measurements of ECD temperature were collected remotely using the OGI camera and a hand-held infrared thermometer (Fluke Corporation, Everett, WA, USA).

Remote sensing measurements were conducted from safe and appropriate offsite observing locations on the side of public roadways and the sites were selected based on a combination of factors including ease of observation and the results of OGI imaging which indicated the potential presence of ECD operational issues. This research effort was not part of any enforcement or compliance activity.

EXPERIMENTAL METHODS

Measurements were conducted at each site for varying periods of time. After the instrumentation was deployed, calibration procedures were conducted prior to measurements being collected. At the beginning of each day, the PFTIR team performed a series of calibrations using a custom-designed calibration cart that contained a telescope and various calibration materials. The PFTIR team performed a Black Body calibration using a black body with an infrared source of known spectral radiance, an Infrared Source calibration to determine atmospheric transmission loss between the flare plume and the PFTIR, a Cold Source calibration to determine radiance generated by the atmosphere between the flare plume and the PFTIR, and a Sky Background calibration to determine the background radiance from the sky. The calibrations were typically done once per day (at the first site of each day), although the Sky Background calibration was conducted more frequently when sky conditions varied during the measurement period. Deployment of the PFTIR and completion of the pre-measurement calibrations were completed at each site in approximately one hour.

The HSI camera also required preliminary system setup and calibration. The initial system setup and calibration was completed at the first site where the HSI was deployed in approximately 90 minutes. System setup and calibration at subsequent sites were generally completed in 5 to 10 minutes.

After deployment and system calibrations were completed, information collected during a pre-deployment OGI camera survey was used to locate the ECD emissions, and align the PFTIR and mid-wave HSI on the source. Measurements were collected at each site for between one and four hours, depending on the frequency and duration of emissions observed from the ECD. The data collected were analyzed for carbon dioxide, carbon monoxide, and other volatile organic compounds in addition to CE determinations using data from the PFTIR.

Passive Fourier Transform Infrared Radiometer:

The PFTIR radiometer analyzes thermal radiation emitted by hot gases in the ECD plume. During the measurement process, the instrument does not transmit an infrared light source through the measurement plane. Instead, infrared energy emitted from the hot gases from the source is the infrared signal, and the instrument acts as a receiver. This approach is possible because the infrared spectra of hot gases are very similar to their absorption spectra, and can therefore be used for identification and quantification of species through emission spectroscopy, just as with absorption spectroscopy. Passive FTIR was chosen for the current study instead of active open-path FTIR monitoring (where the instrument transmits and receives an infrared source) because of potential difficulties of transmitting and receiving an infrared source through a small, elevated plume, and the need for site access and support infrastructure to position the required beam retroreflectors. Figure 1 presents the IMACC PFTIR radiometer.

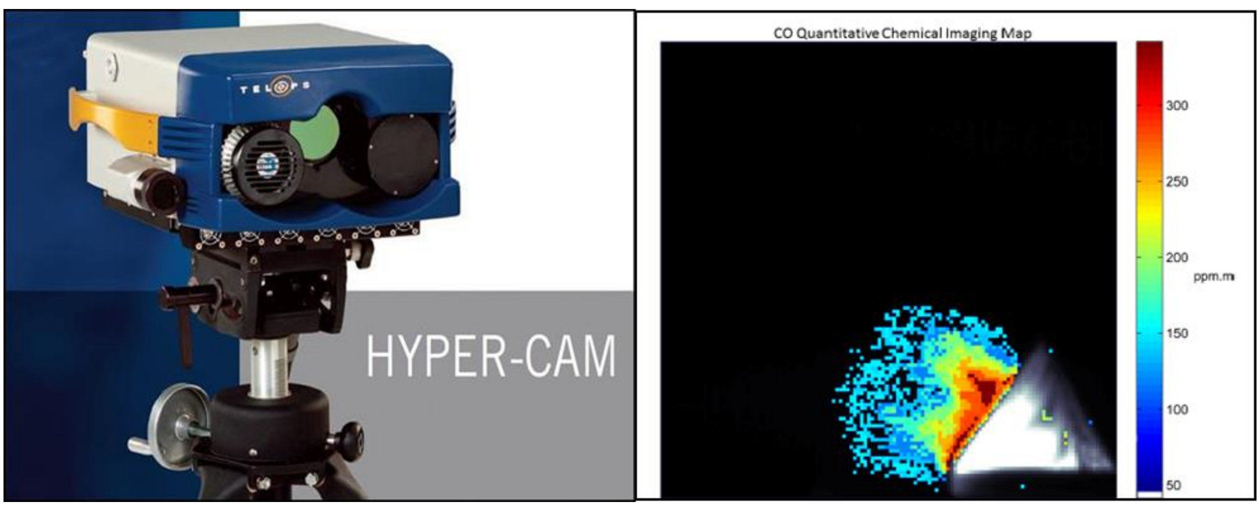
Figure 1. IMACC Passive FTIR Radiometer

The instrument was deployed from the back of a field trailer, and was mounted on a mechanical positional scanner. At each measurement site, the trailer was oriented to provide a clear line of sight between the PFTIR and the emissions source detected during the pre-measurement OGI camera survey. Measurements were collected at 0.5 cm^{-1} spectral resolution, and the instrument field of view was approximately 14” in diameter. Each data point was averaged for 30 seconds, with analyte concentrations in units of ppm-m. Because many of the plumes measured during the study showed weak infrared signal due to overall low combustion throughput, often times it was not possible to make a valid measurement. Subsequently, a data filter was developed to eliminate data points with insufficient infrared signal. The PFTIR was deployed during each day of the measurement campaign at a total of 8 well pad sites.

Mid-Wave Infrared Hyper-Spectral Imager:

The mid-wave infrared HSI is a standoff instrument that uses FTIR technology. Incoming infrared radiation from the vicinity of the source being monitored is modulated using a Michelson interferometer located inside the instrument. A high-resolution spectrum is then recorded for each pixel of a focal plane array detector. By comparing the measured spectrum to a series of reference spectra of known gases, the constituent species can be identified and quantified. The instrument has a nominal spectral range of 3 to 5 microns, with spectral resolution of 0.25 cm^{-1} wavenumber. The instrument field of view consists of 128 by 128 pixels, with individual pixel size ranging from approximately 5 to 166 cm^2, depending on the distance from the instrument to the source. Data collected with the instrument are used to create quantitative chemical imaging sequences, showing the column density, in units of ppm-m, for detected compounds in the instrument field of view. Figure 2 shows the Telops mid-wave hyper-spectral imager, and an example chemical map showing carbon monoxide column density.

Figure2. Telops Mid-Wave Hyper-Spectral Imager



The instrument is mounted on a heavy-duty tripod, and was deployed from the back of a field vehicle, which housed the data acquisition/control computer. The instrument was deployed at each measurement site in a location that provided a clear line of sight to the emissions source, as determined during the pre-measurement infrared camera survey. Measurements were collected with the mid-wave hyper-spectral imager during two days of the measurement campaign (September 10-11) at a total of 5 well pad sites.

Combustion Efficiency Calculation:

One of the goals of the study is to evaluate the combustion efficiency of ECDs at oil & natural gas well pads using data collected with the PFTIR. When the ECDs are operating properly, efficient combustion is achieved by converting saturated hydrocarbons to carbon dioxide and water. However, inefficient combustion occurs when the oxygen supply to the ECD is insufficient, forming products of incomplete combustion such as carbon monoxide, intermediate hydrocarbons, and carbonyls. Combustion efficiency (CE) is defined as the ratio of the mass concentration of carbon dioxide to the sum of the concentrations of carbon dioxide, carbon monoxide, and total hydrocarbons in the plume and is expressed using the following equation:

$$\textit{Combustion Efficiency (\%)} = \frac{[\boldsymbol{Carbon\ Dioxide}]}{[\boldsymbol{Carbon\ Monoxide}]+[\boldsymbol{Carbon\ Dioxide}]+[\boldsymbol{Total\ Hydrocarbons}]} \quad (1)$$

The fundamental output of the remote sensing instruments used in this study is the gas concentration times the path length of the gas, or ppm-m. Since the path length of all gases in the plume is the same, the path length cancels in the ratio given in the equation above. Consequently, for the CE calculation, knowledge of the actual path length through the measured plume is not necessary. At this time, only the PFTIR has the capability of generating CE values but the HSI protocols for determination of CE values are under development by the manufacturer.

RESULTS AND DISCUSSION

The measurement campaign was conducted from September 8-12, 2014. Data were collected with the PFTIR during each day of the campaign, while HSI measurements were collected with the mid-wave hyper-spectral imager during two days of the campaign. The instruments were deployed at a total of 10 representative well pads during the campaign. Table 1 presents a summary of the data collected at each site including the number of data elements (N) acquired by each instrument that passed quality assurance checks.

Table 1. Summary of data collected during measurement campaign

Site	Date	Time	PFTIR (N)	HSI (N)	Number of ECDs at Site (N)
1	9/8/14	13:00 to 15:05	Emissions from ECD not detected	Not at site	1
2	9/8/14	15:31 to 16:10	14	Not at site	2
3	9/9/14	8:00 to 15:16	297	Not at site	4
4	9/10/14	10:00 to 17:16	244	578	2
5	9/11/14	9:35 to 12:05	27	488	2
6	9/11/14	12:41 to 13:31	Not at site	110	10
7	9/11/14	12:15 to 13:50	26	Not at site	4
8	9/11/14	14:25 to 15:17	5	110	4
9	9/11/14	16:11 to 16:35	Not at site	55	1
10	9/12/14	9:00 to 10:40	Emissions from ECD not detected	Not at site	2

In general, emission signals observable by the remote sensing instrument were fairly weak at most of the well pads (at the low end of usability). The amount of gas flowing to and combusted by the ECD raises the temperature of the ECD stack and the emitted plume. If the temperature of the emitted plume becomes too low, the radiated signal to the PFTIR or HSI becomes insufficient for acquisition of usable data. Since the load on the ECD is time-dependent (increases during periodic separator dumps), the signal available to the remote sensing equipment changes with time. At Sites 1 and 10, the ECDs were not sufficiently active during the observations period to execute the measurement (although emissions were detected during the pre-deployment gas imaging camera survey), so no usable data were collected. Analysis of data collected with the PFTIR indicated that most of the ECDs showed relatively high combustion efficiency values (close to, or exceeding 0.95), with little to no detected hydrocarbon emissions. However, data collected with both instruments at Site #5 indicated emissions of hydrocarbons greater than emissions found at the other sites. The following section presents a summary of data collected at Site #5.

Site #5 Emissions Data

Data were collected at Site #5 with the PFTIR and HSI for approximately 2.5 hours on September 11. The PFTIR and HSI were deployed approximately 45 and 78 meters from an active ECD stack at the site, respectively. Figure 3 presents an overhead view of Site #5, showing the location of the PFTIR and HSI during the measurements.

Figure 3. Overhead view of Site #5 with measurement configurations

The PFTIR detected emissions of several hydrocarbons from the stack. A summary of path-integrated concentrations determined from data collected with the PFTIR is presented in Table 2.

Table 2. Summary of PFTIR concentration determinations (ppm-m) at Site #5

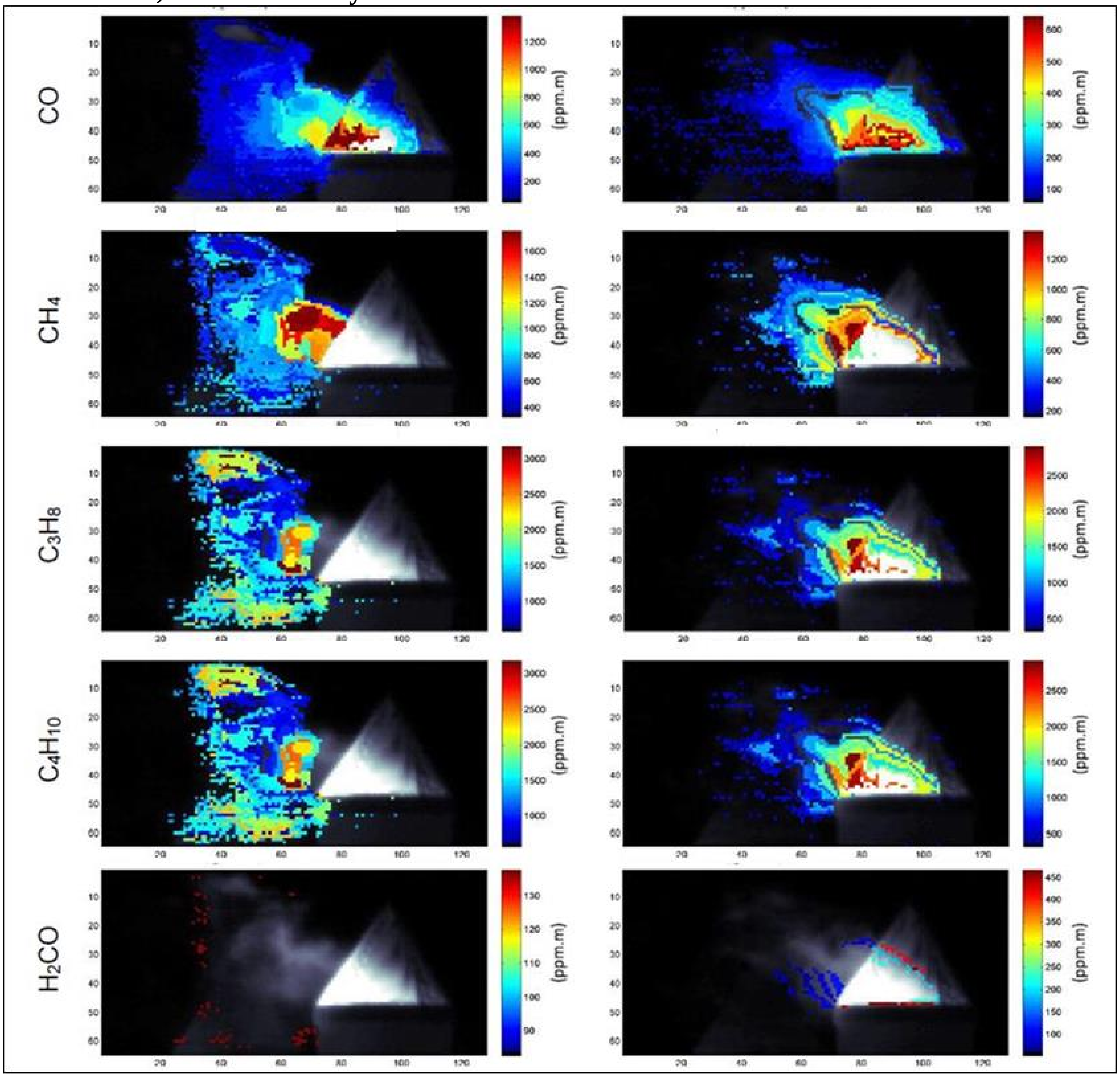
Compound	Minimum	Maximum	Average
Carbon Dioxide	2,960	61,500	18,300
Carbon Monoxide	0	510	184
Methane	92.0	485	258
Ethane	0	224	58.3
Propane	0	36.4	10.8
Pentane	0	197	50.7
Ethene	0	80.0	40.4
Propene	0	53.2	21.0
Cyclopentene	0	57.1	35.8
Total Hydrocarbons[1]	92.0	3140	1170

1. Computed as carbon-weighted sum of all C1 through C5 hydrocarbons

The table shows that most of the lighter alkanes and alkenes were detected in emissions from the site, with relatively higher concentrations of methane, ethane, and pentane.

Measurements collected with the mid-wave hyper-spectral imager also indicated the presence of hydrocarbons in emissions from Site #5. Specifically, analysis of the data detected methane, propane, and butane, as well as carbon monoxide and formaldehyde. Figure 4 presents quantitative chemical map sequences for several compounds detected at Site #5. The top of the ECD stack is located in the lower right hand portion of each image.

Figure 4. Quantitative chemical map sequences of carbon monoxide, methane, propane, butane, and formaldehyde emissions from enclosed combustion device at Site #5

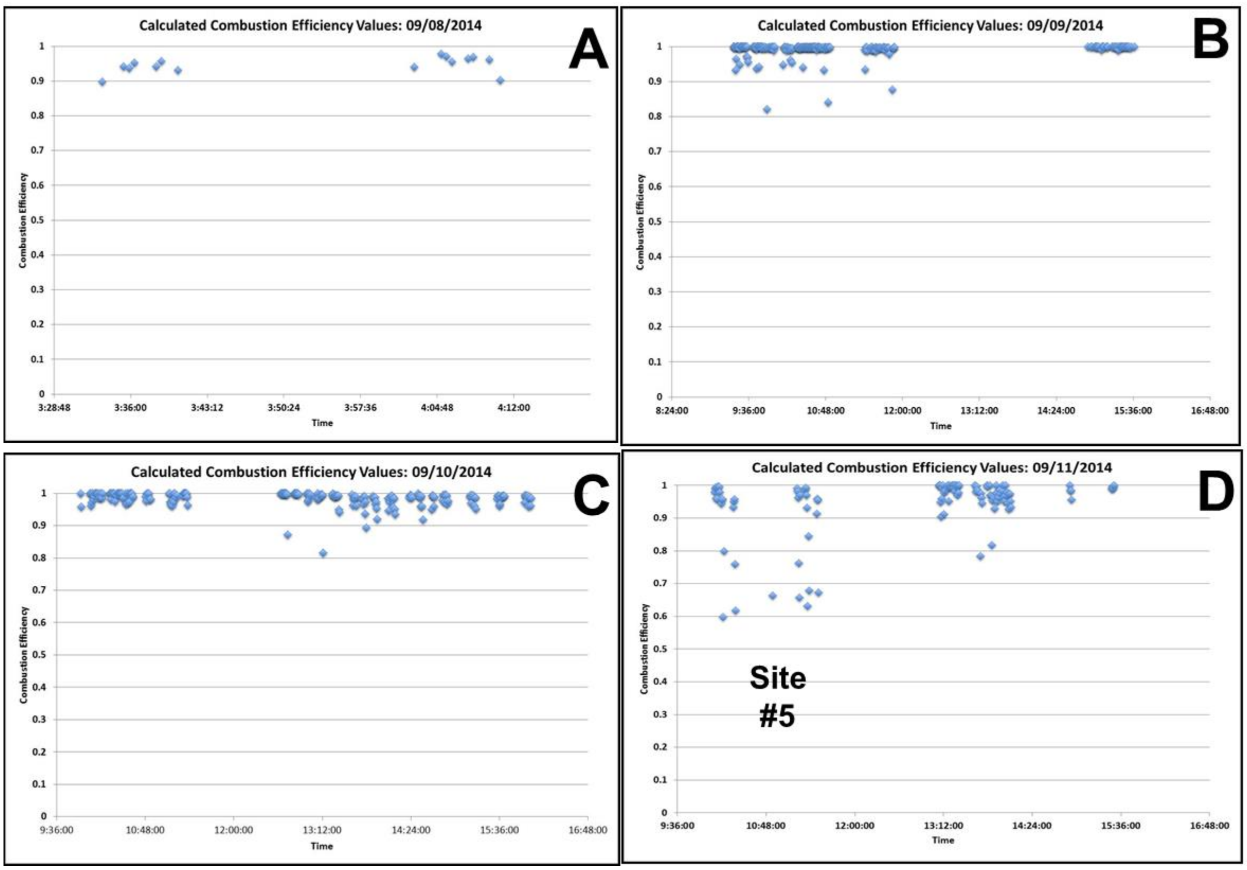


The maps present a spatial distribution of path-integrated concentrations (in units of ppm-m) across the ECD plume.

Combustion Efficiency Estimates

The CE of the ECDs at each site was determined from the field measurements using Equation 1. Daily plots of CE values for data that passed QA acceptance criteria from four of the six sites measured using PFTIR are presented in Figure 5.

Figure 5. Daily calculated combustion efficiency values from PFTIR data. Plots shown for September 8 (A), September 9 (B), September 10 (C), and September 11 (D)



For the study sites, the majority of the calculated CE values are close to, or greater than 98%. There are periods of time were the CE appears to fall below 90% and this is most obvious at Site 5 (Figure 5D). These time periods of relatively lower CE values directly correspond with the observation of increased measurable hydrocarbon emissions from this site (see Table 2). From simultaneous OGI observations, we believe these time periods to be potentially related to flash emission events. In general, when high CE values are registered by the PFTIR, the presence of speciated hydrocarbon emissions could not be confirmed (eg. Table 2), as concentrations were most likely below instrument detection limits. Regarding accuracy of CE estimates for ECDs, significant uncertainty exists from a method development standpoint. Due to the small flare size and low temperatures encountered, the determination of CE is generally more difficult than for larger flare systems.[5] Additional method development work would be required to ascertain the absolute accuracy of the CE measurement for ECDs. So too, the apparent time dependency of the CE is believed to be real, however the magnitude of these drops and the accuracy with which it is determined carries significant uncertainty. Further studies conducted on the use of PFTIR for remote ECD CE assessment would focus on the relationship between the ECD temperature, plume size and variability, with respect to PFTIR effective field of view.

Assessment of PFTIR and HSI remote sensing approaches for ECD assessment

In general, the remote sensing approaches used in the current study were found to be potentially useful for offsite observation of ECD operation for research purposes, if direct onsite measures are not available. Limitations were found in ease of execution, data analysis throughput, and observable ECD temperature ranges. The accuracy of CE determination with the PFTIR approach requires further study and may be complicated by the small size and variability of the ECD plume. As evidenced from Figure 4, the HSI approach provides a superior diagnostic of plume heterogeneity compared to the single element (non-imaging) PFTIR. However, the vast amount of data provided by the HSI approach make even simple determination of CE challenging, and requires significant method development work. Both techniques are best characterized as high-asset value research tools requiring significant set up time and data processing resources, making them relatively impractical for routine use. In the future, other types of emerging multi-channel remote sensing approaches may provide what is essentially a combination of aspects of the two instruments used in the current study, but in a more implementable form. Development of one multi-channel remote sensing approach for flare CE measurements is the subject of a recently announced EPA ORD Phase II Small Business Innovative Research Award [6,7]

SUMMARY

The current study is a collaborative research effort between. EPA ORD and EPA Region 8 to evaluate two commercially available remote sensing approaches for characterization of emissions from oil and natural gas well pad ECDs. This paper provides an overview of two technologies, PFTIR and HSI, that were evaluated during a pilot study in Weld County Colorado in September 2014. This paper also presents a summary of speciated emissions results from one of the well pad sites where relatively high emissions were detected, and CE calculations from data collected at each site. The results of this pilot study indicate that it is important to develop easy-to-use remote approaches for assessment of ECD operational states, as high CE cannot be assumed. In general, the remote sensing approaches used here were found to be potentially useful as research tools for offsite observation of ECD operation if more direct onsite measures are not available. Limitations were found in ease of execution, data analysis throughput, and observable ECD temperature ranges. The presented results are from a preliminary analysis of the data collected.

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KEYWORDS

Passive FTIR, Hyper Spectral Imager, oil and natural gas, well pad, enclosed combustor, combustion efficiency