IMPROVED FLARE EMISSIONS MONITORING FOR PLANT OPERATIONS

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ABSTRACT

Elevated Analytics Consulting (EAC) is committed to furthering the art in industrial flare emissions monitoring through collaborative partnerships using existing technologies. Work conducted by Cimarron Energy (Cimarron), Spectrum Environmental (Spectrum) and EAC, described in this paper, illustrates a novel approach using ground based Active FTIR (AFTIR) combined with an Unmanned Aerial System (UAS) to directly measure flare emissions more accurately. In the 2020 AFRC conference, EAC reported on their work to apply their technology use to monitor flare emissions for an early warning system to optimize plant operations. As discussed, their *EAGLE*™ wireless sensor technology mounted on a UAS is capable of real time flare emissions monitoring. The current work expands this work using a combined AFTIR/UAS system similar to previous work reported by CleanAir Engineering [1] which compares to earlier work using "Passive" FTIR conducted at the John Zink Test facility in Tulsa, OK in collaboration with the Texas Commission on Environmental Quality (TCEQ) and University of Texas in 2010 [2].

A heavy lift UAS operated by a drone pilot integrates a mirror array reflector platform with a ground based PFTIR instrument to allow "reflected" measurements of flare emissions. Initial work validated this approach for subsequent field testing. The concept was developed and tested using a mock mirror array mounted on the drone (see below) to ensure the UAS could maintain position relative to the ground based PFTIR and to confirm sufficient flight time to support the testing protocol. The combined system was tested in windy conditions to evaluate the robustness of the combined system prior to field testing.

Figure 1 - UAS mounted mirror array.

This paper describes the system in more detail and provides initial results. Based on testing validation, this approach may become the standard methodology for future plant wide flare testing to quantify flare performance efficiently and accurately.

INTRODUCTION AND OBJECTIVES

Industrial Gas flares are used world-wide to reduce safety concerns in up-stream and down-stream production of hydrocarbon products. As safety devices, they allow a plant to vent (burn) flammable gases in the most environmentally friendly way possible. Flares are generally classified as non-assisted utility flares, steam-assisted flares, air-assisted flares, pressure-assisted flares, enclosed flares, liquid flares or pit flares. Flares mounted on elevated stacks allow the flare to operate safely away from ground personnel and equipment. However, this open, elevated flame makes direct sampling of flare emissions very difficult and costly. Efforts to monitor flare emissions remotely, using optical techniques, have shown promise. A summary of optical techniques has been provided in a previous AFRC paper in 2018 by the authors [3]. Because optical techniques have shown promise but implementation, setup and testing is expensive and may significantly impact plant operations, these methods have not found regular use for routine flare monitoring.

Flares operate over a wide range of flow rates with widely varying compositions. [3]. A flare must also operate under diverse wind conditions. Therefore, maintaining high combustion efficiency is often very challenging. Monitoring real time flare emissions is important to maintain safe operating conditions. With the exception of observing visible smoke as discussed in 40 CFR §60.18 and §63.11, high combustion efficiency in an elevated flare is based on original work led by the United Stated Environmental Protection Agency (US-EPA) from 1983 – 1986 [4], [5], [6], and more recently on testing sponsored by the Texas Commission on Environmental Quality (TCEQ) in 2010 [2]. These studies examined various operating parameters to assess flare performance as characterized by combustion efficiency (CE). Recognizing the difficulties in measuring flare emissions, optical techniques based on Infra-red spectroscopy (i.e., FTIR) have been used to remotely measure flare CE [3]. However, accurately measuring flare emissions using a land-based FTIR system is challenging due to plume dynamics caused by transient wind conditions. Modern plants rely on a variety of monitoring instruments and equipment (e.g., flow meters, gas chromatographs, leak detection cameras, etc.) to ensure safe continuous operation with minimal impact on the environment. Accurate real-time measurement of flare emissions offers a way to further improve plant operations.

Global flaring is a significant source of gaseous and particulate emissions globally (Figure 2). As shown, Russia contributed 24,091 million cubic meters (mcm) of flared gas (16% total), followed by Iraq with 17,730 mcm (12%) in 2016. By comparison, the United States flared 8,862 mcm (6 %). The global trend for gas flaring and oil production were closely linked between 1996 and 2016 (Figure 3).

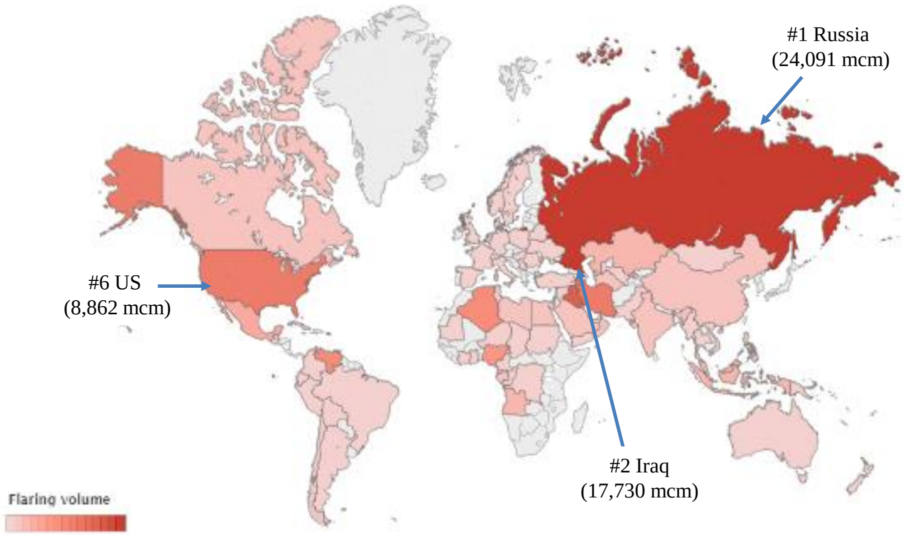

Figure 2 - Global upstream GF map [7]

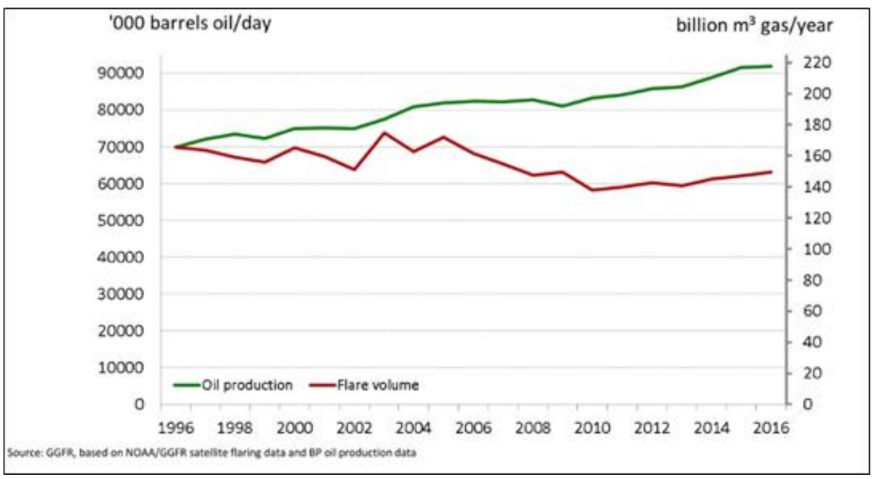

Figure 3 - Global GF and oil production during period between1996-2016 [15]

While gas flaring in some countries remained constant or reduced slightly between 2015 and 2016 (Figure 4), the US and Canada were able to reduce gas flaring during the same period (Figure 5). Since flaring is directly linked to oil production, flaring rates are expected to increase as countries increase oil production (Figure 6).

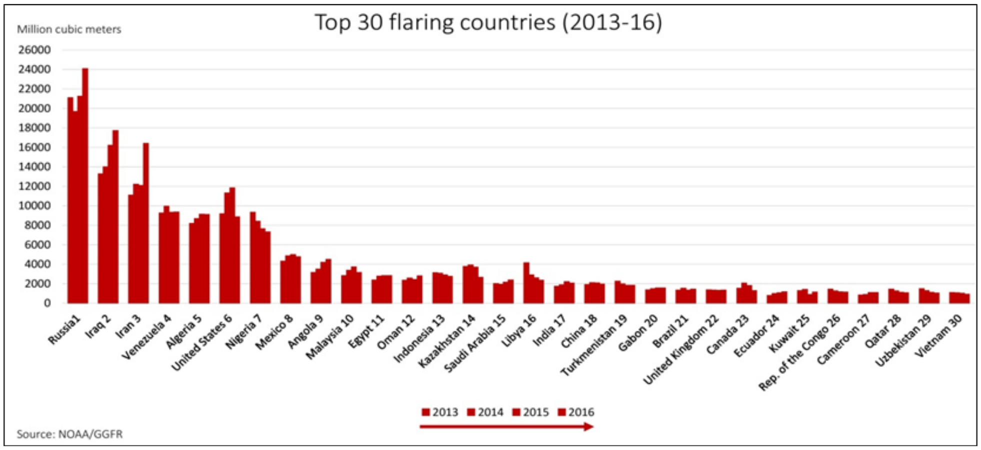

Figure 4 - Top 30 flaring countries [15]

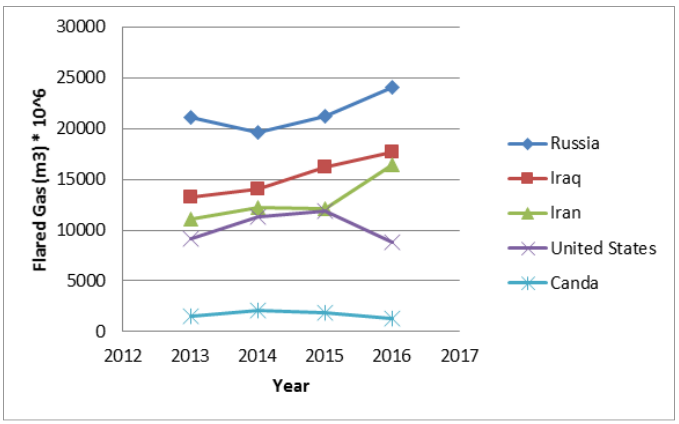

Figure 5 – Gas flaring trends for Russia, Iraq, Iran, United Stated and Canada between 2013 and 2016

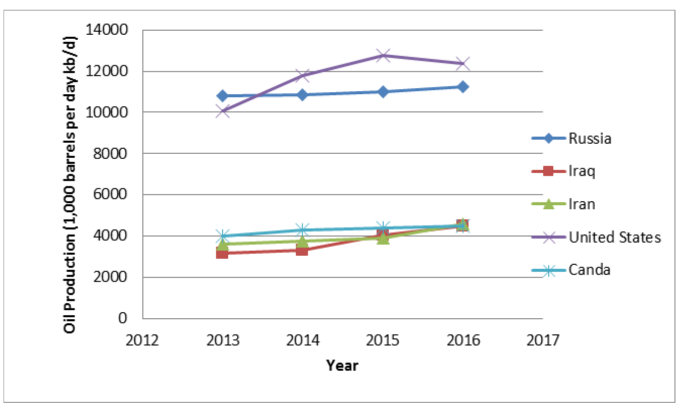

Figure 6 - Oil production trends for Russia, Iraq, Iran, United Stated, and Canada over the period between 2013 and 2016

Based on the global magnitude of flaring, it is imperative that an inexpensive, robust method which is easy to implement in a plant, be developed to monitor and reduce flare emissions. This paper presents recent work that combines EAC's Unmanned Aerial System (UAS) with Spectrum's ground based AFTIR system. The work conducted uses a retroreflector mirror suspended from the UAS coupled with a telescope to focus the IR beam from the AFTIR instrument to measure flare emissions. This system allows improved plume tracking and higher fidelity measurements of real-time flare emissions in a dynamic plume. Given the AFTIR instrument samples at a higher rate than possible in other IR techniques (i.e., PFTIR, OPFTIR), the system can better quantify plume dynamics. This allows plants to improve their downwind dispersion modeling to more effectively protect against safety hazards in an active safety and environmental program.

METHODOLOGY

Flare Efficiency Tests (Previous studies)

Flare testing facilities have been used to analyze flare performance in terms of flame stability, Destruction Efficiency (DRE) and Combustion Efficiency (CE). These tests were conducted under various operating conditions with different flare designs (i.e., flare gas heat content, flare gas flow rate, flare tip design, wind speed, and assist-media).

McDaniel [8] studied the CE and DRE for both SAF and AAF under a wide range of operating circumstances such as vent gas flow rate, heat content and steam to gas ratio. The steam-assisted flare effective diameter was 5.86 inch. The air-assisted flare has a spider burner tip with holes that have an area of 5.3 inch^2 for high vent gas heating value and 11.24 inch for low vent gas heating value. Mixtures of propylene diluted with nitrogen were flared. CE decreased with increasing steam assist flow and high jet velocities with lower flare gas heat content. The study concluded flares achieve a destruction efficiency of 98% or greater if properly operated.

Pohl [9] studied the effect of vent gas velocity, steam to fuel ratio, and flare tip size on CE. Different size flares were tested in no-wind conditions. Steam flow ranging from 0 to 1 lb steam / lb fuel with vent gas velocity between 0.2- 428 ft. /sec for flare gas mixtures of propane-nitrogen with a heating content of 270 – 2,350 Btu/ft3. Testing showed flares firing unsaturated gases were more stable but needed additional air. Flame stability was correlated to gas heat content and jet velocity with flame instability occurring when flame speed was less than tip velocity.

Pohl and Soelberg [10] studied the impact of flare tip design and vent gas composition on CE. A 12-inch “Coanda” steam flare and a 1.5-inch air-assisted flare where flame stability for tip exit velocities between 0.2 to 9.9 ft/sec was evaluated. The tip design was found to effect flame stability and CE was correlated to air to flare gas ratio and flare gas net heating value.

Castineira and Edgar [11] studied the impacts of assist media to flare gas ratios on flare CE. They used a 2-D CFD model to study flare behavior. CFD simulation showed that inefficient combustion may occur with high air to fuel and steam to fuel ratios. They also studied the effect of vent gas velocity to crosswind speed ratio on CE. CFD simulations of a natural gas flare were compared to closed-loop wind tunnel test results. Their work showed the flare CE declined at increasing wind speed.

The Texas Commission on Environmental Quality (TCEQ) conducted tests to examine how low flare gas flow, flare gas heat content, and steam and air assist flow rates affected the CE. A focus for this work was to evaluate whether flares operated within the EPA Regulation 40CFR60.18 could attain a CE of 98% or more. They considered different flare tip sizes and various flare gas mixtures.

Key Factors in Flare Performance

Flare performance (i.e., CE) is affected by flare tip design and various operating parameters The most important parameters are reviewed below:

1. Momentum ratio (MR) is the ratio of flare gas momentum strength to crosswind momentum strength. This parameter assesses how the wind changes mixing in the flare plume. Flame deflection and poor mixing result at low momentum ratio as may occur during purge condition [12]. When the MR is < 10%, the flame stabilizes on the downwind side of stack (Figure 7). Under high cross winds the flame becomes shorter and shorter leading to increased soot formation on the back side of the flame. However, with high tip velocity, unstable combustion occurs leading to poor CE [2].

Figure 7 - Effect of crosswind on flame stability [13]

2. Flare Gas Heat Content reduces CE by producing lower flame temperatures leading to weaker reaction zones leading to flame shearing and reaction quenching. According to Castineira [11] [14] showed flare gas heat contents < 200 Btu/SCF produces CE < 90%. Saturated hydrocarbons with flare gas heat content > 300 Btu/SCF, a stable flame is possible at high tip velocities (Figure 8). Increasing assist media flow rate (i.e., steam, air) lowers flammability but enhances mixing. Practical flare operation confirms flare gas with more unsaturated hydrocarbons requires more assist media (e.g. more steam for C_2H_4).

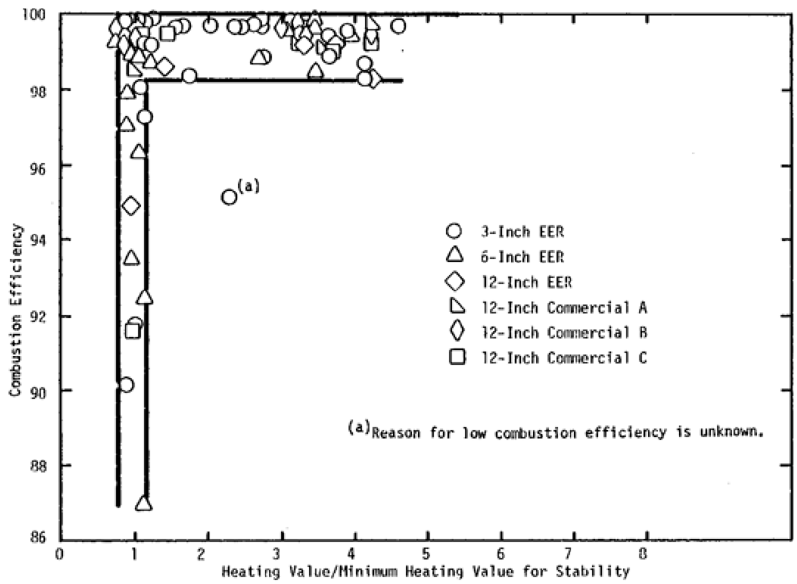

Figure 8 - CE near lower limit of stability for mixture of C3H8/N2 without pilot flame [4]

3. Assist media (steam or air) adds momentum to the flare gas which enhances turbulence, induces surrounding air into the combustion zone and increases flame stability (Figure 9).

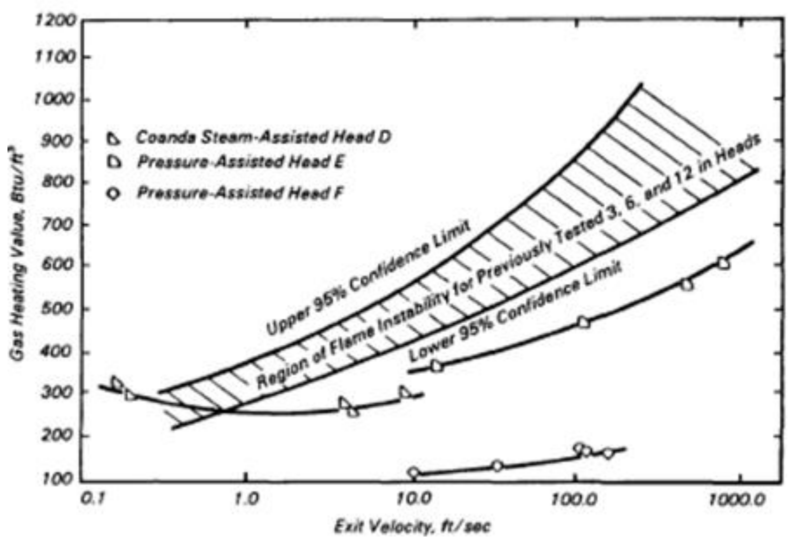

Figure 9 - Flame Stability region of steam-injected and pressure assisted heads [4]

The U.S. EPA identified key parameters that affect flare performance and issued a report summarizing these factors [19]. They have concluded that the minimum flare gas heat content should be > 300 Btu/SCF for assisted flares and 200 Btu/SCF for non- assisted flares. They also conclude that the maximum tip velocity should be in the range of 60 to 400 ft/sec. Finally, they concluded that a flare pilot should always be used to ensure a stable flame [16].

TESTING

The UAS used in the current test was a DJI 600 Pro Octocopter (Figure 10). This UAS modified to suspend the retroreflector mirror (Figure 1) below the drone (Figure 11). Using this device, the AFTIR device was coupled to it as shown (Figure 12).

Figure 10 - EAGLE system mounted on a DJI UAS platform

Figure 11 - UAS with retroreflector mirror suspended below the drone

Based on the previous testing and the established key operating conditions for a gas flare, the test procedure was developed. The procedure was first demonstrated at a test facility as shown below. Results from the testing indicated the drone was able to maintain a stable position in a 10-mph cross wind. AFTIR results confirmed the ability to collect accurate results. Due to a malfunction at the field site where the full test will be performed, field results were not available for this paper but will be reported in a subsequent paper.

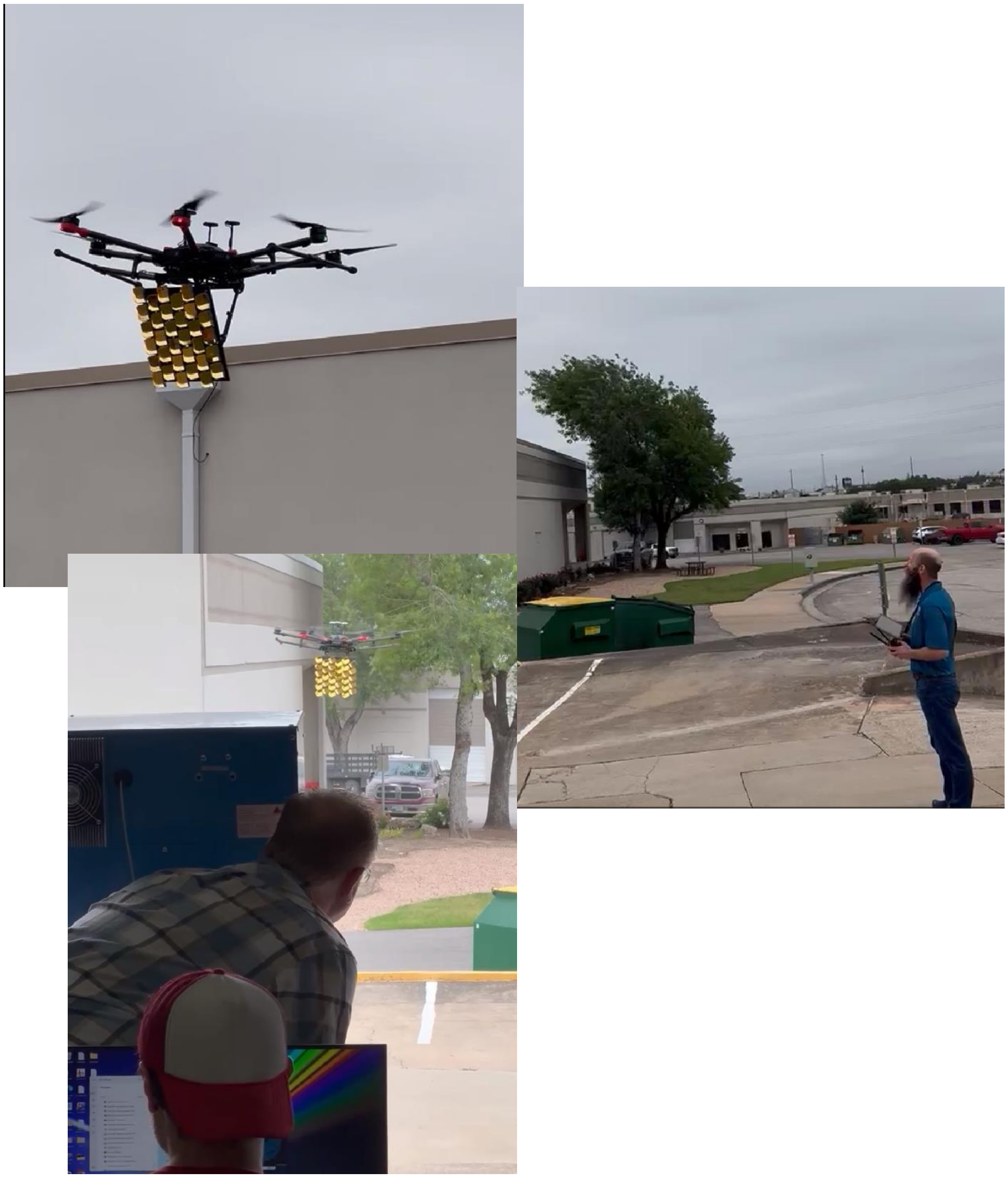

Figure 12 - AFTIR/UAS system in operation at test facility

SUMMARY AND CONCLUSIONS

In summary, the following points can be drawn from this work:

- World-wide flaring is closely linked to oil production.

- Increasing demand for oil indicated increased flaring is likely.
- Safe and environmentally acceptable flare operation requires improved emissions monitoring.
- Previous flare testing has shown well designed and operated flares routinely achieve a CE over 98%.
- Previous flare testing has demonstrated IR-based spectroscopy is able to remotely measure flare emissions.
- Previous UAS based flare testing has also shown the ability to monitor flare emissions remotely.
- Combining UAS with AFTIR devices has resulted in a new technique to accurately and safely measure real-time flare emissions.
- Future field testing using the combined system will be performed with resulted presented elsewhere.

The main conclusion of this paper is that flare emissions can be monitored accurately, and that this technology will help reduce overall flare emissions and improve plant operations.

REFERENCES

[1] C. A. Engineering. [Online]. Available: https://www.cleanair.com/resource/remote-sensing-of-stack-emissions-using-a-uav/ . [Accessed 21 August 2024].

[2] D. T. Allen and V. M. Torres, "TCEQ 2010 Flare Study - Final Report," The Center for Energy and Environmental Resources: The University of Texas at Austin, Austin, Texas, August 1, 2011.

[3] J. D. Smith, R. E. Jackson and Z. P. Smith, "Real-Time Measurement of Industrial Gas Flare Emissions via UAS Technology," AFRC 2018 Industrial Combustion Symposium, Salt Lake City, UT, 2018.

[4] United States Environmental Protection Agency-Office of Air Quality Planning and Standards, "EVALUATION OF THE EFFICIENCY OF INDUSTRIAL FLARES: TEST RESULTS," EPA-600/2-84-095, May 1984.

[5] United States Environmental Protection Agency, Office of Air Quality Planning and Standards, "EVALUATION OF THE EFFICIENCY OF INDUSTRIAL FLARES: FLARE HEAD DESIGN AND GAS COMPOSITION," EPA-600/2-85-106, September 1985.

[6] United States Environmental Protection Agency, Office of Air Quality Planning and Standards, "EVALUATION OF THE EFFICIENCY OF INDUSTRIAL FLARES: H2S GAS MIXTURES AND PILOT ASSISTED FLARES," EPA-600/2-86-080, September 1986.

[7] "The WorldBank," [Online]. Available: http://www.worldbank.org/en/programs/gasflaringreduction#7.

[8] M. McDaniel, "FLARE EFFICIENCY STUDY," EPA-600/2-83-052, July 1983.

[9] J. H. Pohl, R. Payne and J. Lee, "Evaluation of the efficiency of industrial flares: Test Results," EPA-600/2-84-095, May 1984.

[10] J. H. Pohl and N. R. Soelberg, "Evaluation of the efficiency of industrial flares: Flare head design and gas composition," EPA-600/2-85-106, September 1985.

[11] D. Castineira and T. F. Edgar, "CFD for Simulation of Steam-Assisted and Air-Assisted Flare Combustion Systems," *Energy & Fuels,* vol. 20, no. 3, pp. 1044-1056, 2006.

[12] P. E. Gogolek and A. Hayden, "Efficiency of Flare Flames in Turbulent Crosswind," in *Advanced Combustion Technologies, Natural Resources Canada, American Flame Research Committee Spring Meeting*, May 2002.

[13] J. Pohl, P. Gogolek, R. Schwartz and J. G. Seebold, "The Effect of Waste Gas Flow & Composition Steam Assist & Waste Gas Mass Ratio Wind & Waste Gas Momentum Flux Ratio Wind Turbulence Structure on the Combustion Efficiency of Flare Flames," July 2011.

[14] D. Castiñeira and T. F. Edgar, "Computational Fluid Dynamics for Simulation of Wind-Tunnel Experiments on Flare Combustion Systems," *Energy & Fuels,* vol. 22, no. 3, p. 1698–1706, 2008.

[15] U. E. O. o. A. Q. P. a. Standards, "Parameters for Properly Designed and Operated Flares," April 2012.

[16] Enforcement-Alert, "EPA Enforcement Targets Flaring Efficiency Violoations," EPA-325-F-012-002, August 2012.

[17] M. Greiner and A. Suo-Anttila, "Validation of the ISIS Computer Code for Simulating Large Pool Fires Under a Varity of Wind Conditions,," *ASME J. Pressure Vessel Technology,* vol. 126, pp. 360-368, 2004.

[18] J. Smith, R. Jackson, V. Sreedharan, Z. Smith and A. Suo-Antilla, "Lessons Learned from Transient Analysis of Combustion Equipment in the Process Industries," in *AFRC 2019 - Industrial Combustion Symposium*, Hilton Waikoloa Village, Hawaii, September 9-11, 2019.

[19] J. Smith, A. Suo-Anttila, S. Smith and J. Modi, "Evaluation of the Air-Demand, Flame Height, and Radiation Load on the Wind Fence of a Low-Profile Flare Using ISIS-3D," in *AFRC-JFRC 2007 Joint International Combustion Symposium*, Marriott Waikoloa Beach Resort, Hawaii, October 21-24, 2007.

[20] J. Smith, A. Suo-Anttila, V. Sreedharan and Z. Smith, "Simulation of the Thermal-Acoustic Coupling Inside an Industrial Hazardous Waste Incinerator," in *AFRC 2020 Industrial Combustion Symposium*, Houston, Texas (online), October 19-20, 2020.

[21] C. Sondhauss, "About the Sound Vibrations of the Air in Heated Glass Tubes and in Covered Pipes of Unequal Width," *Ann Phy*, vol. 79, p. 1, 1850.

[22] J. Smith, Jackson, R.E., Z. Smith, D. Allen and S. Smith, "Transient Ignition of Multi-Tip Ground Flares," University of Utah, Salt Lake City, Utah, September 17- 19 (2018).

[23] J. D. Smith, R. Jackson and Z. Smith, "Unmanned Aerial System Based Flare Emissions Monitoring," in *AFRC 2017: Industrial Combustion Symposium*, Houston, TX, 2017.

[24] D. T. Allen and V. M. Torres, "TCEQ 2010 Flare Study Final Report," The Univiersity of Texas at Austin, Austin, TX, 2011.

[25] "The WorldBank," [Online]. Available: http://www.worldbank.org/en/news/feature/2017/07/10/new-gas-flaring-data-shows-mixed-results.

[26] D. T. Allen and V. M. Torres, "TCEQ 2010 Flare Study Final Report," Texas Commission on Environmental Quality, PGA No. 582-8-862-45-FY09-04, 2011.