Advanced Emissions Monitoring from Elevated Gas Flares for Early Warning System and Optimization of Plant Operations

Joseph D. Smith, Ph.D., Robert E. Jackson, Zachary P. Smith, Ryan Giedd, Ph.D.
Elevated Analytics Consulting, Inc., Provo, Utah, USA

Abstract

Real-time monitoring of emissions from elevated gas flares is very difficult and expensive due to the relative location of the source and the cost to collect samples for analysis. Elevated Analytics has developed and applied a UAV based sensor system to accomplish this task. Besides providing a snapshot in time of flare emissions, this tool also allows a plant to assess plume distribution and transport in support of an active environmental safety program. By measuring air quality in a region and coupling the readings with CFD predictions, early warning of potentially hazardous conditions is possible which can help protect plant staff and neighbors downwind of the plant. Results from these applications will be presented in this paper as examples of where this technology can be applied. Although this technology has not yet been applied to monitoring Multi-Point Ground Flares emissions, modeling results will be used to illustrate how a swarm of drones might be employed to accomplish this task which has never been attempted to date using any sensing technique.

Elevated Analytics' advanced sensor systems employee a combination of fast acting sensors with wireless transmission technology to quantify local air quality, temperature and relative humidity. This data can be coupled directly to the plant DCS to link plant operations to flare performance. This enhanced feedback process control strategy will allow a plant to operate at peak conditions to maximize its operating profit while ensuring minimum flare emissions. This concept will also be discussed in this paper.

1. Introduction

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. Originally, flares were mounted on elevated stacks where the flare burner and flame would operate safely away from ground personnel and equipment. This open, elevated flame makes direct sampling of flare emissions very difficult and costly. Attempts to monitor the flame emissions remotely, using a variety of optical techniques, have shown promise but the equipment remains prohibitively expensive and complicated to use.

A summary of optical techniques has been provided in a previous AFRC paper in 2018 by the authors [1]. Because these optical techniques are promising but costly and setup and testing greatly impacts operations at the facility, implementation for regular flare monitoring has been impractical.

Multi-point Ground Flares (MPGF) have seen increased use over the last fifteen years. While these flare systems are not elevated, they can include as many as 400-500 flare burners in a geographic area as big as 100 m x 100 m, so their size makes direct sampling difficult if not impossible. To the authors' knowledge, direct sampling of emissions from an MPGF has never been accomplished. MPGFs also present the added challenge of having multiple stages which fire under different conditions with different burner types and/or configurations. This complexity can create a plume which has varying conditions depending on the location in the plume and the speed and direction of the ambient wind.

As noted previously by the authors, flares are designed to operate over a wide range, from very low hydrocarbon flow rates to very high hydrocarbon flow rates [1]. The flare flames must burn under extremely diverse ambient conditions including high wind speeds together with high rain amounts. These flames must also remain lit with highly non-uniform flare gas compositions. Achieving high combustion and destruction efficiencies under these varying conditions are very challenging so flare regulations have been developed to focus on flare operating conditions rather than on actual monitoring of flare flames, with the exception of monitoring for visible smoke using the "Ringleman Number" (e.g., *flares should have visible smoke for no more the 5 minutes in a 2 hour period*) as reported in previous work by the authors [2], and contained in 40 CFR §60.18 and §63.11. Other countries have implemented similar requirements, which are often based on the US requirements. These requirements were developed from data gathered from a series of flare emissions tests led by the United Stated Environmental Protection Agency (US-EPA) from 1983 – 1986 [3], [4], [5], with some notable additional testing done under the direction of the Texas Commission on Environmental Quality (TCEQ) in 2010 [6]. The goal of these studies was to provide operating parameters for flares that would ensure efficient flare performance with minimal emissions as characterized by high combustion efficiency (CE). In the past, measuring the combustion products from a flare to determine CE was difficult and dangerous. Recognizing these difficulties in gathering actual flare emission data, regulations were centered around establishing operating parameters associated with achieve high CE (as demonstrated in testing).

Several optical techniques, as noted above, have been implemented for specific tests but have historically been too expensive for permanent installation and continued operation as previously noted by the Authors [1]. These land-based optical techniques also lose accuracy for composite plumes from multi-burner flares such as MPGFs, where conditions at different plume locations can vary significantly.

Modern facilities, both upstream and downstream, include a variety of monitoring instruments and equipment (e.g., flow meters, gas chromatographs, leak detection cameras, etc.) that are run continuously to help ensure efficient, safe and environmentally friendly operation. Good data from well-designed control systems supports good decision making which leads to improved facility operations.

Since flares are such an integral part of various plant operations, a goal for industry and environmental agencies remains to develop and implement a measurement technique that can be set up quickly, or easily operated permanently, to remotely measure flare emissions without significant interruption to plant operations at a reasonable cost. This paper presents additional details of a novel approach involving use of advanced sensor technology mounted onboard an Unmanned Aerial System (UAS), or "drone", that has previously been demonstrated and described by the authors [1], [2]. This UAS-based sensor package can fly into a flare plume and remotely measure and transmit flare emission data to the ground as a function of plume location and time. This paper provides an update on progress made in developing this new monitoring system with specific emphasis on: enhancements to the ground-based portion, coupling of this system with computational fluid dynamics (CFD) modeling to provide high quality plume dispersion information for early warning, and the addition of machine learning, or artificial intelligence (AI), to provide improved recognition of plant anomalies that could lead to inefficient plant operation and potential safety concerns. This system allows plants to not only monitor the flare directly but provides for accurate dispersion modeling of the flare plume, as well as provide predictions of potential plumes emanating from hazardous gas leaks, in support of an active safety and environmental program.

2. UAS Based Flare Emission Monitoring System Continued Development

The UAS based flare emissions monitoring system described previously [2] has undergone continued development with numerous tests now completed. The system, EvA's EAGLE™ sensor system, has been tested on several commercial flares and undergone well documented tests of MPGF flare tips at Zeeco's flare test facilities in Broken Arrow, OK.[1] Details of these results can also be found in the authors' previous papers [7], [2].

Figure 1 - EAGLE system mounted on a DJI UAS platform

[1] See for example https://www.youtube.com/watch?v=onwCQksqtxo&t=2s

The EAGLE™ system can be mounted on a variety of modern drone systems. An example of the system mounted on a DJI Matrice 600 Pro is shown in Figure 1. The Matrice 600 is a relatively large drone; however, the sensor system, including wireless communications, has seen considerable size and weight reduction over the past year with the latest packages weighing approximately 200 grams. This lighter weight makes it possible to mount the EAGLE™ units on relatively small drones. The communications of the sensor's data can be integrated into the flight control package of the drone or it can be stand-alone (i.e., independent of the drone system) communicating directly to a land-based computer such as the plant's digital and control system (DCS) or some other dedicated computer/server. The EAGLE™ data may also transmit the data directly to the cloud using either long range Wi-Fi or 4G/5G cellular networks.

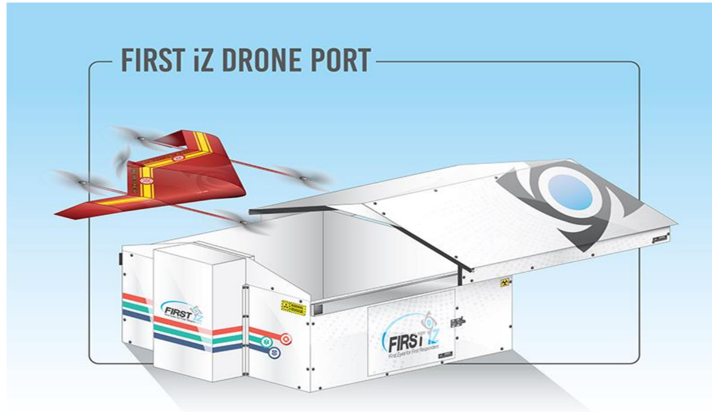


Figure 2 – Drone ports such as this one for first responders are also available for flare monitoring

3. Flare Monitoring

The EvA EAGLE™ monitoring systems can be deployed rapidly in a very cost-effective manner to monitor any type of flare. The drone units have been demonstrated using drone deploy platforms such as the drone port shown in Figure 2. This droneport enables the drones to be virtually hands-free. The platforms have charging pads built into the port landing pad so that when the drone lands it automatically starts recharging the batteries. Opening of the drone port and deployment of the EAGLE™ drone are all done autonomously, saving manpower and expense and providing for systematic, regularly scheduled surveys. For times when special deployment is needed, the drones can be completely controlled by a plant UAS pilot. This provides flexibility of resources, allowing the same drone to be used for other tasks such as visual inspections of the flare or of any other equipment or facilities at the plant.

This system can monitor MPGFs as well, with emissions from all areas of the plume determined using multiple EAGLE systems. While a single EAGLE equipped UAS can determine emissions throughout a normal single point elevated flare plume, for larger plumes, such as those from an MPGF, a swarm of multiple EAGLE drones can be used to take multiple measurements at the same time as is illustrated in Figure 3. Each EAGLE drone device transmits its sensor input to a ground station data acquisition system (DAQ) or the plant DCS.

The rapid response time of the sensors, combined with the possibility of monitoring at multiple locations at the same time, allows for levels of detail in flare emissions data never before possible. This level of detail will allow for: improved flare operation, improvements to CFD based flare models due to increased availability of data for validation, and improved flare designs.

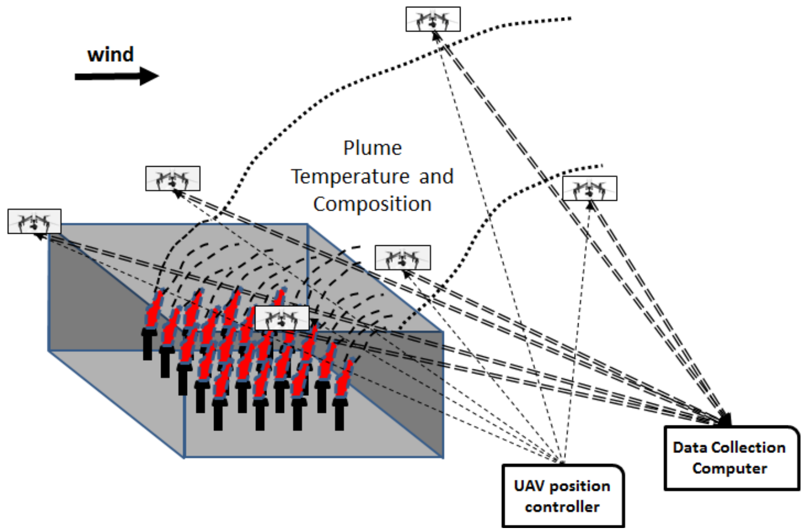


Figure 3 – Multiple EAGLE sensor devices can be used to form a swarm to monitor emissions from at multiple points in MPGF plume simultaneously

The flare monitoring technology will involve multiple permanently installed ground-based sensory stations and at least one mobile drone-based sensory station as illustrated in Figure 4. Each station will have machine learning (AI) capability to perform local data analysis (edge computing) as well as a mass memory system to record all flaring event raw data.

Each station is designed to intelligently acquire data for every single flaring event. The flare will be monitored using the drone and ground stations. After the initial "fingerprinting" or pattern learning process, the network of EATGLE stations will compare each new flare event to the library parameters collected during the initial "fingerprint'" process. If one of these subsequent events does not fall within an acceptable comparison or error window, the system will let the user know that this flare is not performing the same as previously, indicating an anomaly that can be further investigated (or repaired), providing the user with immediate feedback that the flare is not performing properly as it did when originally tested at optimum performance. The "fingerprint" of acceptable flare performance can also indicate potential plant performance anomalies contributing to flare performance deviations. If desired, the full raw data set can be subsequently processed and completely analyzed from the Cloud. New library "fingerprints" can be learned by the stations and sent to the Cloud database in between flare events to further specify detailed flare and plant performance.

The technology uses a set of gas sensors to acquire concentration measurements of carbon dioxide, carbon monoxide, select hydrocarbons (e.g. CH_4), and other non-specific types of volatile compounds (VOCs). The drone platform allows it to probe the flare plume at different locations to map gas concentrations with a much higher resolution than possible using existing technologies, since most technologies, including the ground based optical techniques discussed previously, provide spatially averaged data. The spatial resolution made possible with the EAGLE network of sensors can provide "fingerprints" of acceptable performance that includes spatial variations as well as time variations. Thus, a condition, which may show acceptable spatially averaged properties, could be found to be outside of the proper flare or plant operating conditions. For example, data from the drone may show high CO or unburned hydrocarbons in a certain region of the plume that isn't typical even though the overall plume averages remain close to the same. This indicate blockage or other anomaly that can be easily corrected when first detected which if left untreated could lead to severe deterioration of the flare and other plant equipment.

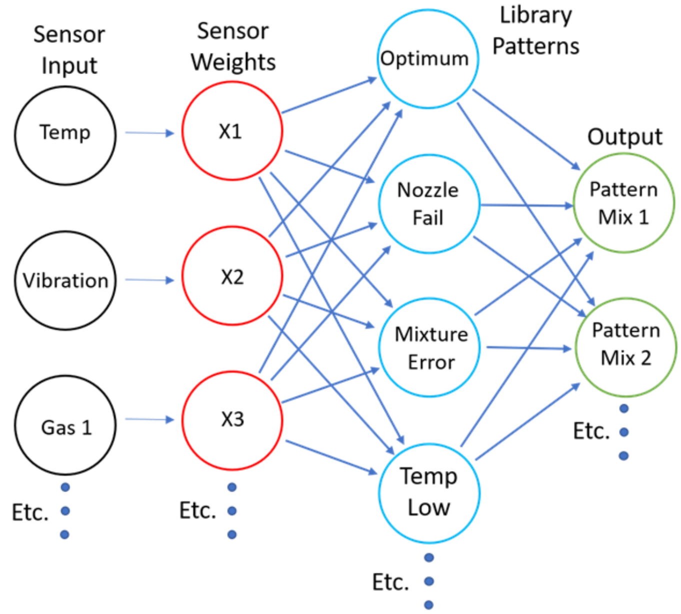


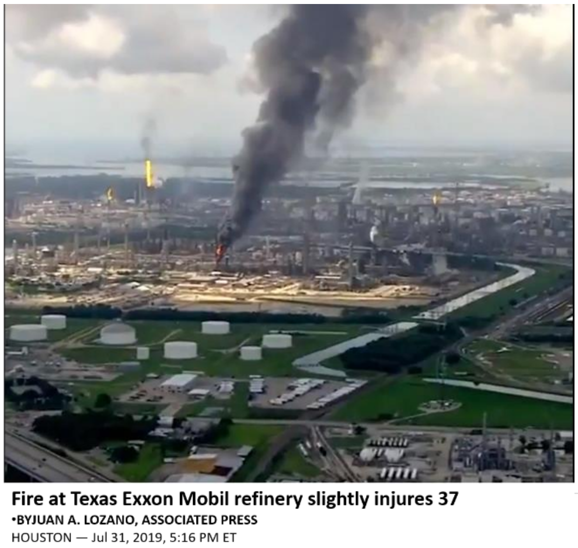
Figure 4 - Flare monitoring network example

The technology can also acquire high-speed acoustic and vibration data that may be used to correlate with gas concentration data to form a vector that represents a mathematical convolution of all these combined signals. Using this information, the stations can be taught to recognize flare events, within some natural variation, using a simple fixed weight neural network that represents a form of AI or machine learning.

4. Plant Safety Environment Enhancement with EvA EAGLE™

Understanding all details of conditions throughout a plant is the most important first step in providing for ultimate plant safety. Consider the recent accident at the ExxonMobil Baytown refinery on July 31, 2019 (see Figure 5). In this case, the plant experienced a significant fire in their ethylene plant and implemented safety precautions for "down-wind" plant personnel and nearby citizens. The EAGLE system would have the ability to fly during these events to report on local conditions to update these safety precautions as needed.

Safety for all plant personnel and for surrounding neighbors will be enhanced by accurate information of all emissions from whatever source, be it flares, vents, or leaks. The data from the EAGLE monitoring neural network can be used as starting boundary conditions for an LES



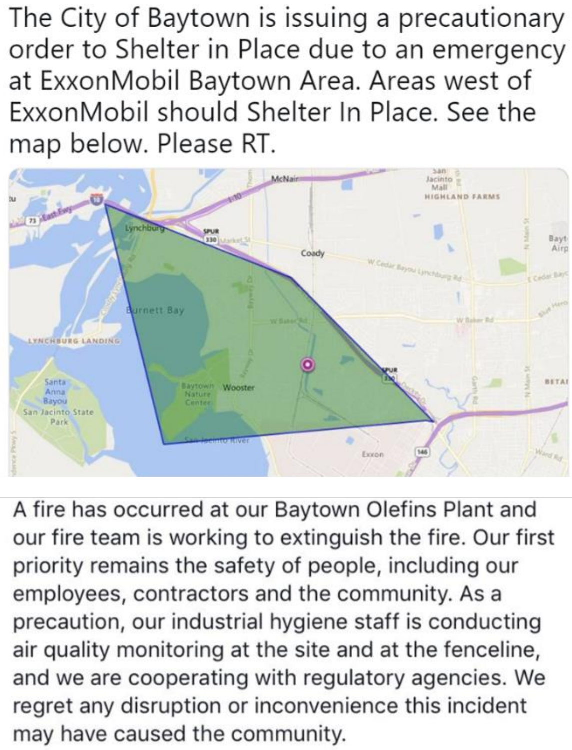


Figure 5 - Fire at Exxon Mobil refinery illustrates value of the EAGLE first-responder monitoring system (see https://abcn.ws/2K68945)

based CFD simulation. An example of a dispersion model using C3d[2], a fast and accurate LES based CFD code, is shown in Figure 3. The simulation results shown represents a hypothetical unignited release of low concentrations of H_2S in a 20-mph wind, showing a 5 ppm H_2S iso-surface. This type of active dispersion modeling will provide fast and accurate predictions of plume dispersion and downwind concentrations.

This combined tool can then be used in active warning systems for plant personnel and surrounding neighbors. Having the detailed starting boundary conditions will provide levels of detail in the dispersion model that have hitherto been very difficult to obtain. Most dispersion models treat the starting condition as a point-source release. The EAGLE™ monitoring neural network will provide details from the entire sensor network that will significantly improve the dispersion model, providing fewer false alarms. All of this will provide greatly enhance plant safety, improved neighborhood relations, and an enhanced environmental policy. The AI capability of the EAGLE™ neural network will provide for optimum plant performance. The examples discussed above illustrate how "fingerprints" of optimal plant performance for a flare system can significantly impact plant performance. This network can be expanded to include the other plant instrumentation such that all plant anomalies can be recognized rapidly leading to improved plant performance, efficiency and safety.

[2] Explained in more detail in previous AFRC papers by the authors [8]

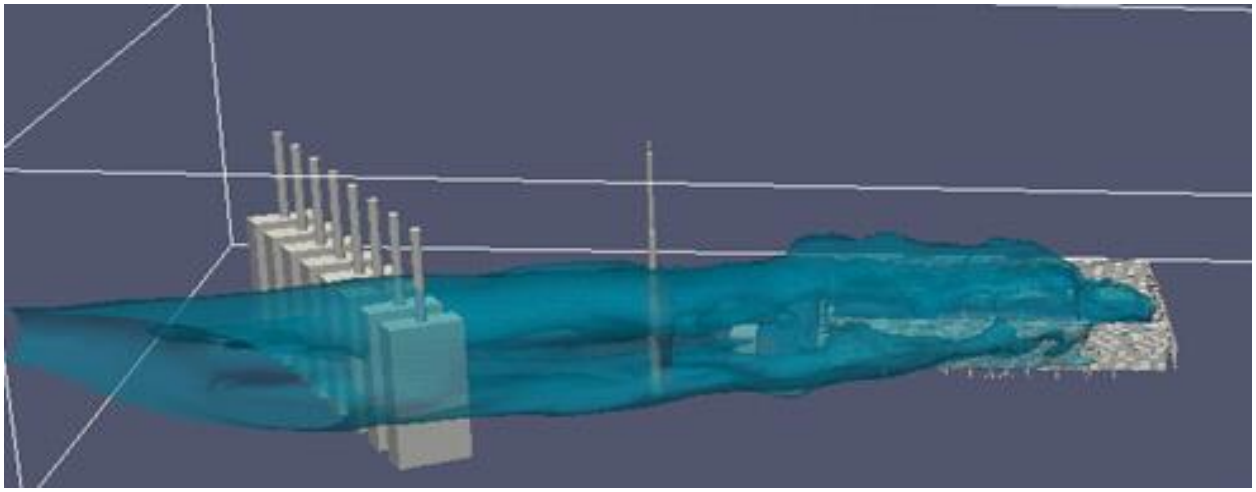


Figure 6 - Dispersion modeling using C3D, an LES based CFD software, provides detailed downwind information.

5. Conclusions and Recommendations

The new UAS, or drone-based sensor system, EAGLE™, has seen additional development with an expanded sensor suite, improvements to incorporate swarms of drones, and is now under development as a neural network with machine learning (i.e., Artificial Intelligence or AI). While sensing of flare emissions remains the core focus, the EAGLE™ system shows great promise for many other applications including vagrant methane emissions from pipeline leaks, oilfields, and landfills. It has also been implemented on drones for first responders as a means of providing early assessment of hazardous conditions before the responders arrive on the scene. The EAGLE™ system shows promise for monitoring emissions from all flares with high accuracy and selectivity and it can be used to monitor emissions from even large MPGFs which have hitherto been impractical to monitor. The EAGLE™ network of monitors can be coupled with an accurate, fast, CFD code, such as C3d, to provide the most accurate downwind dispersion modeling currently available. The AI capability of the EAGLE™ neural network will provide the ability to improve plant safety, efficiency, and environmental responsiveness.

6. References

[1] 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.

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

[3] 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.

[4] 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.

[5] 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.

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

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

[8] J. D. Smith, R. Jackson, A. Suo-Anttila, S. Smith and D. Allen, "Achieving Environmental Compliance through Proper Destruction Efficiency of Low-Profile Multi-Tip Flare Systems," in *American Flame Research Committees 2014 - INDUSTRIAL COMBUSTION SYMPOSIUM*, Hyatt Regency Hotel Houston, Texas, September 7 –10, 2014.