Realtime Methane Emission quantification and reporting with upstream flaring.

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1. Introduction - Abstract

Reducing greenhouse gas emissions such as CO_2 is important in limiting the impact of global warming and helping to meet the goals of the Paris Agreement.

Over the last few years, more focus has been given to the impact and significance of methane (CH_4) emissions, reflecting its higher Global Warming Potential and short atmospheric residence time, meaning that it has a major role in the rate at which warming occurs in the coming decades.

The oil and gas industry are not the only source of CO_2 and CH_4, but it has a significant role to play in helping to reduce GHG emissions. For many production and refinery facilities, flaring is one of the main sources of CH_4 emissions, and whilst agreements such as the World Bank 'zero routine flaring' initiative support reductions from flaring, many flares cannot simply be eliminated as they play an essential safety role.

It is a widely held belief that flares release 2% of gas as unburnt hydrocarbons. However, a growing body of research is revealing a much more complex picture in which some data shows flares operating at >99% efficiency whilst other results of 95% or even less have been published [1]. Efficiency is affected by process conditions, such as gas flow rates and gas composition, as well as weather conditions. Real-time monitoring of combustion efficiency for individual flares is therefore a key part of accurate reporting and the basis upon which tangible opportunities for safe flare reduction can be identified.

Panametrics, a Baker Hughes business, has been designing & manufacturing ultrasonic flare flow meters for over four decades and learned the capabilities and limitations of this ultrasonic measurement technology.

Over the last few years, flare.IQ has been developed, which is a predictive analytics technology based on the outputs of the ultrasonic flare meter, installed on numerous flares around the globe. It is deployed on assisted flares (mainly seen downstream) for flare control and non-assisted flares (mainly seen upstream) for real-time Combustion Efficiency (CE) and Destruction and Removal Efficiency (DRE) monitoring.

At the John Zink facilities in Tulsa, Oklahoma, in conjunction with bp, successful trials of flare.IQ as a method for CH_4 emission tracking were conducted. In this paper, we present some of the experiences and challenges encountered in that work and discuss the implications for more widespread use of predictive systems of this kind.

The emergence of new targets, legislation and taxation have also highlighted the importance with which such systems need to satisfy established standards of traceability. Further presented are steps being taken to adopt a 'fiscal mindset' to the deployment of flare.IQ drawing upon knowledge and experience built up from Baker Hughes' established businesses. Return from field experience has been instrumental to further improve the computation model and its deliverables for operators, with the addition of CO_2 equivalent as an available output coming from flare methane slip.

2. CH_4 emission monitoring and reporting

The most known GHG is carbon dioxide, but methane with a Global Warming Potential (GWP) of 28 times greater than the same mass of carbon dioxide emissions on a 100-year basis according to the Intergovernmental Panel on Climate Change, and over 80 times more powerful on a 20-year basis, makes it the second most abundant GHG after CO_2 [2].

During COP26 in November 2021 in Glasgow, the "Global Methane Pledge" was launched to catalyze actions to reduce CH_4 emissions by at least 30% below 2020 levels by 2030. There is a steep rise of new policies, rules, and regulations to support and regulate CH_4 emission quantification and reporting, including flaring [3].

2.1. OGMP2.0 and MGP (Methane Guiding Principles)

The Oil & Gas Methane Partnership 2.0 (OGMP 2.0) is the United Nations Environment Program's flagship oil and gas reporting and mitigation program that was created by the Climate and Clean Air Coalition in 2014 as a voluntary initiative to help companies reduce CH_4 emissions in the oil and gas sector [4]. OGMP 2.0 is a comprehensive, measurement-based reporting framework that is designed to improve the accuracy and transparency of methane emissions reporting. This is key to prioritizing methane mitigation actions in the sector. If you cannot measure it, you cannot fix it.

OGMP has taken a leadership role in serving as the basis for upcoming methane policies, rules, and regulations around the world. OGMP has issued several Technical Guidance Documents (TGD) describing the practice for CH_4 emissions quantification, following the different OGMP levels. There is a Technical Guidance Document on flare efficiency [5].

Methane Guidance Principles (MGP) is a voluntary initiative with the aim to drive efforts in five priority areas to reduce methane emissions from natural gas production, processing, storage, and transport. The members develop and share practical tools and guidance to help others to learn from their experience and put those lessons into practice [6].

2.2. Rules and regulations

In the EU, there is the existing Climate & Air Quality Framework. The climate law is to reduce Greenhouse Gas (GHG) emissions (including methane) by at least 55% by 2030 and achieve net zero by 2050. There is the ETS (Emissions Trading Scheme), with carbon price of approx. 70 to 100 euro per tCO_2. ETS does not currently regulate methane emitting activities, but emissions from power plants and energy intensive industries.

For future EU law, there is the proposed methane legislation to be finalized in 2023. The scope covers upstream oil & gas, coal and gas transmission & distribution and LNG (Liquefied Natural Gas). Its objective is methane emission Monitoring, Reporting and Verification (MRV) based on the OGMP 2.0 framework, and it includes non-routine flaring. Weekly inspections of flares or continuous Combustion Efficiency and Destruction and Removal Efficiency monitoring will be mandatory. There are three positions with regards to the DRE requirement: European Parliament proposed "at least 99%", the European Commission says, "complete combustion" and EU 27 countries says, "at least 98%". They need to get to an agreement for final legal text which will take time and will last - if all goes well - until the end of 2023.

In the United States (US), the Inflation Reduction Act (IRA) – Methane Emission Reduction Program (MERP) includes an emissions charge applied only to methane emissions from specific types of facilities that are required to report their GHG emissions to the EPA's Greenhouse Gas Emissions Reporting Program (GHGRP). The Emission Charge will be $900/mt methane for 2024 reported emissions, $1,200/mt for 2025, $1,500/mt for 2026 and beyond. On November 11, 2022, the US Environmental Protection Agency (EPA) released its Supplemental Proposal to update and strengthen standards for the oil and natural gas sector to reduce CH_4 and volatile organic compounds from new facilities and CH_4 from existing facilities. The final rule is expected to come out in 4Q 2023. Flares or other combustion devices would need to achieve 95% reduction in CH_4 and VOC emissions, and flaring would be subject to more comprehensive monitoring requirements. On November 30, 2022, the Department of the Interior's Bureau of Land Management (BLM) published a proposal to require operators of federal and Indian oil and gas leases to take steps to avoid the waste of natural gas. Final rule is expected in 4Q 2023. Oil-well gas could not be flared or vented unless it is deemed unavoidably lost; Royalty payments will be applied on oil-well gas above 1 MCF per month of flared gas.

In November 2022 the Environment and Climate Change Canada proposed Regulatory Framework for Reducing Oil and Gas CH_4 Emissions. The proposed rule was expected to be introduced sometime in 2023 making flaring prohibited at oil production sites, while other hydrocarbon destruction equipment at natural gas sites would need to operate at 99%+ control efficiency.

2.3. Flare monitoring technologies

Flare combustion efficiency measurement and monitoring have been a long-standing challenge. The traditional method of extractive sampling, developed by the EPA in the 1980's and more recently demonstrated by the TCEQ (Texas Commission of Environmental Quality) study has been considered as the most reliable method for flare efficiency measurement [7]. However, it is not suitable for field application due to system complexity.

Recent developments in optical gas imaging, as shown in the multispectral infrared imager developed by Zeng et al [8], have been used to monitor flare efficiency in the field. Since the key component is the delicate infrared camera, harsh operating environment poses challenges to the technique, especially for continuous reliable long-term flare CE monitoring. Passive/active FTIR technology has also been used for flare CE monitoring. Due to system complexity and CE measurement uncertainty, this method has shown several challenges.

Differential Absorption Light Detection and Ranging (DIAL) is an optical technology based on differential laser absorption spectroscopy to measure hydrocarbon concentrations along the laser scanning line in the plume downwind of the flare stack. Flare gas mass emission rate in the plume can be calculated from the measured 2D/3D hydrocarbon concentration map and wind speed. Coupled with the total flare gas flowrate, flare DRE can be calculated. This method has been used for research and spot-check of flare efficiency, but can be challenging for continuous flare efficiency monitoring due to system complexity, size and lack of automation, especially applying offshore.

As the oil & gas industry works towards flare emission reductions, another important aspect is to improve flare combustion efficiency. Flare operation conditions, such as flowrate, heating value in the combustion zone, and flare gas compositions etc. are controllable factors which have effects on flare CE/DRE as demonstrated in the TCEQ studies. Weather conditions, especially wind speed, have a major impact on flare performance. High crosswind will not only decrease flare combustion efficiency, but also cause the flame to burn at the side wall of the flare tip resulting damages to the tip. Johnson has shown that even ambient wind could negatively impact flare efficiency, especially for flare gas of low heating values [9]. Since all the changes in both operation conditions and wind speed can happen instantaneously, continuously monitoring of flare combustion is required to track the flare efficiency and emissions.

3. bp aim 4 – Reducing Methane

bp has set out 10 net zero aims in support of its ambition to be a net zero company by 2050 or sooner and to help the world get to net zero. One of them, bp's aim 4, involves a plan to deploy methane measurement technology across major oil and gas facilities by the end of 2023. bp has also set a methane intensity target of 0.20% by 2025 using its new measurement approach, moving away from a target based on general industry methodologies, and is focusing on achieving reductions across key methane sources, including fugitives, combustion, and flaring. The deployment of new measurement technology represents a major step-change in the industry's approach to detecting, quantifying, and reducing methane emissions.

Flaring is one of the main sources of methane for the oil & gas sector, so bp continues to focus on flare reduction activity and to support the World Bank's Zero Routine Flaring by 2030 initiative, which brings together stakeholders to collaborate and eliminate routine flaring from operated oil assets by 2030.

bp continues to work with key stakeholders on activities designed to improve detection, measurement, quantification, verification and reporting of methane emissions. bp is:

- a signatory to the Methane Guiding Principles (MGP);
- working with the Environmental Defense Fund (EDF) and has announced a three-year program to advance technologies and practices to help reduce methane emissions.
- a key contributor to the development of the Oil and Gas Methane Partnership, or OGMP 2.0

3.1. Using Digital metering to help reduce methane emissions.

For oil and gas production, reducing emissions associated with flaring is a key challenge. While flares can be one of the major sources of CO_2 and CH_4 emissions, they also play a critical safety role, so they cannot simply be switched-off. But to fully understand how well the flares are operating, the combustion efficiency must be tested. Increasingly, this is being done by the latest computational fluid dynamics (CFD) techniques to understand how flares behave over the full range of operational and weather conditions as shown By Black *et al*. in their paper [10].

In 2020, this was taken one step further – by making this kind of information available in real-time to one of bp's facilities, meaning that any changes in flare performance can be identified rapidly and managed. In a successful trial on Glen Lyon – a floating production, storage, and offloading vessel, west of Shetland – bp trialed the use of flare.IQ, a predictive analysis technology developed by Panametrics, a Baker Hughes business. flare.IQ provides flaring performance information continuously, using the power of cloud computing to run complex models remotely and feeding it back to bp facilities in seconds. Following this trial, flare.IQ is being onboarded across all bp's production assets and is currently ongoing acceptance testing and commissioning.

Recognizing the importance of reducing emissions from flaring, bp is sharing these insights and developments with their partners for example through MGP (Methane Guiding Principles), OGMP2.0 and at conferences like this one.

4. Ultrasonic Flare Flow measurement

Flare flow measurement is one of the most challenging flow applications given its large turn down ratio. There are various flow measurement technologies available such as ultrasonic, venturi (dp) or thermal. Each technology has its own pros and cons. Ultrasonic flare metering has become the most proven, robust technology for meeting those measurement challenges and regulatory requirements in flare gas applications and is considered by the industry as best fit for purpose.

4.1. How does it work (sensors)

Using ultrasound to measure flow velocity has been a well-known technique [11]. Over the years, many different types of ultrasonic flowmeters have been developed—the operating principle varies from transit-time to Doppler and to Transflection [12]. Among these, transit-time based ultrasonic flow measurement has become the most popular method thanks to its superior accuracy and robustness.

Transit-time ultrasonic flowmeters take advantage of a simple principle called "time of flight" as illustrated in Fig. 1. Specifically, the time it takes for an ultrasonic signal pulse to travel against the flow (i.e., upstream), t_{up}, is longer than the time it takes following the flow (i.e., downstream), t_{dn}. The difference between upstream and downstream traveling times, Δt, is directly proportional to the flow velocity as shown in equation (1)

$$V = \frac{P}{2\cos\theta}\left(\frac{1}{t_{dn}} - \frac{1}{t_{up}}\right) = \frac{P}{2\cos\theta}\left(\frac{\Delta t}{t_{dn}\, t_{up}}\right) \qquad (1)$$

where V is the flow velocity to be measured, P is the ultrasonic path length, and θ is the acute angle between the ultrasonic path and the axis of the flow cell or pipe section. Each pair of ultrasonic transducers alternatively acts as an ultrasound transmitter and receiver sending and receiving ultrasonic pulses respectively. Δt can be measured accurately for a given flowmeter configuration with fixed path length and traveling angle. With the measurement of flow velocity, volumetric flowrate can be calculated based on the flow velocity and flow cell cross-section area. However, the flow velocity measured by the ultrasonic beam is an average line velocity along the ultrasonic beam path. One must transfer the line velocity measured by ultrasonic flowmeter to the cross-section average velocity to calculate the volumetric flowrate.

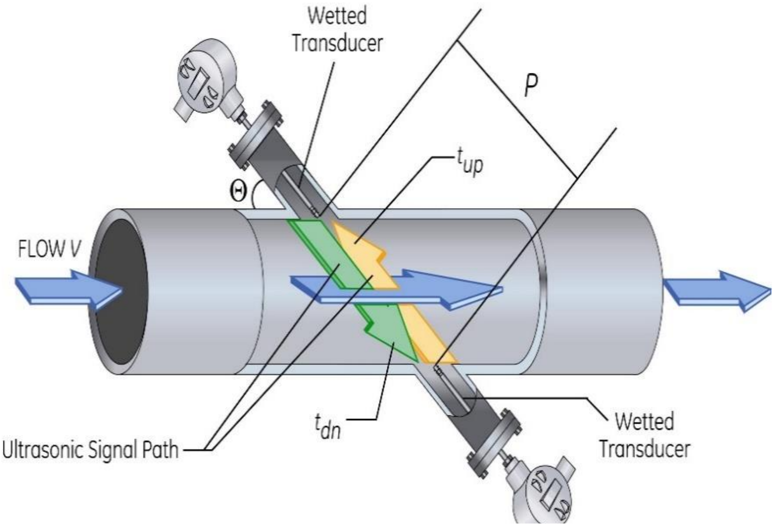

Figure 1 The operating principle of a transit-time based ultrasonic flowmeter.

Since the flow rate is measured from the fluid velocity in the conduit, accuracy of the measurement can also be affected by the measured wavefront velocity profile, which will usually deviate from the developed velocity profile, a parabolic profile that is a function of the Reynolds number.

4.2. Challenges

As stated above, flare measurement is one of the most difficult applications due to a wide range of challenging process conditions. To start, a flare system is designed to handle large gas flows in large size pipes which in case of emergencies can go up extremely high, while under normal operating conditions, the flow is in the extremely low end of the range in that same large diameter pipe. A second major challenge for flare gas flow measurement is the significant gas composition variation due to different processes involving both light and heavy hydrocarbons. For flares installed at refineries or petrochemical plants, these variations are larger compared to upstream applications.

By choosing the right frequency of the modulated ultrasonic signal (typically at 50 kHz or 100 kHz)-a compromise between time resolution and signal loss, nanosecond time resolution can be achieved with modern electronics and signal processing, which enables measurement over a wide range of flow velocity. It can cover a velocity range of 0.03 m/s to more than 120 m/s for a typical 2-path flow meter (a longer path length is used for low flow measurement and a shorter path length for high flow rate measurement) while maintaining a robust and reliable measurement covering the wide turndown ratio and maintaining a reasonable accuracy, assuming a fully developed flow profile. This high turndown ratio is critical for flare metering application where flowrate is low at normal operation condition and extremely high during flaring events.

Other challenging process conditions can be saturated or wet gas, especially during night conditions when the ambient temperature is dropping and cooling down the gas inside the pipe to below the hydrocarbon dewpoint causing it to condense. Contamination and buildup can occur; Corrosive gases can be present; Temperature excursion up to 300°C are possible, or down to cryogenic levels at LNG plants, for example. Stratified flow (non-isothermal flow) can occur at large diameter, especially slow-moving flow where the heavier gas sinks to the bottom and the lighter gases go to the top resulting in different flow velocities.

4.3. Straight run – Flow profile

Another crucial point of consideration is the flow profile effects at the meters' location, especially at compact (offshore) installations with limited available straight runs caused by upstream single or double bends, in plane and out of plane bends, expanders, reducers, and other disturbances. Low flow at low pressure in large pipes are not the ideal conditions that provide sufficient forces for a well-defined flow profile. Hence, the above-mentioned disturbances could result in long lasting disturbed flow profiles, crossflow and or swirl effects and when present at the location of the ultrasonic flow meter, can cause substantial flow measurement deviations.

For installations without the required straight run, flow profile disturbance and flow rate measurement can be corrected by running computational fluid dynamic (CFD) calculation based on existing piping isometrics, meter location and actual ultrasonic measurement path configurations.

4.4. Multipath

For custody transfer measurement in gas transmission pipelines, multipath ultrasonic meters have been applied successfully for over 25 years now. These meters are designed with multipath configurations ranging from 3 – 8 paths (or more) to isolate the meter from upstream flow disturbances and to improve the capability to deal with non-ideal flow profiles. Looking at the changing flare metering landscape now, where accuracy requirements are getting more stringent, users may not need to go all the way to 8 paths but moving away from single and dual path meters is the way forward for flare meters. For some challenging flow profiles, considerations of 4-path configurations have been mentioned.

4.5. Calibration

Another recommended practice that can be taken from multipath gas metering devices is calibration. A gas meter is typically calibrated at a 3rd party flow facility at calibration conditions as close as possible to normal process operating conditions to achieve highest accuracy. For flare meters, the same can be done to adjust the meter for any bias, and hence, provide a more accurate meter. Thus, calibration of the flowmeter over different velocity points in the factory or at a 3rd party flow facility is required to achieve accurate flow rate measurement. To enable this, there might be an ask to the industry for providing large size (up to ~30 inch), low pressure gas flow testing capability of flow velocity ranging from 0.03 to 120 m/s.

4.6. Tolerances

Accurate dimensions and nozzle angles are critical enablers for ultrasonic flowmeters providing accurate flow reading. With meter body manufacturing, it is common to take 3D measurement with a CMM machine. Checking and controlling 'as built' dimensions through hot or cold tap procedure welding nozzles can be challenging during field installations. To reduce the uncertainties to some extent, a new field tool is under development to enable ex-situ measurements to determine the path inside the pipe. For avoiding this challenge and uncertainty altogether, moving to prefabricated flow cell could be considered. Welding nozzles to a flow cell in the fabrication shop provides better control on tolerances and allows minimizing them. If followed by installing the wetted ultrasonic transducers during FAT (Factory Acceptance Testing), accurate 'as built' path dimensions can be taken before the flow cell is shipped to site and installed in the flare line. Moving towards non-wetted transducers can help reducing the risks / uncertainties associated with dimensions, but one should be mindful about introducing reliability risks with regards to the (dis)bonding of the crystal to the face of the inserted holder in case of temperatures excursions that can occur during (emergency) flaring events.

4.7. Flowmeter key outputs

Ultrasonic flow meters have proven to be able to provide robust and reliable flow rate measurement based on the ultrasound traveling time, as well as the measurement of speed of sound of the media, for instance flare gas mixture. Both volumetric flow rate as well as speed of sound are two key inputs for flare.IQ from the ultrasonic flowmeter.

American Gas Association Report No.10, 2003, Speed of Sound in natural gases and other related hydrocarbon gases describes the standard method using virial equation of state to calculate speed of sound based on various gas compositions with very high accuracy (<0.2%) within defined limits. [13]

Along the same lines, in 2009, Hammond developed an empirical method using gas virial equation of state to derive the total average molecular weight (MW) based on speed of sound in the gas [14]. For a typical ultrasonic flow meter used in flare gas applications, MW derived from speed of sound measurement can potentially achieve accuracies for natural gas comparable to AGA10. In case of flare gas applications with known concentration of inert gases, it will help to further enhance the accuracy of the MW calculation.

5. Flare Combustion Efficiency (CE) Monitoring

Monitoring and measuring industrial flare combustion efficiency has been a longstanding challenge. With the tightened regulations and requirements for flaring, major progress has been made in understanding flare combustion and operations in recent years.

5.1. Need (real-time quantification and reporting)

The OGMP Technical Guidance document – flare efficiency provides guidelines approved by the United Nations Environment Programme (UNEP) steering group. For compliance with Level 4 quantification methodologies either direct measurement, measurement-based emission factors and or process simulation are required. [5]

The following are considered as providing level 4 estimates for continuous or intermittent flaring:

Gas flow to the flare	Continuous direct measurement or measurement-based indirect estimate using a mass balance/process simulation. For batch flaring, engineering calculations are also appropriate
Gas composition	Continuous measurement or sample measurement In cases where the methane content can be assumed to meet a regulated specification (e.g. underground gas storage, gas transmission, gas distribution and LNG terminals), the gas specification compositions may be applied[6]
Destruction efficiency[7]	Measurement-based methane destruction efficiency applied or destruction efficiency determined through the application of correlations based on representative sampling Engineering calculations can also be used, where applicable

Figure 2 Considered as providing level 4 estimates. Source: OGMP technical Guidance Document for flare efficiency

- Within the EU, regulated specifications and quality standards may be applied.
- Combustion efficiency is often used interchangeably with destruction efficiency, and they are, therefore, often confused. Destruction efficiency is a measure of how much of the original hydrocarbons are destroyed (to form CO_2 and CO), while combustion efficiency is a measure of how much of the original hydrocarbons burn completely and are transformed into CO_2 and water vapor.
- Applies to non-aspirated flares (i.e., aspirated, or assisted, flares are flares that do use steam, air, or other gasses to aspirate additional air in the combustion zone)

5.2. Solution for Real-time flare monitoring and reporting

Recently, Panametrics has developed a unique method for real-time flare combustion monitoring based on parametric model considering all the factors affecting flare combustion efficiency [15]. These factors include flare gas net heating value in the combustion zone (NHVcz), flare flowrate, flare gas exit velocity, crosswind at flare tip, flare tip diameter and gas composition etc. This is the flare.IQ solution.

flare.IQ parametric modeling is based on existing experimental data and computational fluid dynamics calculations. This method can be deployed to both upstream and downstream flare systems (assisted and un-assisted flares) to achieve maintenance-free emission monitoring of Combustion Efficiency (CE) and Destruction and Removal Efficiency (DRE) and optimization of the combustion efficiency for assisted flares through a control feature for steam, air, and fuel gas assists. This technology also provides Predictive Emissions Monitoring System (PEMS) for flares such as Volatile Organic Compounds (VOC) – of which methane is typically the main component with upstream flaring - as well as CO, CO_2 and conversion to CO_2eq. The current flare.IQ installed base is approximately 200 flares globally.

5.3. How does flare.IQ work (Parametric model)

Flowrate, NHV, crosswind and MW of flare gas mixture are some of the key process factors affecting flare combustion efficiency. From the CFD studies and existing test data of flare combustion, all the factors, either single factor alone or combination of several factors have shown strong correlation to flare CE and thus the effect can be described using numeric models as shown in figure 3. flare.IQ will support both the molecular weight or NHV input based on gas analyzers or calculated from speed of sound from ultrasonic flare flow meter. In case of the latter, flare.IQ needs both flowrate and speed of sound as measured by the ultrasonic flowmeter as inputs to derive the average gas MW and net heating value (NHV).

5.4. What does flare.IQ provide (PEMS outputs)

From the calculated CE, Destruction and Removal Efficiency (DRE) can be derived since they have near linear correlation. Based on the calculated CE/DRE, emissions of unburned hydrocarbon, CO, CO_2, and CO_2 equivalent (CO_2eq) can be calculated. Even though, this method has been used to monitor emissions for both assisted and non-assisted flares, it is particularly suitable for upstream application because upstream flare configuration is much simpler, usually without any assist gases and with relatively stable gas composition mainly consisted of natural gas. With limited instrument update, such as a commercial grade anemometer for windspeed measurement, this method can be deployed to any upstream flare systems equipped with ultrasonic flowmeter for reliable, accurate and continuous flare combustion efficiency and emission monitoring.

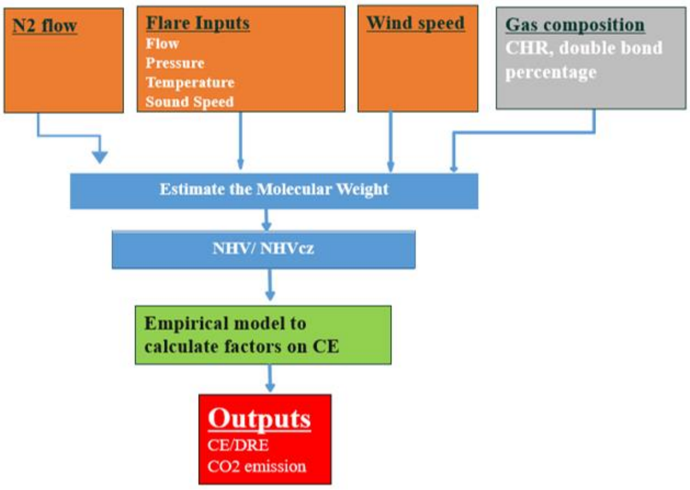

Figure 3 Schematics of the flare combustion efficiency monitoring method

Providing a real-time CE / DRE measurement enables improving & controlling processes better, may result in significant (reported) emission reductions. As this method is based on the ultrasonic flow meter sensors mounted in-situ, the readings are not affected by weather conditions such as mist, clouds and rain, resulting in stable measurement with excellent repeatability. In case of co-located flares, flare.IQ distinguishes CE / DRE from LP to HP flare.

Combining the CE / DRE measurement capability to the ultrasonic flare flow meter and bringing this toward methane emission quantification and reporting associated with flaring brings up the need to push the ultrasonic flow measurement technology towards ‘fiscal’, meaning reducing uncertainty from the measurement.

5.5. Periodic verification

To ensure flowmeter performance, periodic meter performance verification, typically yearly or bi-annual is required / recommended. Panametrics developed a method for ultrasonic flowmeter digital verification based on speed of sound check and meter diagnostics check. For speed of sound check, using patented virial state equation and gas mixing rules, theoretical speed of sound of a given flare gas mixture was calculated and compared to that measured from ultrasonic flowmeter to ensure that flowmeter speed of sound measurement is accurate, as flow measurement accuracy depends on the speed of sound measurement accuracy. To enable Digital Verification, Modbus communication between the flowmeter and flare.IQ is required.

Speed of sound calculation from this patented method is consistent with AGA10 method for all the applicable gases. In addition to the speed of sound check, meter diagnostics check will check flowmeter key parameters, such as signal strength, signal quality, and transit time etc. to make sure they are within the allowed ranges. This digital flowmeter verification would allow customers to check and verify flowmeter performance periodically without site visits from flowmeter service engineers, which is especially helpful for offshore applications.

6. Emission Quantification and reporting

For (methane) emission quantification and reporting associated with flaring, the measurements consist of two elements:

- Total flow or volume (ultrasonic flow meter like (X)GF868, or another brand)
- Emission analytics (flare.IQ)

6.1. Measurement Approach

For almost all bp upstream assets existing, ultrasonic flare meters are utilized. flare.IQ can work with any ultrasonic flare flow meter which provides flowrate and speed of sound. The flare.IQ deployment is based on the existing Bently Nevada System 1™ asset diagnostics platform, which provides the data acquisition, visualization, analytics, and notifications to help support bp's business strategy.

The ultrasonic flow meter will measure the total flare flow volume and the readings will be transmitted to the flare.IQ software. The flare.IQ module will take care of analyzing the input data and calculating a set of values representing efficiency and emissions of the flare, providing an update up to 5 to 10 seconds.

The typical flare.IQ inputs are:

Measurement	**Required / optional**	**Notes**
Total Molecular Weight (MW)	Required	Kg/kmol
Flare Flow (QFlare)	Required	Flare flow, measured in standard flow units, Sm3/h. Qflare includes N_2 flow upstream of the flare flowmeter.
N_2 Upstream / Downstream Flow	If applicable	Total nitrogen flow upstream of flare flowmeter, measured in standard flow units, Sm3/h.
Cross Wind Speed (u)	Required	Measured in velocity units, such as m/s, ft/s, etc.

It outputs the following results:

Extractions	**Description**	**Units**
CE	Combustion Efficiency, defined as the percentage of carbon mass in the fuels of the flare gas that is completely converted to carbon dioxide.	%
DRE	Destruction and Removal Efficiency. The DRE quantifies the percentage of a specific compound in the flare gas that is converted to a different compound.	%
E-CO	Carbon monoxide emissions.	Kg/h
E_CO_2	Carbon dioxide emissions.	Kg/h
E_VOC	Emissions of volatile organic compounds.	Kg/h
E_CO_2eq	CO_2 equivalent emissions. This is the total effective CO_2 emissions, where the amounts of all hydrocarbon emissions are converted to the equivalent amount of CO_2 that would have the same greenhouse gas effect.	Kg/h
Flare.IQ status	Status of the calculated efficiency and emissions results, based on data quality and/or communication status.	None

6.2. Verification of flare.IQ

Regulation of methane emissions from flaring remains in its infancy, but it is anticipated that future reporting will require the same expectations of measurement traceability that underpin other emissions reporting. Moreover, if these measurements provide the basis upon which emissions reduction opportunities are identified, sustained, and demonstrated then it is essential that the operating boundaries for the use of flare.IQ are well understood and documented. Validation is therefore a critical part of bp's Aim 4, however, as there are no international standards or reference standards relating to how flare.IQ operates, only verification is possible.

With flare.IQ being the most novel technology of the available solutions, testing that against some reference was a key element of the journey. But there is no approved reference method for assessing flare efficiency. This limits the ability to report DRE and emissions with normal standards of traceability. The experimental test conducted that utilizes the nearest thing that is available to a reference method, is the privately operated flare testing facility at John Zink in Tulsa, OK (JZ) a flare manufacturer, and was augmented with computational fluid dynamics (CFD) to extend the range of conditions tested. This work may be used to help inform the industry of the current gap. See the photo at figure 4.

Figure 4 the flare.IQ extractive sampling testing at John Zink, Tulsa, OK

6.2.1. Experimental testing at John Zink

The purpose of the experiment was to test flare.IQ performance under various controllable flare process conditions, as well as different flare tip designs. As described in detail below, the test matrix includes three different exit velocities covering low, medium, and high exit velocities, three different NHVvg conditions of low, medium, and high heating values, and three flare tip designs. Two of the three flare tips provided by John Zink were 14-inch non-assisted straight pipe flare tip and 8-inch pressure-assisted multi-arm flare tip, with effective flare tip diameter of 11 inch and 5.26inch. The third flare tip provided by GBA-a flare tip manufacturer-was a single arm pressure-assisted 8-inch flare tip with an effective tip diameter of 5.2 inch.

The selected exit velocities of 0.2 m/s, 0.6 m/s and 5 m/s are typical for normal flare operation range. NHVvg of high heating content (~920 BTU/SCF), medium heating content (~600 BTU/SCF) and low heating content (less than 300 BTU/SCF) were selected to cover all the range of possible flare NHV scenario for upstream operations. The flare tip exit velocity can be controlled by total flowrate of the vent gas. The NHVvg was adjusted through the dilution of Tulsa city natural gas (TNG) using N2 with a defined flowrate ratio. Each test point requires 5 minutes of testing for a valid measurement and has 3 consecutive repeats, or continuous measurement of 15 minutes to minimize variations. For all the variation of test conditions, there are 75 valid test points measured at the JZ testing facility.

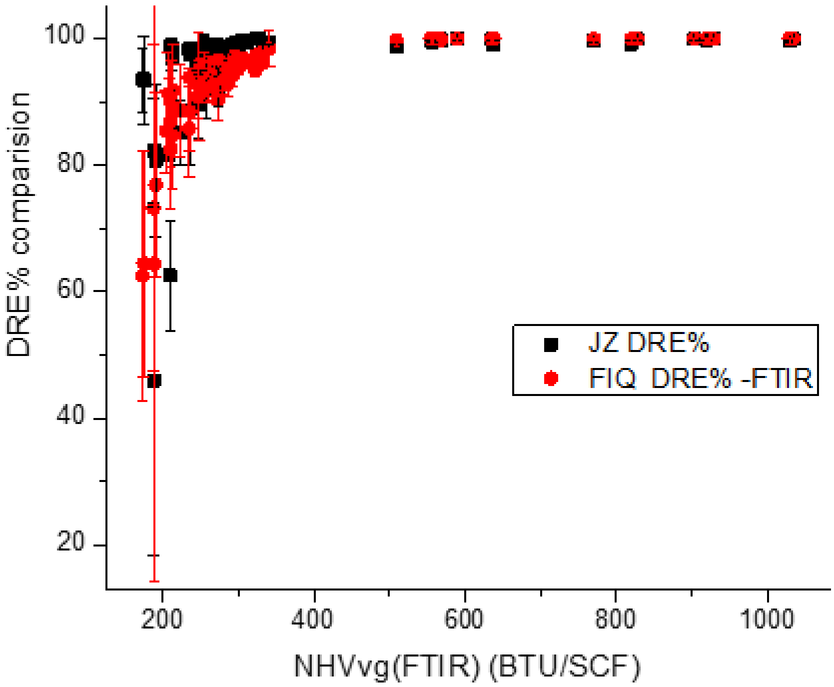

Figure 5 Comparison of DRE results from flare.IQ and JZ testing

As shown in figure 5, flare.IQ successfully assesses changes in DRE from the critical variables of flow, gas composition, flare tip geometry and crosswind speed. Verification aligns with previously published research that efficiency of a lit flare changes because of these variables. Flare combustion follows a complex trend in which DRE rapidly deteriorates once net heating value falls below 300BTU/SCF. This trend is further affected by flow rates and crosswind speeds. As these factors can change quickly, continuous tracking of flare performance is useful. As shown in the plot, DRE calculated from flare.IQ matches the test results for flare gas net heating value (NHV) region above 300 BTU/SCF, with an average difference of 0.83%. Below 300BTU/SCF CE and DRE values change rapidly and are difficult to measure accurately using currently available technology, as shown by large uncertainties from both flare.IQ and JZ extractive sampling method.

6.2.2. Computational Fluid Dynamics (CFD) calculation

Computational fluid dynamics (CFD) has been demonstrated as an effective tool to augment physical flare testing. It was used to test flare.IQ for extreme conditions, especially for high crosswind conditions which cannot be controlled in physical testing. CFD models of flares have been verified against internationally recognized reference data-flare combustion data of Sandia flame D.

Verified CFD models can be used to extend the range of conditions under which flares can be tested. This has allowed the effects of cross winds to be assessed. As a result, flare.IQ verification includes verification for wind speeds more than 20m/s, conditions which have previously been reported as the point at which wind begins to significantly affect DRE.

Calculated test cases also include conditions of Low momentum flux ratio (low gas flow/ high cross wind) conditions which cannot be tested empirically. At low Momentum flux ratio (MFR), the CE /DRE deteriorates, demonstrating the importance of tracking wind speed as part of the measurement. As shown in the plot below, the CE results from CFD calculation and flare.IQ are following the same trend and match very well for regions of NHV>300 BTU/SCF. For regions below that, flare combustion becomes unstable, and CE deteriorates dramatically, which leads to large CE uncertainty for both measurement and calculation.

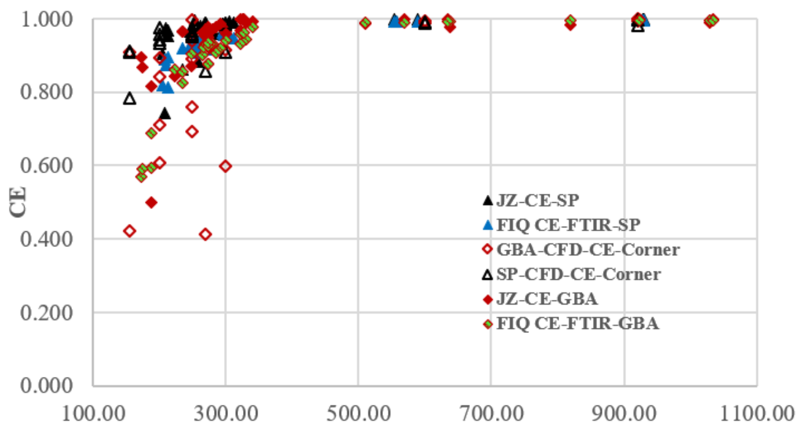

Figure 6 Comparison of CE results from CFD, flare.IQ and testing

6.2.3. Uncertainty analysis of flare.IQ

The uncertainty analysis of flare.IQ combustion efficiency (CE) calculation is carried out in accordance with evaluation of measurement data, Guide to the Expression of Uncertainty in Measurement (GUM 1995 with minor correction). Uncertainty of this model as a system includes the uncertainty analysis of the following steps:

- System error $(e_{CE})_s$:: based on uncertainties of all the input variables and their sensitivity coefficients, system error can be derived.
- Model uncertainty $(e_{CE})_m$:: since flare.IQ CE is a model derived from test data. The error of flare.IQ CE calculation comparing to the test data is the model uncertainty.
- Test data uncertainty $(e_{CE})_e$:: the test data is used as a reference of model development. They are measurement data with certain errors.
- Combined uncertainty $(e_{CE})_c$: based on independent uncertainty of system error, model uncertainty and test data uncertainty, the combined absolute uncertainty can be calculated.

Reported emissions can be accompanied with an estimate of uncertainty and conform to OGMP2.0 Level 4/5 requirements. The derivation of uncertainty is essential if reported values are to conform with OGMP2.0 reporting requirements. Table 1 shows the flare.IQ uncertainties for two typical flare operation conditions.

Table 1 – flare.IQ typical CE uncertainty

conditions	Minimum	Normal	Maximum
MW(g/mol)	24	17.3	NA
NHVvg(BTU/SCF)	319.16	905.52	NA
NHVmass(MJ/kg)	10.59	42.43	NA
Tip diameter(m)	0.3	0.4	NA
Flare flow(sM^3/hr)	100	600	NA
Crosswind (m/s)	3	8	NA
Exit velocity (m/s)	0.55	1.39	NA
CE(%)	95.65	99.06	NA
$(e_{CE})_c$ (%)	3.26	1.55	NA
$(e_{CE})_s$ (%)	0.76	0.17	NA
$(e_{CE})_m$ (%)	3.03	1.17	NA
$(e_{CE})_e$ (%)	0.95	1.05	NA

6.3. Regulatory acceptance (Technically defensible, auditable, and traceable)

Given the fact continuous (methane) emission quantification and reporting with flaring are a 'virgin' territory where the industry has to learn defining reasonable requirements and industry standards are not (yet) available, it was decided to follow the most common practices and principles known for custody transfer measurement and similar measurements, that are internationally recognized by the industry and can be applied to methane emissions quantification and reporting for flaring as well.

The approach for obtaining regulatory acceptance was based on three major pillars: providing technically defensible, auditable, traceable data for both the flow metering part as well as the flare.IQ part for CE & PEMS.

For the flow metering part some of the applicable standards are: API14-10, HM58 and ISO17089-2. For the flare.IQ part this is API21.1 and OGMP2.0.

Guidelines drafted by OGMP2.0 for reporting methane emissions from flaring included provision for the use of process simulation models and applicable engineering calculations to determine destruction efficiency. The requirement does not stipulate the need for continuous tracking. However, OGMP2.0 does not currently contain levels of detail on requirements such as traceability and uncertainty that are commonplace in other measurement systems. Real time methane emission quantification and reporting by means of flare.IQ and ultrasonic flare measurement technology does comply with OGMP2.0 level 4 requirements (emission measurement at source level) which - when carried out for at least 3 years – will qualify operators to obtain gold standard or level 5 (site level).

7. Conclusions

In this paper, we present an integrated system for flare emission monitoring and reporting, which includes both flare flow and flare efficiency measurement. As ultrasonic flare measurement moving toward fiscal, this puts a new set of more stringent requirements on the measurement.

We did see that ultrasonic flow measurement technology for flares is accepted by the industry as fit for purpose, that can handle the typical challenging conditions in a flare process environment. Industry Best practices from other measurements (Ultrasonic Custody Transfer) can be leveraged to reduce the uncertainties (multipath, reduce fabrication tolerances, calibration). Whilst CFD and flow profile modeling can help with analyzing the estimated k-factor at the meter's location, calibration of fully assembled ultrasonic flare flow meters will be recommended for lowest uncertainty as well as multipath flare meters moving forward.

For flare combustion monitoring, flare.IQ is an interesting breakthrough technology that is based on ultrasonic flow measurement that can help control, monitor, and optimize flare operations (CE / DRE) and reduce greenhouse gas emissions such as methane. It replaces static emissions factors with real-time CE / DRE measurement and brings 24/7 methane quantification and reporting that is consistent with OGMP2.0.

The experimental testing at John Zink, augmented with CFD work, has helped gain understanding about flare.IQ technology and to what extent it has potential to bring significant operational and environmental insights and savings (carbon tax, ETS, steam savings). The accuracy was found to be <0.83% above 300 BTU/SCF. Uncertainty analysis has shown a calculated combined uncertainty $(e_{CE})_c$ of 1.5% based on independent uncertainty of system error, model uncertainty and test data uncertainty.

Further work is needed to explore how to deploy and use flare.IQ effectively but this is outside of the scope of this paper.

We're entering virgin territory and time is of the essence. Realtime CE / DRE Flare emission monitoring standards do not exist (yet) and finding suitable test facilities is challenging. Everyone in the industry is working on the same goal from a different angle - while facing different challenges – all depending on each other. The work presented in the paper is a great demonstration of constructive collaboration between many organizations involved.

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