Newest methodology for flare validation

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Abstract

The oxidation by burning of disposed gases containing combustible elements such as volatile organic compounds (VOCs), natural gas (or methane), carbon monoxide (CO), and hydrogen (H_2) is known as 'Flaring'. This process is used to manage the safe disposal of waste and emergency relief gasses generated by refineries, petroleum production, chemical industries, ammonia fertilizer plants, etc. Flaring is typically used for day-to-day waste disposal as well as the last line of defense in an emergency blow down condition. In recent years as efforts have been made to reduce global CO_2 and CO_2eq emissions, flares have been recognized as significant sources both of carbon dioxide and methane, it is also acknowledged that as flares have primarily been considered safety relief devices little rigorous focus has been made to understand their emissions under all operating conditions. Consequently, there is a strong interest among operators and suppliers in both understanding and maximizing the combustion efficiency of flares. In response to this challenge, CCA, headquartered in Gioia del Colle (BA) Italy, in cooperation with GCL, has pioneered a new methodology for precisely measuring flare efficiency on an industrial scale.

Introduction

The efficiency of flare combustion is influenced by several key factors: the flammability, auto-ignition temperature, net heating value, density [1], mixing of gases within the flare's combustion zone [2]. Incomplete combustion, known as "inefficient" flaring, can lead to the release of unburned fuel [3], volatile organic compounds [4], and carbonous soot or black carbon [5, 6, 7]. Since most flare gas contains a high concentration of methane [8], a short-lived climate pollutant with a significantly higher global warming potential than CO_2 [7], inefficient flaring can emerge as a major source of greenhouse gas emissions.

The direct measurements of the flare performance in open space are particularly difficult to be realized and the repeatability and accuracy of the results are far to be optimal, furthermore determination of the impact of such variables such as flare gas composition, cross wind and simulated rain has proved challenging. In order to eliminate these difficulties, at the CCA testing site in Gioia del Colle Italy a new methodology for flare validation has been implemented. By the use of the 48 MW boiler test rig combustion chamber as an envelope volume to confine the flare combustion process it is possible to control both cross wind velocity, combustion duty and exhaust composition in reliable end repeatability conditions. The test facility also brings together state of the art gas blending stations with access to multiple feed gas compositions.

A testing method validation has been performed and a preliminary test measurement executed on a generic flare tip model properly designed in accordance with good engineering practice, are here presented.

Three distinct elevated flare reacting flow mixing regimes have been identified as possible conditions to be investigated by this new methodology. (see Figure 1) [9]

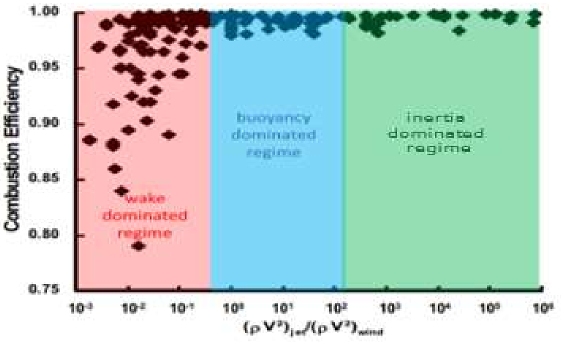

Figure 1: Combustion efficiency as a function of momentum flux ratio. [9]

Firstly, in the **inertia-dominated regime** in which the high-velocity jet facilitates jet-mixing, resulting in consistently high combustion efficiencies. The inertia dominated regimes are typical of flares operating under emergency and blow down conditions, this typically occurs only across 5% of a flares operating life. The second is the **buoyancy-dominated regime** where the velocity decreases and eddy quenching or stripping becomes possible. The last is the **wake-dominated regime** characterized by low velocity or high crosswind where the flame is drawn downwards and stabilizes within the vortex trail off the stack. A flare will typically spend almost 95% of its life operating under these lower flow conditions.

Experimental Rig in the CCA Testing Area

At the CCA testing area several combustion processes can be simulated and tested on an industrial scale by means important testing infrastructures. The CCA boiler test rig was designed in order to test boiler burners of up to 48 MW capacity. This furnace, one of the largest in Europe, continues to be utilized by CCA for assessing various boiler burner technologies across different fuel types. Its dimension is 4.5 meters in width, 6 meters in height, and 12 meters in length internally. With its closed design, the rig enables precise measurements of O_2, CO, CH_4, other unburnt hydrocarbons, and CO_2 at its outlet. View ports along the length of the chamber allow for detailed flame monitoring as well as emissions probing at the flame. This detailed flame monitoring could be crucial for further extrapolation to CFD analysis and validation. A schematic representation of the facility is illustrated in Figure 2.

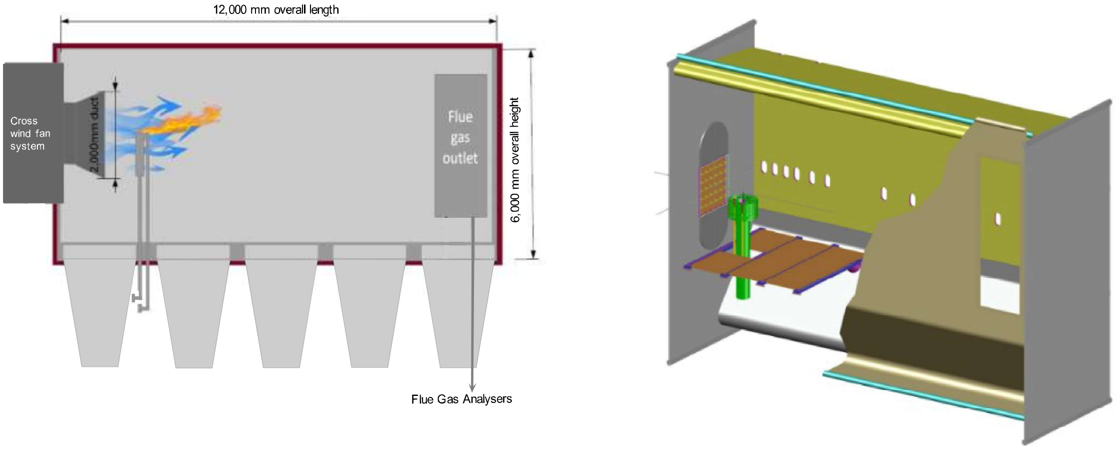

Figure 2: CCA furnace used for flare testing.

To conduct flare tests, modifications were made to the inlet, enabling the wind simulation by means of air supply through a square injector upstream the fare 1.514 x 1.515 meters size. Flow straighteners were installed in the air inlet to minimize turbulence. Two high-capacity fans are utilized to deliver ambient temperature air at rates of up to 138 tons per hour, resulting in crosswind speeds of up to 14 meters per second (equivalent to 50 km/h or 27 knots), typical of wind speeds at flare elevations which can reach heights of 200m. A demonstrative test campaign will be conducted on a benchmark flare tip supplied by Greens Combustion Ltd. . The 16-inch pipe flare is equipped with an integral wind shield, flame retention devices and two pilots. has been positioned 2 meters downstream from the air inlet. This range of flare size is sufficiently large to produce combustion and destruction efficiency results that are not scale dependent. The expected flare flow range for the experiments is from 0.5 to 2.0 MW. This range ensures the flame's complete development downwind of the flare tip, without any contact with the walls, ceiling, or floor of the working section. In order to ensure adequate aerodynamic similarity with the performance of industrial flare, calculations were conducted on the scaled-down version of full-size flare.

Probes and analyzers on experimental rig

Gas composition at the combustion chamber outlet was analyzed via extractive sampling of both wet and dry flue gases. A heat-traced sampling line delivered wet flue gases to an FTIR (Fourier Transform Infrared Spectroscopy) calibrated for CH_4, CO, and CO_2 measurement, as well as to a RATFISCH analyzer for total hydrocarbon assessment. Another sampling line directed flue gases to a cooling system, removing water vapor and providing dry flue gases to HORIBA PG350, and NOx analyzers.

In order to validate the test rig metering devices, a comparison between the theoretical CO_2 and that measured via HORIBA PG350 was made. Figure 3 presents the comparison between the experimental CO_2 emissions measured with respect to the theoretical ones. The squared R value of the correlation is $R^2 = 0.9929$, showing a high goodness of the measurements.

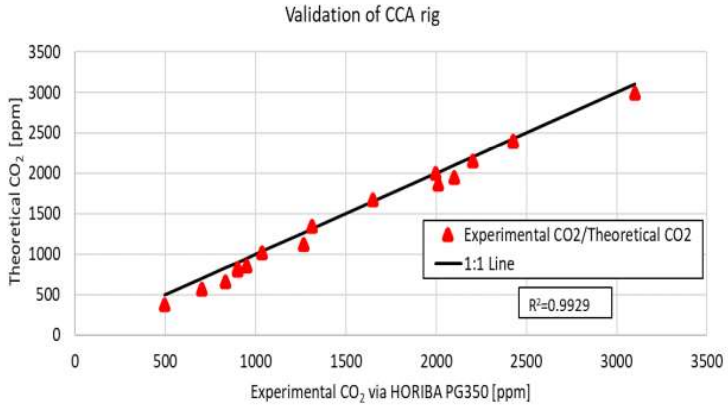

Figure 3: Validation of CCA metering devices.

Flare Efficiency Parameters

To assess the efficiency of flares, three key parameters are commonly used: Flare Combustion Efficiency (CE), Destruction Efficiency (DE), and Destruction and Removal Efficiency (DRE). These parameters quantify how effectively flares oxidize hydrocarbon components. In the literature, different way to calculate these parameters are applied, in this paper that are calculate as following:

Combustion Efficiency (CE): This parameter measures the proportion of total hydrocarbons (THC) completely burned in the flare to produce CO_2 and water vapor. It is expressed as the ratio of the volume concentration of emitted $[CO_2]$ to the sum of $[CO_2]$, $[CO]$, and unburned hydrocarbons $[THC_w]$.

$$CE = \frac{[CO_2]}{[CO_2] + [CO] + [THC_w]}$$

Destruction Efficiency (DE): DE quantifies the extent to which introduced hydrocarbons undergo oxidation into non-hydrocarbon compounds (CO_2, CO, and water vapor). It is calculated as the ratio of the sum of $[CO_2]$ and $[CO]$ to the sum of $[CO_2]$, $[CO]$, and unburned hydrocarbons.

$$DE = \frac{[CO_2] + [CO]}{[CO_2] + [CO] + [THC_w]}$$

Destruction and Removal Efficiency (DRE): DRE, like DE, assesses the transformation of hydrocarbons into non-hydrocarbon forms. However, it is determined by comparing the mass flow rates of hydrocarbons entering and leaving the flare.

$$DRE = 1 - \frac{\dot{m}_{out}}{\dot{m}_{in}}$$

Results

During the initial test campaign, 16 distinct test conditions were recorded. The flue gas composition was recorded every second. The fuel flow was varied in a range of 90.46 to 12.7 kg/h, which given the 16-inch tip diameter, corresponded to velocity from 26.8 to 3.7 cm/s (typical range for the *"low pressure"* flare kind, in that we can identify as "wake dominated regime"). After this validation, the Combustion Efficiency (CE) and Destruction Efficiency (DE) were compared. Figure 4 shows that the differences between CE and DE exists when CE is less than 96%. The squared R value of the correlation is $R^2 = 0.99$, showing a good agreement between CE an DE. The right side of the figure displays a frame capturing the flare in a wake-dominated regime, examined in CCA.

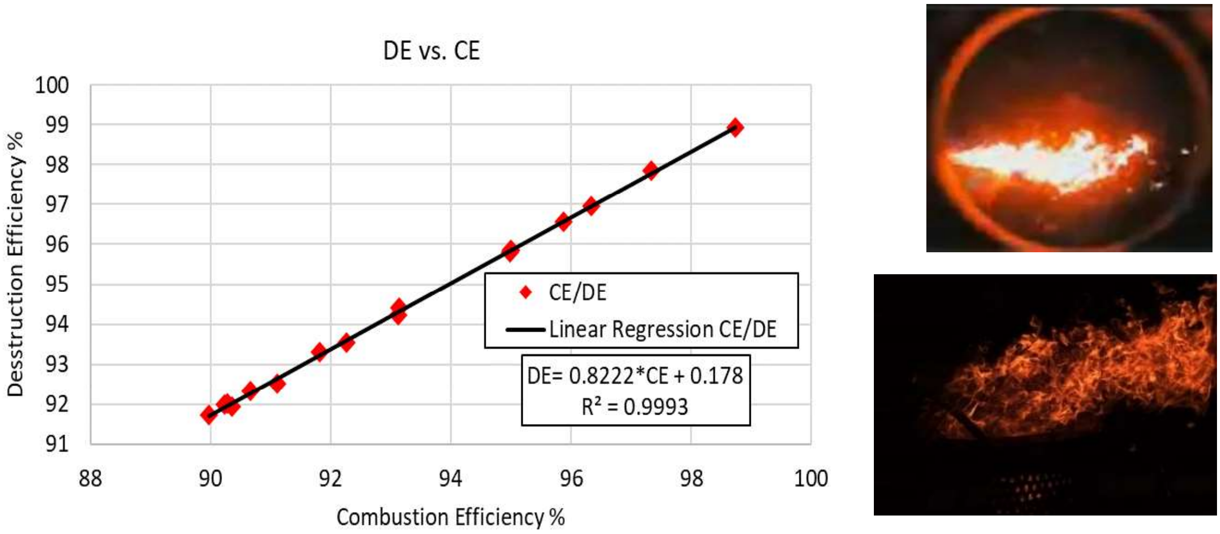

Figure 4: Combustion Efficiency vs. Destruction Efficiency

Figure 5 presents the combustion and destruction efficiency in function of wind velocity. During this testing regime it was found that combustion and destruction efficiencies decreased from almost 99% at low cross wind to around 90% when wind speed increased to near 11.5 m/s, Further tests were conducted at higher wind speeds and low flare flow conditions where flare combustion efficiency dropped to 75% at 14 m/s cross wind speed. These efficiencies notably surpassed those typically observed in 1 to 4'' pipeflares and their subsequent correlations, indicating that industrial-sized flares are less prone to combustion efficiency reduction in high crosswind conditions however while the flare will remain alight in these conditions combustion and destruction efficiency is substantially impacted. The presence of a wind shield and flame retention devices on the tested flare tip likely contributed to mitigating the impact of wind speed on combustion and destruction efficiency. These tests were carried out in "wake dominated regime". In future, this experimental methodology can be used in order to test flares in "inertia dominated regime". Furthermore, testing should be expanded to understand the impact on combustion efficiency as a flares component such as the windshield start to degrade over time.

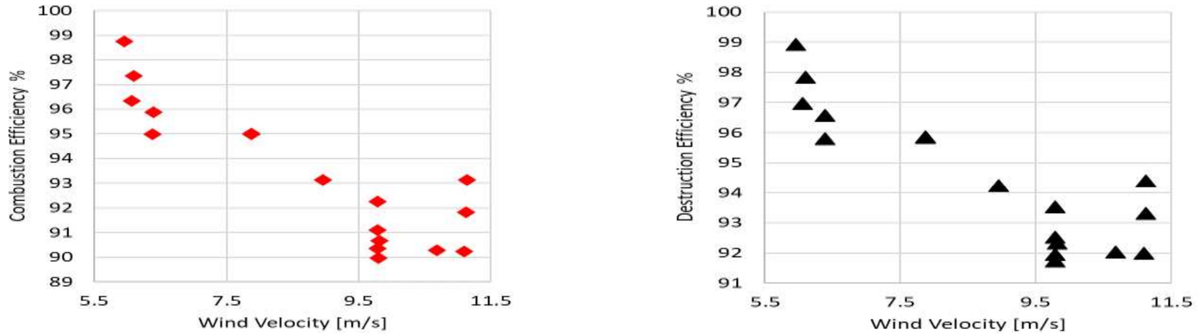

Figure 5: Effect of cross wind velocity on combustion and destruction efficiency

Conclusions

The paper underlines the possibility to be effective in the carbon emission control improving the flaring operation by a deeper understanding of the combustion process. A new testing capability can be used to measure in controlled and repeatability condition, different flare nozzles in scaled size. This new tool, available in an open testing platform, can be used as a basic to understand and validate different solutions and functional models.

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