Closed Loop Flare Control Using a Video Imaging Spectral Radiometer

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INTRODUCTION

Video Imaging Spectral Radiometry (VISR) has emerged as the only practical method to directly and continuously monitor flare performance. The VISR method provides real time measurements of flare combustion efficiency (%) and a smoke index (0-10) at a 1-sec temporal resolution. In addition to these two metrics, the VISR method provides a measure of fractional heat release, flare footprint and flare stability. These parameters are provided with no latency, making the VISR method well suited for control loops. In this paper, we examine how a VISR system can be used to control a steam assisted flare. An experiment was performed at Zeeco's test facility in Tulsa, Oklahoma on March 29th, 2019 with the VISR method deployed as part of a closed loop flare operating system. The results from the experiment and implications for future flare control methods are discussed.

Video Imaging Spectral Radiometry Background

Video Imaging Spectral Radiometry utilizes a multi-spectral Infrared (IR) imager to simultaneously measure the relative concentrations of combustion products, carbon dioxide (CO_2), and unburned hydrocarbon (HC) at the pixel level. The relative concentrations of CO_2 and HC levels measured at each pixel are used to calculate the Combustion Efficiency (CE) for that pixel, which is a path-averaged CE for a column of combustion gases represented by the pixel. Flare CE at the pixel level is determined by the following equation (Allen and Torres, 2011).

$$CE(\%) = \frac{[C]_{CO2}}{\sum_i n_i[C]_{HCi} + [C]_{CO} + [C]_{CO2}} \times 100 \qquad (1)$$

Where

CE(%) =	Combustion efficiency, %;
$[C]_{CO2}$ =	Volume concentration of CO_2 in the plume once combustion has ceased
$[C]_{CO}$ =	Volume concentration of carbon monoxide (CO) in the plume once combustion has ceased
$[C]_{HCi}$ =	Volume concentration of the i-th HC compound remaining in the plume once combustion has ceased
n_i =	Number of carbon atoms in the i-th HC compound

i =	i-th hydrocarbon compound in the flare vent gas. When there is only one compound, i=1.

A CE value representing the flare performance at any given moment is calculated by averaging CE values of the pixels that represent the outer layer of the combustion zone of the flare. **Figure 1** demonstrates a typical combustion envelope.

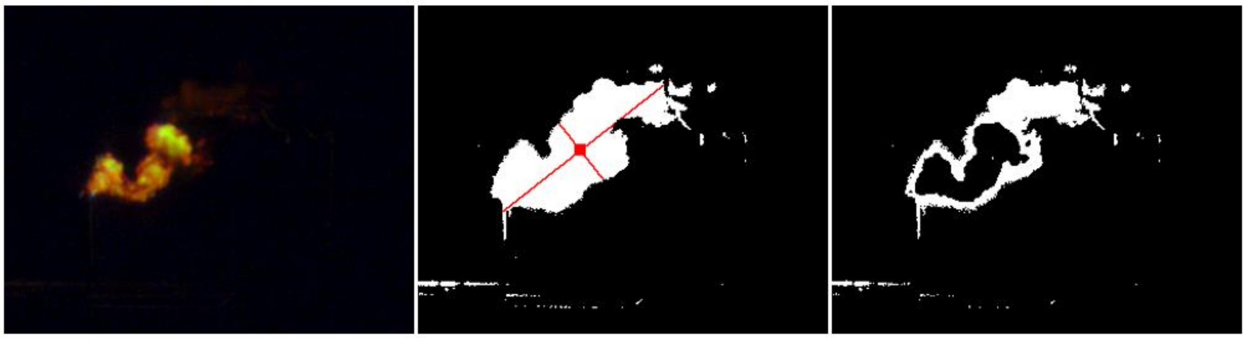

Figure 1: VISR spectral image (left), flare footprint (center) and combustion envelope (right).

In addition to CE, the VISR method produces other useful flare performance metrics. Smoke Index (SI) is provided as a measure of particulates (IE soot) in the combustion envelope. SI is a unitless number ranging from 0 to 10. SI is generally correlated to opacity, though the correlation is not linear. An SI value less than 1 indicates that there are no visible emissions. As SI climbs above 2 there will generally be visible emissions present in the combustion envelope. **Figure 2** shows two flare images with corresponding SI values.

Figure 2: Flare with SI = 5.6 (left) and SI = 1.5 (right)

In addition to SI, the VISR method provides three additional performance metrics. Flare Footprint (FF) provides the cross sectional area (in ft^2) of the flame and associated high temperature postcombustion gases perpendicular to the line of sight of the VISR instrument. Fractional Heat Release (FR) in BTU/min is measure of the Mid Wave Infrared (MWIR) fraction of the total heat released by the flare. Although FR does not measure the total heat release of the flare, it is highly correlated to the total heat release. Flame Stability (FS) is a measure the fluctuation of flame radiance within each second. FS ranges from 0 to 100 with 100 being most stable

The VISR imager has a high frame rate (up to 30 frames per second) which results in a data acquisition cycle of approximately 33 milliseconds. The integration time (analogous to shutter time in other cameras) is even shorter. The extremely short measurement time means that the path length through the plume depth can be considered constant for each measurement (frame). This addresses the significant limitation of other imaging based technologies with long data acquisition cycles (e.g., 1 second). The VISR method is designed for continuous monitoring and all calculations are performed at frame rates. As a result, VISR performance metrics are provided at a 1-second temporal resolution with no latency. This makes the VISR method well suited for both continuous monitoring and feedback for closed loop control of flare operations.

Experiment Setup

An experiment was conducted at Zeeco's test facility in Tulsa, Oklahoma on March 29th, 2019. The purpose of the experiment was to demonstrate the feasibility of using VISR performance metrics as feedback to enable closed loop control of a steam assisted flare. Specifically, the experiment sought to use SI as an input to the control loop to automatically control the position of a steam valve, ensuring smokeless operation without human intervention.

The Zeeco QFS-16 Steam assisted flare tip with (2) HSLF flare pilots was used for all experiments. The rate of steam assist for this flare type has a direct impact on visible emissions. The VISR imager was positioned approximately 433 feet from the QFS-16 flare tip. In addition, a visible camera was placed approximately 150 feet from the flare tip. The visible spectrum images were not used during the experiment, but they provide a reference to examine the results of the control loop. **Figure 3** shows the approximate positions of the VISR imager and visible camera.

Figure 3: Approximate position of flare, VISR imager and visible camera

The VISR system was connected to a wireless bridge which transmitted the performance metrics to a Modbus TCP capable interface positioned near the flare. The VISR Modbus TCP interface also provided analog 4-20mA current outputs for CE and SI. An Allen-Bradley MicroLogix 1400 Programmable Logic Controller was positioned near the flare to read the 4-20mA analog VISR outputs (CE and SI). The PLC was also connected to an Assured Automation 2" V-ball actuated control valve via 4-20mA Electro-pneumatic positioner and pneumatic actuator to control the level of steam assist. **Figure 4** shows the architecture of the closed loop and the equipment. The control loop was designed such that the flare would operate smokelessly, while also minimizing steam consumption. It is desirable to operate at the minimum steam rate required, both to reduce costs from the steam resource as well as to prevent and over steam condition resulting in low combustion efficiency. The PID control was constantly trying to operate at the incipient smoke point by increasing steam when smoke was observed (SI > 1) and decreasing steam when there was little or no smoke (SI < 1). Combustion efficiency was recorded but was not used as a control point for this experiment. The steam rate required to introduce a negative impact on the Combustion Efficiency for this flare was much higher than the steam rate at the incipient smoke point.

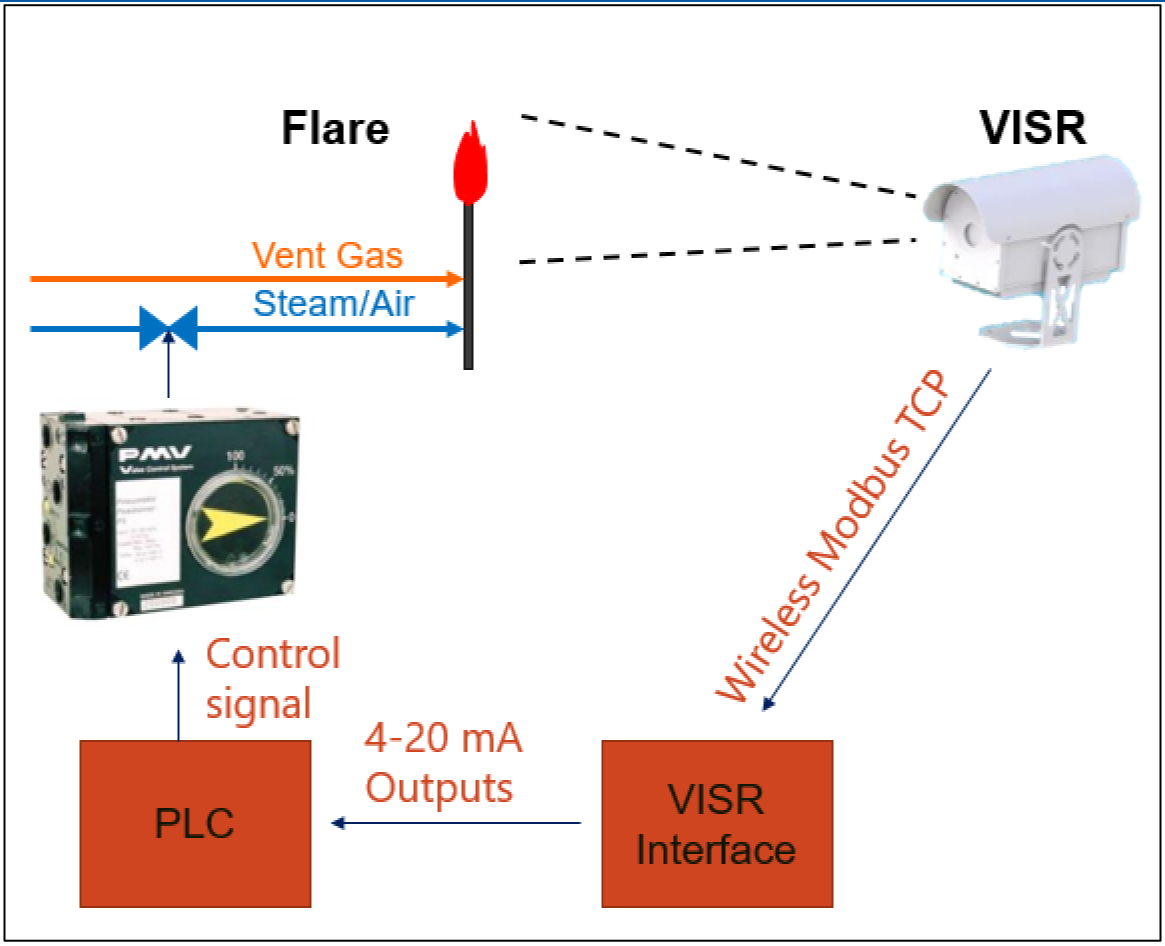

Figure 4: Configuration of equipment for closed loop control.

Propane was used as the vent gas. The flow rates for fuel gas and steam were recorded, as were the position of the steam valve and the VISR performance metrics.

Experiment Results

Three experiments were performed to examine the performance of the control loop under different process conditions.

Test 1

In Test 1, the fuel flow rate was set to 1334 lb/hr and held constant throughout the test. The steam position valve was initially set manually to 5%, which resulted in a steam flow rate of 252 lb/hr. This steam to fuel ratio resulted in visible emissions, confirmed by the VISR performance metrics. The SI at the beginning of the experiment was above 2, indicating visible emissions were present. **Figure 5** below shows the time series plot of SI, fuel flow rate and steam valve position. Throughout the tests, the smoke conditions indicated by SI were confirmed by the Zeeco operator and documented by the video captured by the visible camera.

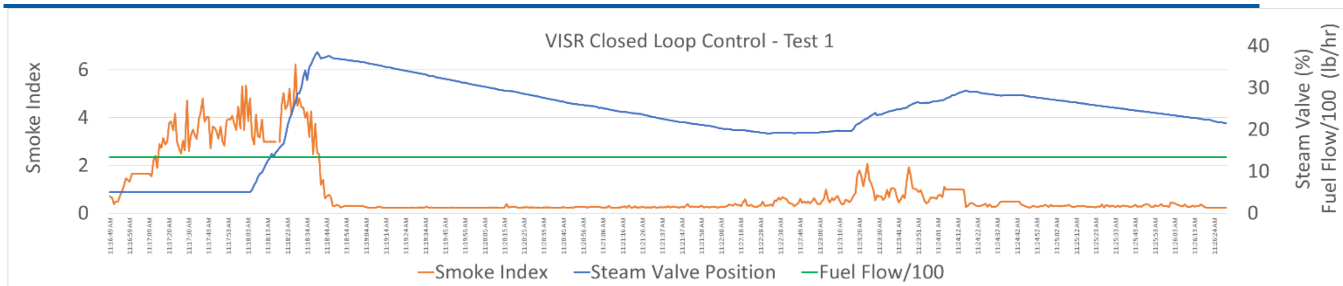

Figure 5: Time series plot of SI, Steam Valve Position and Fuel Flow rate for Test 1

At approximately 11:18 AM, control of the steam valve was handed over to the control loop. The control loop detected the visible emissions based on a threshold applied to the SI value. As a result, the control loop began to increase the steam valve position. Over the next 1 minute, the control loop increased the steam valve position from 5% to approximately 40% until the SI value fell below 1. A SI value below 1 indicates that there are no visible emissions. With the steam valve opened to 40%, the steam flow rate was approximately 750 lb/hr. The control loop, having achieved smokeless operation, then began to slowly reduce the steam rate by closing the steam valve. Over the next four minutes, the steam valve position was reduced from 40% down to 20% by the control loop. Once the steam valve position reached 20%, the smoke index rose above 1 indicating incipient smoke. This feedback caused the control loop to again increase the steam valve position to approximately 30% over the next minute until the SI dropped below 1. The total duration of this experiment was 10 minutes, and the control loop exhibited the ability to automatically adjust the steam level based on SI values. Further tuning of the control loop could likely reduce the swing of the steam valve position (between 40% and 20%) given the fact that the flare conditions were held constant.

Test 2

Test 2 was designed to challenge the control loop by changing the flare process conditions. At approximately 11:27 AM, the process fuel flow rate was increased from 1300 lb/hr to 2000 lb/hr. The control loop remained in control of the steam valve position during this transition. Before the fuel rate was increased, the steam valve position was at approximately 20% with a SI < 1. The increased fuel flow caused the SI to rise above 1.5, which in turn caused the control loop to begin increasing the steam flow rate. Over the next 1 minute, the control loop increased the steam valve position from 20% to 30%, with the resulting SI again falling below 1 indicating that visible emissions had been eliminated. **Figure 6** shows the time series plot of SI, fuel flow rate and steam valve position.

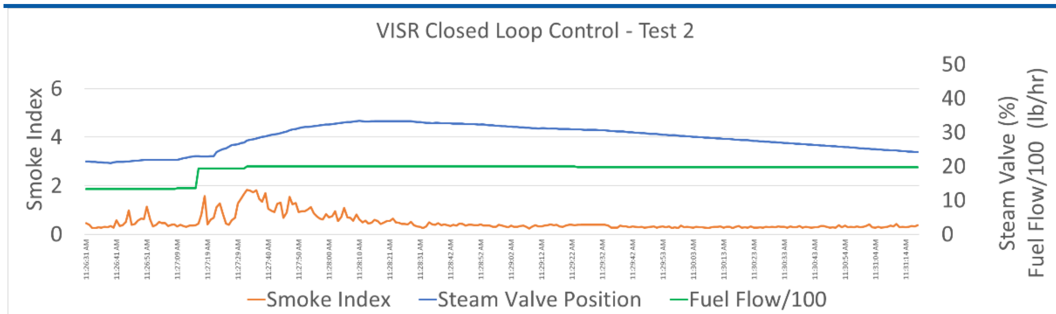

Figure 6: Time series plot of SI, Steam Valve Position and Fuel Flow rate for Test 2

The significant capability demonstrated in Test 2 was the automated response of the control loop to the increased flow rate and resulting increase in SI. Although the flow rate was the only process condition to change, the change in SI was immediate and the control loop responded appropriately to ensure continuous smokeless operation. This direct feedback control should also work well for more complex process conditions.

Test 3

In Test 3, the fuel flow rate was again increased to test the response of the control loop. At approximately 11:32 AM, the fuel flow rate was increased from 2000 lb/hr to 3000 lb/hr. The steam position valve was at approximately 25% before the fuel gas flow rate was increased and the SI was less than 1. The increased flow rate resulted in an elevated SI, which in turn produced a response from the control loop. The steam valve position was automatically increased from 25% to 35% over the approximately 1 minute, which reduced the SI to a level below 1 (indicating smokeless operation). **Figure 7** below shows the time series plot of SI, fuel flow rate and steam valve position.

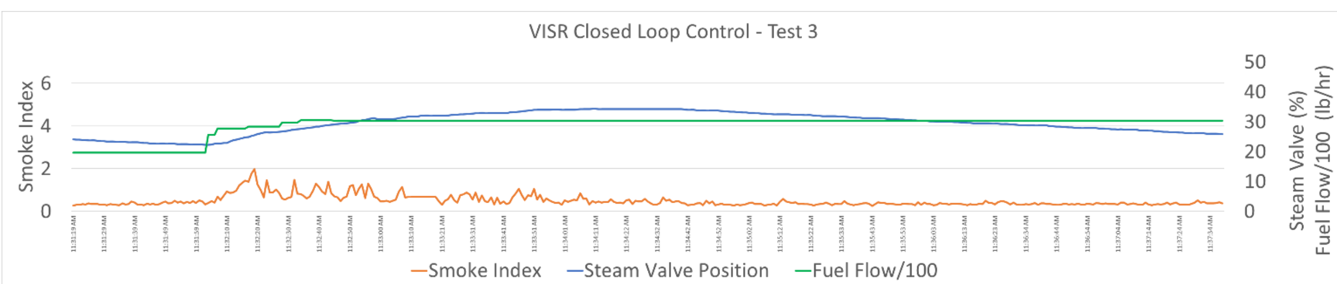

Figure 7: Time series plot of SI, Steam Valve Position and Fuel Flow rate for Test 3

The relevant observations from Test 3 are similar to that of Test 2. The control loop, utilizing direct feedback from the VISR method, was able to adjust the steam level automatically in response to the changing process conditions maintaining smokeless operation without human intervention.

Conclusions and future work

This experiment has demonstrated the feasibility of using VISR performance metrics as direct inputs to a control loop. The control loop was able to ensure smokeless operation using the minimum steam level for each fuel flow rate. The 2010 TCEQ flare study determined, among other things, that optimal flare performance is achieved when the flare is operated at the incipient smoke point. This experiment has demonstrated a practical and deployable method to continuously operate a flare at the incipient smoke point. Although the experiment design was rather simple with respect to changing process conditions, the principles demonstrated should be transferable to more complex flaring conditions. The VISR data is a direct measurement of flare conditions with no latency, making it quite suitable for this type of control. It is anticipated that the same control could be applied to both maximize CE while ensuring smokeless operation even in the presence of rapidly changing process or environmental conditions.

Due to the time and resource constraints for this experiment, the CE signal from VISR was not incorporated into the control logic even though the CE signal was made available to the PLC. As a result, the experiment focused on the smoke condition (due to increase in fuel) and did not test flare over-steaming scenarios. In future work, both CE and SI can be included as input to the control logic, and test conditions can be included that will cause fuel (flare vent gas) decrease to create an over-steaming condition (low CE). The control loop is expected to reduce the steam to bring the CE back to a set value. In such a control loop, SI and CE effectively set an operating window between the smoke conditions and over-steam conditions. Future work is planned to test more complex control strategies with more process variables applied, including changing fuel gas composition in addition to changing flow rate. Longer term deployments at real world flares are also planned to demonstrate the ability to control and optimize the flare under changing environmental conditions. The techniques demonstrated through this experiment have wide ranging applications for flare control, including compliance demonstration, greenhouse gas reductions and smokeless flare operation.

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