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EVALUATION OF FLAME LENGTH IN MULTI-JET NON-PREMIXED NATURAL GAS FLAMES DILUTED WITH CO₂

Pedro Ferreira Nicoloso

Isaias Mortari Machado

Felipe Roman Centeno

Fernando Marcelo Pereira

Universidade Federal do Rio Grande do Sul

Rua Sarmento Leite 425

Porto Alegre, 90050-170, Brazil

pedronicoloso@gmail.com, imortarim@gmail.com, frcenteno@mecanica.ufrgs.br, fernando@mecanica.ufrgs.br

Paulo Roberto Pagot

PETROBRAS – Petróleo Brasileiro S.A.

Rio de Janeiro, RJ, Brazil

pagot@petrobras.com.br

Abstract. *Combustion in offshore flares can diminish pollutants released to the environment but at the same time affects negatively the working areas due to the safety requirements on the platform. For this reason, the subject of this work is to perform an experimental study of a small scale multi-jet flare with turbulent non-premixed flames having two burners placed side-by-side to understand the flame length by varying fuel and diluent flowrates, and distance between burners. Experimental measurements for multi-jet configuration indicates that the flame length is maximum when flames are completely merged and slowly decreases with the separation distance and presents its minimum value when the single jet configuration is reached for S/d is equal to 10.*

Keywords: *natural gas combustion, multi-jet flames, non-premixed flames, flame length*

1. INTRODUCTION

Combustion is the primary source for high power density applications, such as in gas turbine systems, but also seen in domestic applications like stoves and even industrial flares to avoid hazards in the environment. Turns (2000) states that combustion can occur with or without a flame. In a general manner, a flame can be classified either as premixed, for example, annular combustors of jet engines, or as non-premixed (diffuse), seen in tubo-annular combustors of jet engines with a crossflow or offshore flares with or without the crossflow, which is the subject of this study. Flaring in oil platforms is vital to reduce releases of gaseous pollutants to the atmosphere which generally burns unused natural gas in multiple burners since storage is not viable. In this scenario, a turbulent non-premixed vertical flame take place in each burner. Furthermore, the flame is considered overventilated since the environment has enough air to burn the injected fuel without extinction (quiescent fluid). Pagot (2002) inform that a major concern on the platforms is the thermal radiation hazard in the offshore working areas, where most of the energy released from the combustion reaches the platform, deteriorating the painting, equipment and plastic, and most importantly causing dangerous conditions to operators. Another concern is the flame length that is also a safety concern during combustion and it is an important factor to be studied in depth.

In the study of multi-jet flames the interaction between the jets and the behavior of the flames are some typical problems to be analysed. The shape and configuration of the burners can cause flame length to vary significantly during combustion. When two diffusive flames are sufficiently far from one another, there is no interaction between them and combustion occurs as single jets. As the separation distance decreases for the multi-jet configuration, combustion is altered and the flame length varies. Putnam and Speich (1963) conducted some experiments in multi-jet flames without CO₂ and concluded that the flame length increases as the separation distance diminish and is maximum when the flames are attached to each other. Menon and Gollahalli (1988) noticed that this phenomenon occurs due to a lack of air to complete combustion. Lenze, *et al.* (1975) also conducted experimental studies that the flame length increases as the burners distance decreases. Chigier and Apak (1975) conducted studies in multi-jet with swirl effect in the incoming air for combustion and the flame length is highly dependent of quantity of air during combustion, meaning that the swirl effect decreases the flame length.

Another phenomenon that can happen in both single and multi-jet flames in the lift-off height. The lift-off height represents the distance above the burners head where the flame is stabilized. Kalghatgi (1981) and (1984) emphasize

that a non-premixed flame in still air will lift from the burners lip and form a stabilized flame when the flowrate increases up to a point where it overcome a value known as the lift-off stability limit. In the study, it is also shown that the lift-off height is proportional to the exit velocity of the jet and it is independent of the burners diameter for a given gas. In addition, if the fuel flowrate is increased more than the blow-out limit, the flame is extinguished. In cases where the flames are not between these limits it is known as attached to the burners head. For multi-jet flames, Byeong *et al.* (2004) shown that the separation distance, S , between the burners affect the blow-out limit and the characteristics of the flame. If S/d is small enough, the flames are merged and behaves as a single burner of a larger area and the blow-out limit is higher for flames that interact to one another due to withstand larger flowrates in the exit of the burner.

The present work performs an experimental study of multi-jet turbulent non-premixed flames. A lab-scale flare having two burners placed side-by-side was developed to understand the influence of fuel and diluent flowrates, and separation distance between burners on the flame length. Experimental measurements of flame length for multi-jet and single jet are the main topics of this work.

2. METHODOLOGY

The present work is an experimental study with two burners of stainless steel tubes placed side-by-side with non-premixed vertical flames. The tubes are fixed on a metal guide structure that are connected to a rail and one of the burners is attached to one side and the other moves to create the separation distance between the flames. The gaseous fuel used in this experiment is natural gas (composition: 90.8% CH₄, 6% C₂H₆, 1.2% C₃H₈, 0.5% CO₂ and 1.55% N₂) that is diluted with CO₂ (99.2% purity). The concentration of the diluent in the mixture varies from 0 to 30% in steps of 15% in volume and all scenarios consists of equal total power for a given flowrate of fuel. In addition, two circular burners of identical port area with diameter 6.6 mm, and a separation distance from each other varying from 0 to 50 cm along the x direction, as shown in Fig. 1. All burners consist of overventilated flames and have the same fuel flow, measured by flowmeters, with 3 ranges of flow rate from 3 to 5 L/min with steps of 1 L/min while in still air. Combustion starts with a pilot flame that ignites the natural gas that leave the nozzle on a fully developed regime.

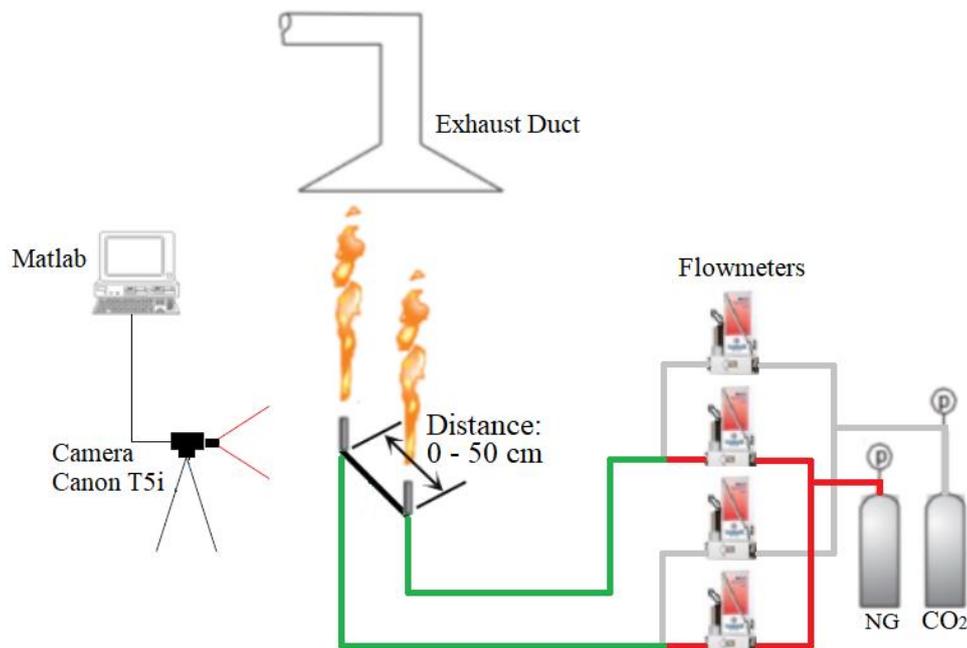


Figure 1. Experimental apparatus to measure the flame length during combustion

Flame geometry (length and lift-off height) are analyzed by capturing images in each fuel flow and diluent concentration with T5i Canon camera in burst mode and further processed in Matlab®, similarly as performed by other studies in the literature of Llanos (2017). The blow-out conditions will be observed during the tests by changing the fuel velocity and diluent concentration while taking pictures. To obtain an average value of the flame length, one hundred and fifty images were capture for each position for a given flowrate. To ensure the correct measurements of flame length and lift-off distance a laser beam is pointed at all times to the burners exit. The separation distance and the measurements of this study were analyzed by steps of the burners diameter. The Matlab® software is used to converts the picture to a binary form and to read the number of pixels present in the image, then pixels are converted to millimeters by a reference size place on the stainless steel burners.

3. RESULTS

The main objective of this study is to understand the flame length in a multi-jet configuration. The measurements of diffuse vertical single jet flames obtained in this experimental study were compared to multi-jet diffuse vertical flames for the same concentration of CO₂ on the mixture as shown in Fig. 2 by the straight lines. The single jet scenario presents equal flame length for different positions on the rail and for this reason this value is kept constant.

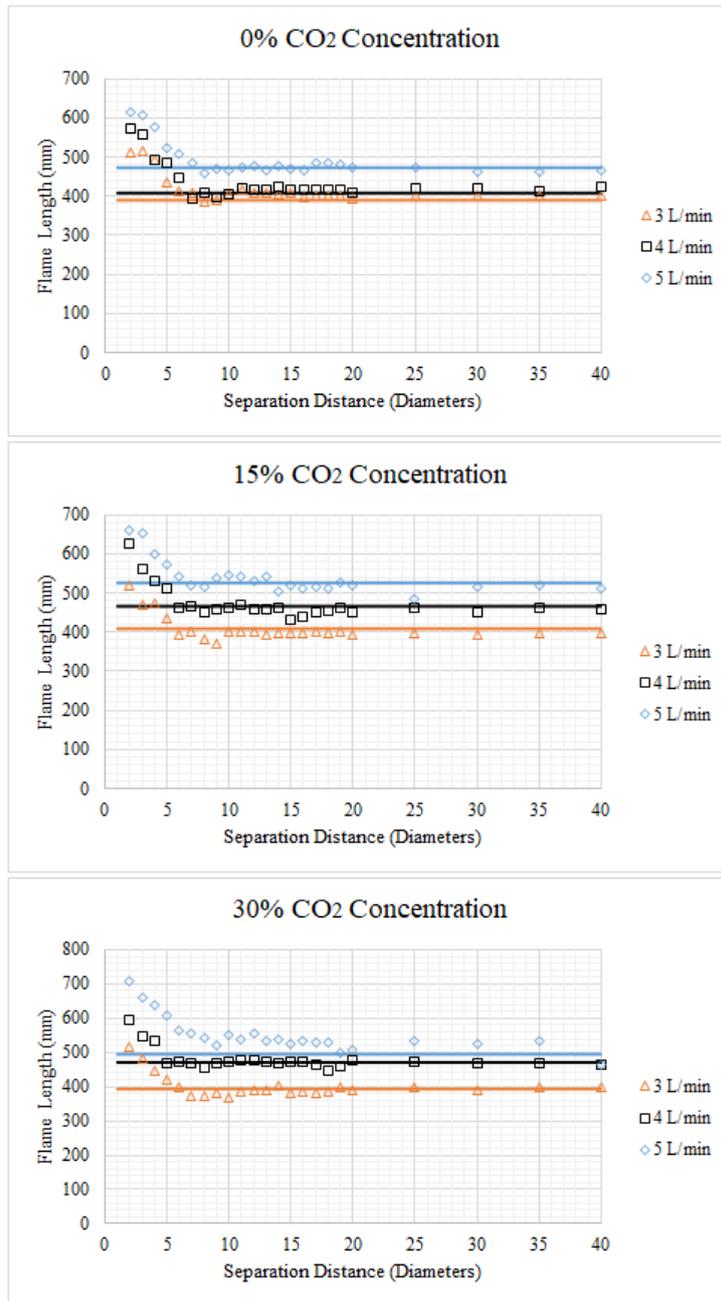


Figure 2. Effects on the flame length by varying the separation distance and CO₂ concentration on the mixture

Fig. 2, shows that higher fuel flowrate increases the flame length even when the CO₂ concentration on the mixture is injected on the line. As more mass of fuel is necessary to oxidize and more air in need to complete combustion, the flame length become larger as the flowrate increases. For all scenarios analyzed, the flames were attached to the burners head. Llanos (2017) states that for a single burner the lift-off distance is proportional to the addition of diluent and flowrate of the fuel, in this case, when the flames are placed far from each other, it is expected to occur no influence on the parameters measured and obtain the same results as single jets. For two burners placed side-by-side as illustrated in this experiment, the influence of adding diluent and increasing the fuel flowrate was not sufficient to notice the lift-off distance and blow-out limits. All flames were stable for 30% concentration of CO₂, which means that the fuel flowrates

or CO₂ concentrations in this study must become greater to notice the lift-off or blow-out limits and further research is necessary to prove the multi-jet stability region.

The flame length is highly influenced on the separation distance and this distance dictates the amount of air available in each flame to complete combustion. When the separation distance is minimum, in all scenarios, the flame length is maximum given that the flames are merged and considered a single jet of a larger area. As the separation distance increases, the flame length is shorten until the single jet region is reached and no interaction is noted. For the flowrates in this study, the single jet is reached when the separation distance, S , is approximately 10 diameters of the burners exit. In other words, single jet occurs when S/d equals to 10 and further increase in the separation distance do not affect the combustion and flame length.

As the fuel flowrates remains constant, Fig. 3, and the concentration of CO₂ is further increased, the flame length become larger due to the delay to complete combustion. The CO₂ creates a barrier for the oxygen to reach the fuel and the effect is the larger flame length shown for the flowrates of 4 and 5 L/min. For lower fuel flowrates, such as 3 L/min, the flame length decreases as the CO₂ concentration is higher, nevertheless the flame length is also maximum for higher concentration of CO₂.

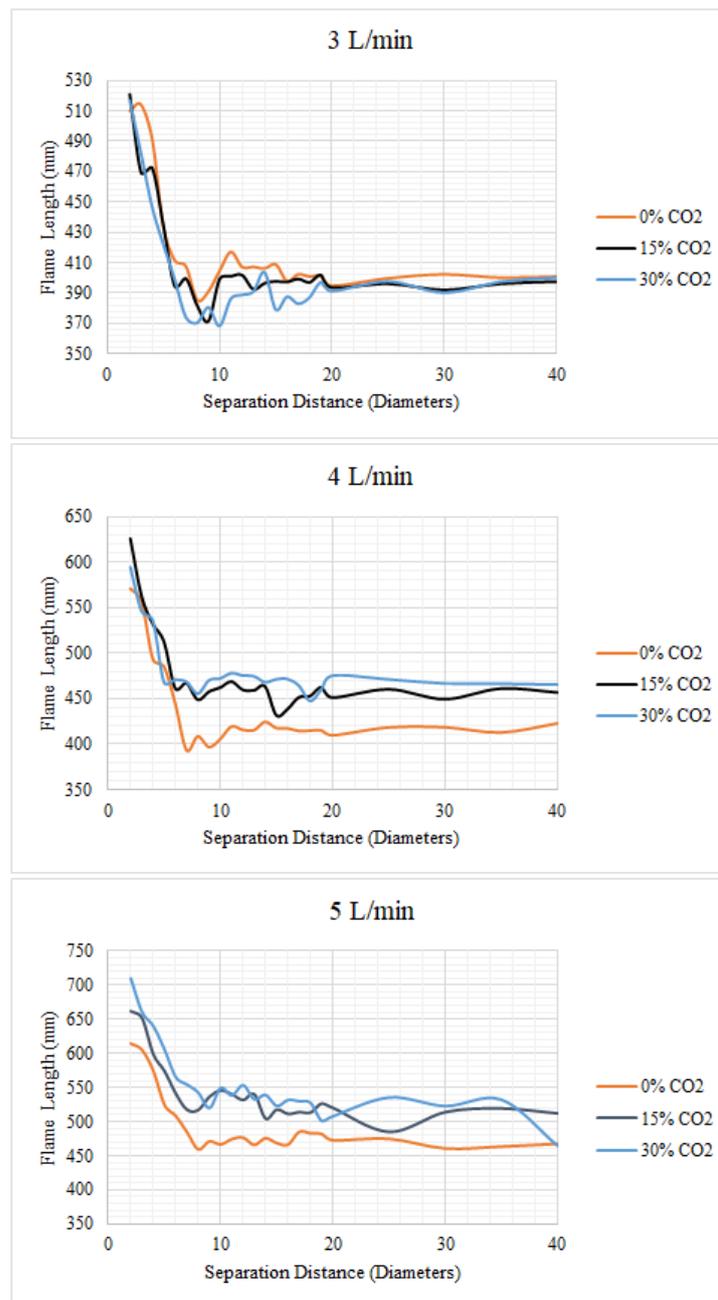


Figure 3. Effects on the flame length for equal fuel flowrate by varying CO₂ concentration and the separation distance

4. CONCLUSIONS

The flame length of multi-jet configurations is highly dependent on the separation distance and fuel flowrate. The results shows that until S/d ratio is approximately 10, one flame is affected by the other and for higher values, the single jet region is reached. The flame length is maximum when the burners are next to each other, merged flames, and decreases slowly until the single jet regime take place. For 0 to 30% concentration of CO₂ the flames were stable and the lift-off distance and blow-out limits were not noticed. All the flames were attached to the burners, nevertheless further research is necessary to illustrate the stability of the multi-jet flames.

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6. RESPONSIBILITY NOTICE

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