EVALUATION OF SOOT FORMATION IN SYNGAS CONFINED FLAMES ON THE OEC USING LEAN CONDITIONS AND ACETYLENE DOPING

Mariana Wilfinger[a], Paulo Roberto Freitas Neves[a], Alex Álisson Bandeira Santos[a]

[a] SENAI CIMATEC – Campus Integrado de Manufatura e Tecnologias, Brazil.

Abstract: The combustion process will continue to be one of the main sources of energy for some time. However, this process causes environmental impacts with its use, which brings global problems such as the greenhouse effect and particulate emissions, such as soot. Therefore, studies are needed to make more sustainable and efficient combustion processes. With this in mind, the use of biomass gasification has been studied, resulting in a fuel known as syngas, composed largely of hydrogen and carbon monoxide, which, as it comes from biomass, has a reduced effect on emissions. Studies of combustion are also carried out in lean conditions that allow reduced emissions. In this context, the work aims to present the experimental study of the correlation between syngas use, the oxygen enhanced combustion (OEC) technique in lean conditions with acetylene doping, in a confined diffuse flame and its associated effects on soot formation. The laser light extinction technique was used to measure the concentration of soot. Soot concentration were evaluated in equivalence ratios of 0.7 and 1.0, 21 and 30% of volumetric oxygen content in the oxidant and acetylene doping of 5% (by volume). Analyzing the results in the condition of using OEC associated with lean conditions in syngas burning, it was noticed an increase in the soot concentration trend compared to the result without enrichment.

Keywords: soot, syngas, lean combustion, acetylene doping.

AVALIAÇÃO DA FORMAÇÃO DE FULIGEM EM CHAMAS CONFINADAS DE GÁS DE SÍNTESE NA OEC USANDO CONDIÇÕES POBRES E DOPAGEM DE ACETILENO

Resumo: O processo de combustão continuará sendo uma das principais fontes de energia por algum tempo. No entanto, esse processo causa impactos ambientais com seu uso, o que traz problemas globais como o efeito estufa e as emissões de partículas, como a fuligem. Por isso, são necessários estudos para tornar os processos de combustão mais sustentáveis e eficientes. Com isso em mente, o uso da gaseificação de biomassa tem sido estudado, resultando em um combustível conhecido como gás de síntese, composto em grande parte de hidrogênio e monóxido de carbono, que, como vem da biomassa, tem um efeito reduzido sobre as emissões. Estudos de combustão também são realizados em condições pobres que permitem a redução das emissões. Nesse contexto, o trabalho tem como objetivo apresentar o estudo experimental da correlação entre o uso de gás de síntese, a técnica de combustão intensificada de oxigênio (OEC) em condições pobres com doping de acetileno, em uma chama difusa confinada e seus efeitos associados na formação de fuligem. A técnica de extinção de luz laser foi usada para medir a concentração de fuligem. A concentração de fuligem foi avaliada em razões de equivalência de 0,7 e 1,0, 21 e 30% do conteúdo volumétrico de oxigênio no oxidante e dopagem com acetileno de 5% (em volume). Analisando os resultados na condição de uso de OEC associado às condições pobres na queima do gás de síntese, percebeu-se um aumento na tendência da concentração de fuligem em relação ao resultado sem enriquecimento.

Palavras-chave: fuligem, gás de síntese, combustão pobre, dopagem com acetileno.

1. INTRODUCTION

Population growth in recent decades has led to extensive use of fossil fuel combustion, which in turn causes damage to the global environment, the main source of air pollution being emissions from all types of combustion systems. Carbon monoxide (CO) and nitrogen oxides (NOx) are produced by burning fossil fuels and are proven to be the causes of global warming and climate change. To reduce this damage to the environment, most developed countries have tightened emission regulations, which also reinforce studies on the clean use of fuels and techniques to increase process efficiency.

With the need for industries to increase the efficiency, reliability and flexibility of their processes, improving their competitiveness, optimizing energy use and environmental performance, new changes are developed based on new raw materials for industrial processes [1]. Additionally, according to [1], the global energy situation demands the urgent development of an alternative to current energy sources through combustion, in order to reduce dependence on fossil fuels, ensuring sustainability.

In this context, one of the alternatives is the use of synthesis gas (syngas), a product of biomass gasification. According to [2], syngas is mainly used due to its renewable condition and clean combustion, as opposed to burning coal, for example. This gas is primarily composed of hydrogen, carbon monoxide and nitrogen, with concentrations depending on the nature of its obtainment.

At the end of the 90's, the oxygen-enriched combustion process (OEC – Oxygen Enhanced Combustion) appeared, which consists of a controlled process that causes an increase in the concentration of O_2 in the conventional oxidizing current (atmospheric air).

According to [3], the application of OEC in combustion systems brings considerable benefits, such as increased productivity and efficiency of heat transfer processes, in addition to providing a smaller volume of exhaust gases and reduced fuel consumption.

This is a technique already widespread in processes that work at high temperatures such as steelworks, production processes for ceramic parts, heating and drying processes of materials and waste incinerators, but it is still little used in power generation plants and in the industry of oil and gas.

The use of this technique associated with burners can lead to greater soot formation in certain regions of the flame [4], and as soot is an important participant medium in thermal radiation, it can with its properly controlled interaction with the OEC, bring the increase of thermal efficiency in the burners, increasing the heat transfer from the flames to the heating surfaces through thermal radiation.

Another technique that has been used for a little over a decade is combustion under lean combustion conditions (lean combustion - LC), which aims to reduce emissions as well as increase energy efficiency [5]. In it, combustion takes place under conditions of fuel/oxidant mixtures with an excess of the oxidant, being poor in fuel. With this, the mixture between fuel and oxidant is more easily achieved, as well as lower flame temperatures are identified, and, consequently, some important pollutants have their emission reduced, such as NOx and CO.

Despite having advantages from the point of view of obtaining and emissions, the use of synthesis gas is restricted by the low energy and exergetic efficiencies presented during its burning. Among other factors, this is due to the low rate of soot formation in the flame, due to the low amount of carbon in the fuel, in addition to being a gas rich in hydrogen [6].

Although according to [7], soot is capable of damaging equipment in addition to being harmful to the environment and human health, being characterized as one of the most dangerous toxic components of exhaust gases. In research, it was stated that its presence in combustion it is critical to raise the levels of heat transfer by thermal radiation, which leads to an increase in thermal efficiency and burning productivity [8].

Thus, seeking to increase this particulate in the burner, doping with acetylene is used as a strategy, since experimental evidence indicates it as an important intermediary in the soot formation process [8]. Studies have investigated syngas burning with the aim of analyzing their energetic characteristics, flame propagation and pollutant emissions [9-13].

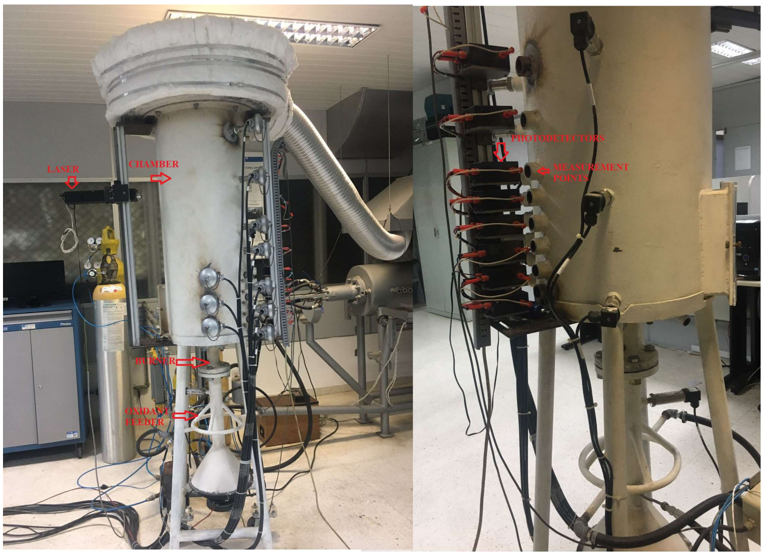
In [14] studied the burning of syngas under LC conditions in a porous medium. Researchers analyzed the effects of high pressures in flames with LC synthesis gas [15].

The objective of this work is to evaluate the coupled influence of OEC and confined combustion under lean mixture conditions in the burning of synthesis gas with acetylene doping, verifying the effects on soot formation under the proposed conditions.

2. EXPERIMENTAL SETUP AND METHODOLOGY

The experimental setup is shown in Figure 1. The construction of the experimental burner was inspired by the combustion device developed by [16]. The flame was generated in a vertical cylindrical combustion chamber, which consisted of burner with two concentric tubes. Syngas flowed up through the internal tube, while air, or enriched air, flowed through the annular region between this tube and the larger diameter concentric tube. Syngas flow rates were controlled by valves and metered by rotameters. Soot concentration were evaluated in equivalence ratios of 0.7 and 1.0, 21 and 30% of volumetric oxygen content in the oxidant and acetylene doping of 5% (by volume).

Soot concentrations were measured along the flame length using the laser light extinction technique at eight points. The laser system was mounted on a step-motor driven horizontal translation table, which allowed the beam coming from laser to reach the flame at any desired level. The laser was of He-Ne, with a wavelength of 632.8 nm. As the power output from the laser was only about 3mW, background radiation was blocked from the flame by narrow band pass interference filters, at the laser wavelength. The light was transformed into an electrical current signal by the photodetectors, and registered by data acquisition.



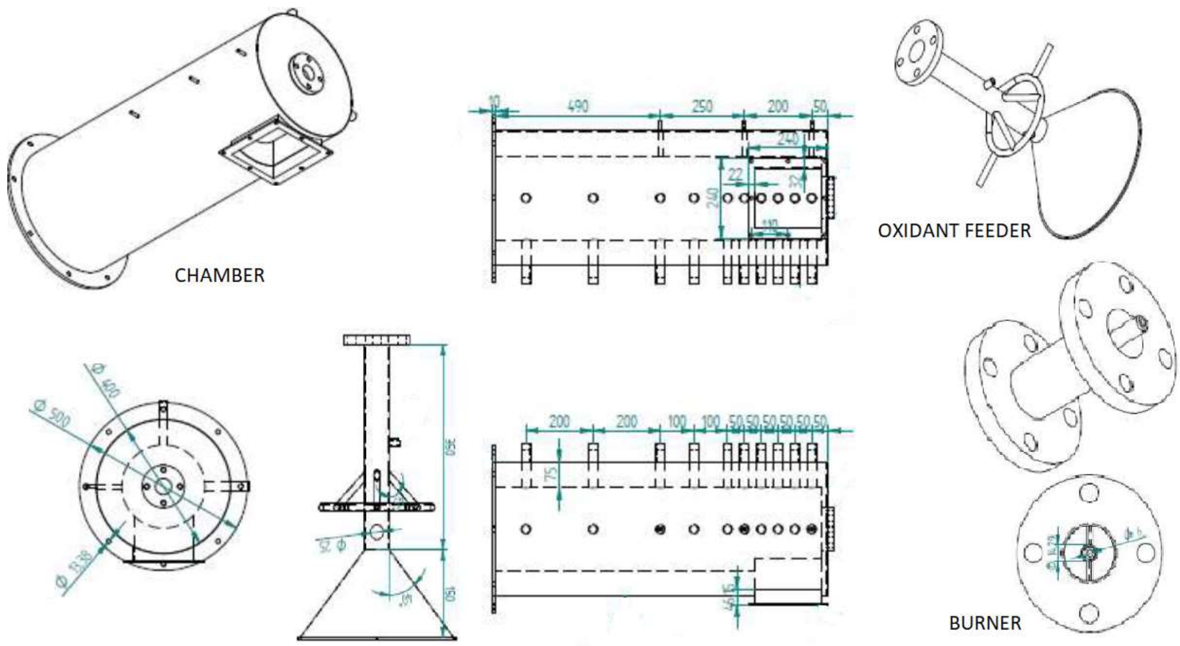


Figure 1. Experimental Setup.

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Soot volume fraction (ppm) was calculated from the laser light extinction data using the Rayleigh limit of the Mie theory, so that:

$$\phi = \frac{\lambda}{6\pi \operatorname{Im}\left|\frac{m^2-1}{m^2+2}\right|} K_{abs} \quad (1)$$

$$K_{abs} = \frac{1}{L}\ln\left(\frac{I_o}{I_L}\right) \quad (2)$$

λ , is the laser wavelength, L the optical path length, Io and IL the laser beam intensity, before and after traversing the flame, and m is the refractive index, adopted as m = 1.90-0.55i, according to [17].

3. RESULTS AND DISCUSSION

The Figure 2 presents the soot concentration in the basis case (equivalence ratio 1.0 and 21% O_2 volume). Figure 3 presents the results of equivalence ratio 1.0 with enrichment level 9% and without C_2H_2 doping, as also enrichment level 9%, C_2H_2 doping 5%.

There was an increase in the concentration of soot with the use of OEC in relation to the base case (without enrichment). Especially in the condition of doping use with 5% acetylene. The tendency to increase the concentration along the chamber remains in the condition of enrichment, and it is not possible to notice its reduction in the flame oxidation zone from the 6th measurement point.

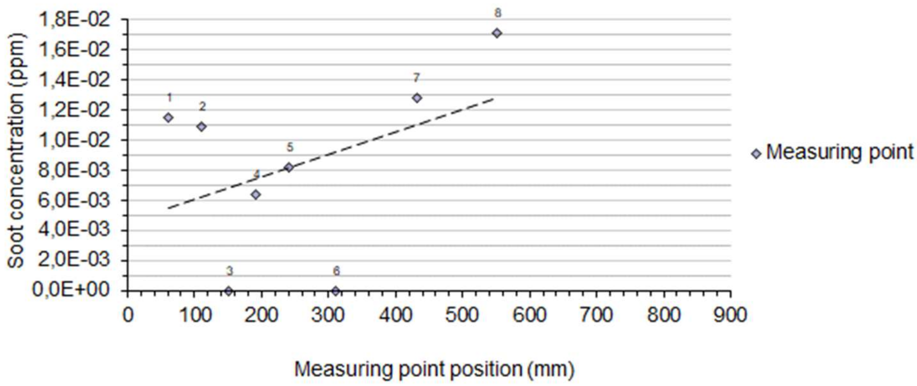

Figure 2. Soot concentration in combustion chamber: Equivalence ratio 1.0, basis case.

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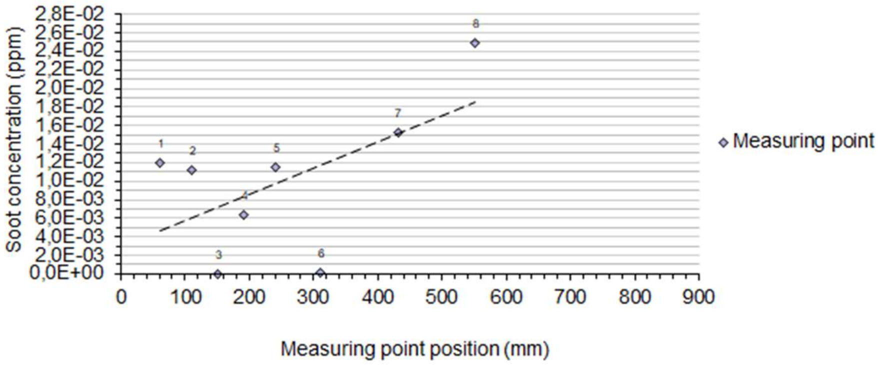
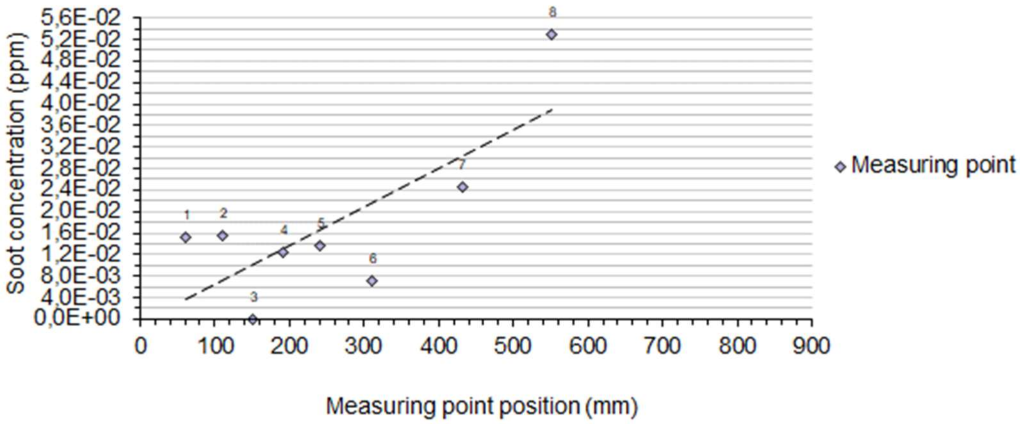


(a)



(b)

Figure 3. Soot concentration in combustion chamber: (a) Equivalence ratio 1.0, enrichment level 9%, without C_2H_2 doping, (b) (a) Equivalence ratio 1.0, enrichment level 9%, C_2H_2 doping 5%.

The Figure 4 presents the soot concentration in the lean condition basis case (equivalence ratio 0.7 and 21% O_2 volume). Figure 5 presents the results of equivalence ratio 0.7 with enrichment level 9% and without C_2H_2 doping, as also enrichment level 9%, C_2H_2 doping 5%.

Analyzing the results of the figures, there was a noticeable influence of doping on the increase in the concentration of soot along the flame. There was influence on the start of the flame in the condition of 5% of acetylene doping. It is known that syngas does not have a tendency to form soot in its combustion, reducing its efficiency in energy emission [4]. This result of a slight increase in the concentration of soot allows us to infer a possibility of increased efficiency in these flames with the use of acetylene doping.

This is possibly due to the fact that acetylene is a soot particle formation nucleous, it promoted greater growth in its concentration in the flame pyrolysis zone, with 5% doping.

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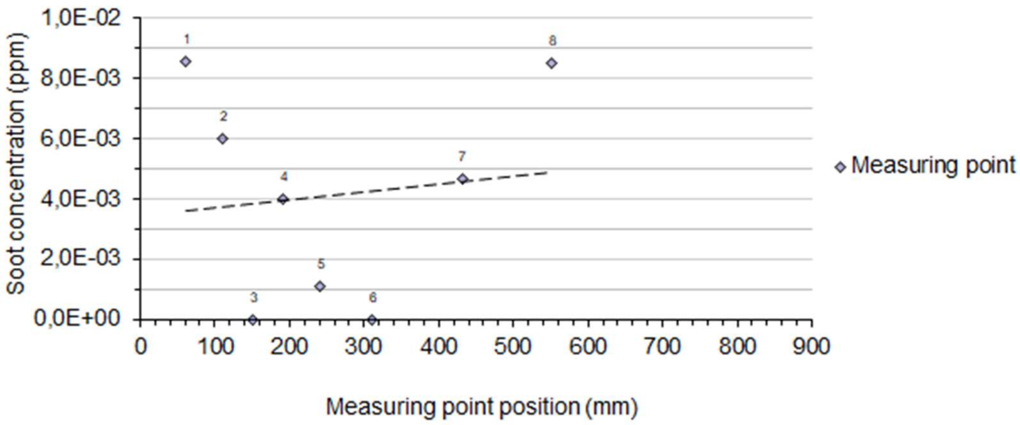
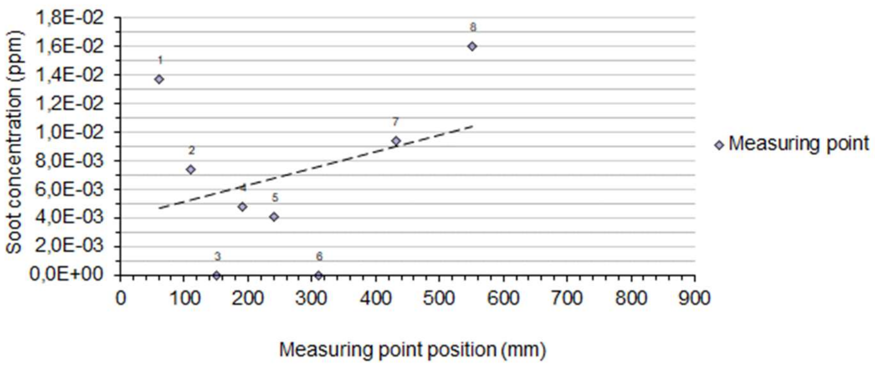
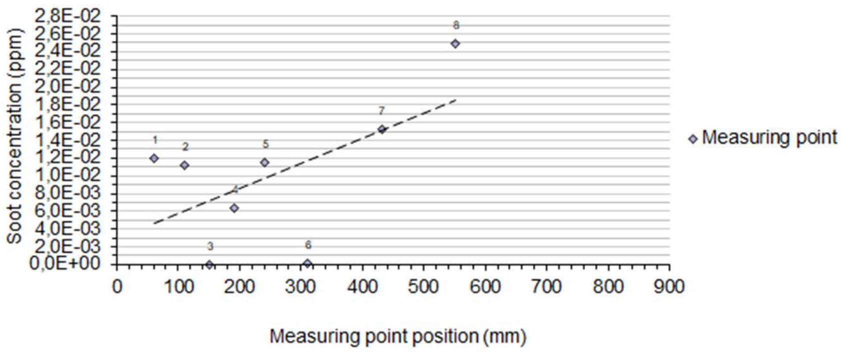


Figure 4. Soot concentration in combustion chamber: Equivalence ratio 0.7, basis case.

Analyzing the results in the condition of using OEC associated with LC in syngas burning, it was noticed an increase in the soot concentration trend compared to the result without enrichment. This is due to the influence of OEC on the early flame formation of soot particles and agglomerates, in combination with the influence of acetylene.



(a)



(b)

Figure 5. Soot concentration in combustion chamber: (a) Equivalence ratio 0.7, enrichment level 9%, no C_2H_2 doping, (b) Equivalence ratio 0.7, enrichment level 9%, C_2H_2 doping 5%.

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4. CONCLUSION

• A grater increase in the soot concentration trend was observed compared to the result without enrichment, when the OEC was associated with flames with an equivalence ratio of 0.7 and acetylene doping than verified for the equivalence ratio 1.0. But the concentration levels for the 0.7 condition were lower than the 1.0 condition. This must have been due to the higher flame temperature level in the condition with an equivalence ratio of 1.0, promoting a higher soot concentration. As a benefit of the operation with the condition of 0.7 due to its lower temperature, there is a tendency to reduce the formation of NOx.

• The association of proposed techniques in the syngas burning (a fuel with a future for industrial application) brings some promising aspects for its application in industrial burners. Some aspects need to be better understood for the effective development of equipment.

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5. REFERENCES

[1] GÓMEZ, Henar Olmedo; CALLEJA, Miguel Castaños; FERNÁNDEZ, Luis Aldea; KIEDRZYńSKA, Aleksandra; LEWTAK, Robert. Application of the CFD simulation to the evaluation of natural gas replacement by syngas in burners of the ceramic sector. **Energy**, [S.L.], v. 185, p. 15-27, out. 2019. Elsevier BV. http://dx.doi.org/10.1016/j.energy.2019.06.064.

[2] BARAIYA, Nikhil A.; CHAKRAVARTHY, S.R.. Effect of syngas composition on high frequency combustion instability in a non-premixed turbulent combustor. **International Journal Of Hydrogen Energy**, [S.L.], v. 44, n. 12, p. 6299-6312, mar. 2019. Elsevier BV. http://dx.doi.org/10.1016/j.ijhydene.2019.01.115.

[3] BAUKAL, JR., C. E. **Oxygen-enhanced Combustion**. 1a ed. New York: CRC Press, 1998.

[4] SANTOS, Alex Álisson Bandeira; GOLDSTEIN, Leonardo; FERRARI, Carlos Alberto. An experiment on the effect of oxygen content and air velocity on soot formation in acetylene laminar diffusion flame produced in a burner with a parallel annular coaxial oxidizer flow**. International Communications In Heat And Mass Transfer**, [S.L.], v. 36, n. 5, p. 445-450, maio 2009. Elsevier BV. http://dx.doi.org/10.1016/j.icheatmasstransfer.2009.02.001.

[5] Dunn-Rankin, D. **Lean Combustion – Technology and Control**. 1a ed. New York: Academic Press, 2008.

[6] KOZLOV, V.e.; TITOVA, N.s.; CHECHET, I.V.. Modeling study of hydrogen or syngas addition on combustion and emission characteristics of HCCI engine operating on iso-octane. **Fuel**, [S.L.], v. 221, p. 61-71, jun. 2018. Elsevier BV. http://dx.doi.org/10.1016/j.fuel.2018.02.062.

[7] SKEEN, S.A.; YABLONSKY, G.; AXELBAUM, R.L.. Characteristics of non-premixed oxygen-enhanced combustion: ii. flame structure effects on soot precursor kinetics resulting in soot-free flames. **Combustion And Flame**, [S.L.], v. 157, n. 9, p. 1745-1752, set. 2010. Elsevier BV. http://dx.doi.org/10.1016/j.combustflame.2010.04.013.

[8] SANTOS, Alex Álisson Bandeira. **Investigação do uso da combustão enriquecida com O2 em chamas confinadas de gás natural**. 2010. 273 f. Tese (Doutorado) – Pós-Graduação em Energia e Ambiente, Universidade Federal da Bahia, Salvador.

[9] Kobayashi, H., Otawara, Y., Wang, J., Matsuno, F., Ogami, Y., Okuyama, M., Kudo, T., Kadowaki, S. Turbulent premixed flame characteristics of a CO/H2/O2 mixture highly diluted with CO2 in a high-pressure environment. **Proceedings of the Combustion Institute**, [S.L], v. 34, p. 1437-1445, 2013.

[10] SAFER, K.; TABET, F.; OUADHA, A.; SAFER, M.; GÖKALP, I.. Simulation of a syngas counter-flow diffusion flame structure and NO emissions in the pressure range 1–10atm. **Fuel Processing Technology**, [S.L.], v. 123, p. 149-158, jul. 2014. Elsevier BV. http://dx.doi.org/10.1016/j.fuproc.2013.10.019.

[11] OTHMAN, N F; BOOSROH, M H. Effect of H2and CO contents in syngas during combustion using Micro Gas Turbine. **Iop Conference Series**: Earth and Environmental Science, [S.L.], v. 32, p. 012-037, mar. 2016. IOP Publishing. http://dx.doi.org/10.1088/1755-1315/32/1/012037.

[12] Wilfinger, M. M., Santos, A.A.B., Macedo, E.A.S., Oliveira, T.D., 2018. Análise da Eficiência da Combustão Confinada de Gás De Síntese em Condições de Misturas Pobres com Dopagem de Acetileno Associada à OEC. **Congresso Nacional de Engenharia Mecânica**,10. Maio, 2018. Salvador, Brazil.

[13] ILBAS, M. The effect of thermal radiation and radiation models on hydrogen–hydrocarbon combustion modelling. **International Journal Of Hydrogen Energy**, [S.L.], v. 30, n. 10, p. 1113-1126, ago. 2005. Elsevier BV. http://dx.doi.org/10.1016/j.ijhydene.2004.10.009.

[14] VOSS, S.; MENDES, M.A.A.; PEREIRA, J.M.C.; RAY, S.; PEREIRA, J.C.F.; TRIMIS, D.. Investigation on the thermal flame thickness for lean premixed combustion of low calorific H2/CO mixtures within porous inert media. **Proceedings Of The Combustion Institute**, [S.L.], v. 34, n. 2, p. 3335-3342, jan. 2013. Elsevier BV. http://dx.doi.org/10.1016/j.proci.2012.06.044.

[15] GOSWAMI, M.; VAN GRIENSVEN, J.G.H.; BASTIAANS, R.J.M.; KONNOV, A.A.; GOEY, L.P.H. de. Experimental and modeling study of the effect of elevated pressure on lean high-hydrogen syngas flames. **Proceedings Of The Combustion Institute**, [S.L.], v. 35, n. 1, p. 655-662, 2015. Elsevier BV. http://dx.doi.org/10.1016/j.proci.2014.05.057.

[16] FERREIRA, D.S. **Queimadores pulsantes para baixas emissões de poluentes**. 2001. 165 f. Dissertação (Mestrado) – Pós-Graduação em Transmissão e Conversão de Energia, UNESP, Guaratinguetá.

[17] IULIIS, S. de; BARBINI, M.; BENECCHI, S.; CIGNOLI, F.; ZIZAK, G.. Determination of the Soot Volume Fraction in an Ethylene Diffusion Flame by Multiwavelength Analysis of Soot Radiation. **Combustion And Flame**, [S.L.], v. 115, n. 1-2, p. 253-261, out. 1998. Elsevier BV. http://dx.doi.org/10.1016/s0010-2180(97)00357-x.