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An experimental study of combustion stability and emissions characteristics of a surface-stabilized combustion burner fueled with natural gas-syngas blends

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Abstract. The aim of this paper is to investigate the effects of replacing natural gas with synthetic gases on the combustion stability and the combustion pollutants of a surface-stabilized combustion burner. We evaluated three synthetic gases with high hydrogen contents ranging from 60% H_2 to 75% H_2. The experimental study was carried out under different input power conditions (300 to 500 kW/m^2) and equivalence ratios. The results obtained in this work indicate that combustion stability of natural gas in a surface-stabilized combustion burner is significantly affected by the addition of synthetic gases, which in this case was held constant to obtained equimolar mixtures of synthetic gas and natural gas. This result seems to be explained by the variations of some important combustion properties, mainly the laminar burning velocity and the adiabatic flame temperature. On the other hand, it was found that CO emissions slightly decrease with increasing H_2 concentration. This behavior is attributed to the increase of the OH radical.

1. Introduction

Natural gas (NG) is used in a wide range of combustion applications, including both industrial and residential applications. Although NG is generally considered a clean fuel, it is a hydrocarbon gas mixture that, similar to other fossil fuels, in a typical combustion process emits carbon dioxide (CO_2), carbon monoxide (CO) and nitrogen oxides (NOx). Therefore, great efforts have been focused on the development of cost-effective strategies to reduce the emissions of these pollutants on NG-fueled applications. One of these strategies is mixing the natural gas with alternative fuels to improve some combustion properties, which additionally can contribute to extend the lifetime of natural gas reserves [1–3].

Synthetic gases (syngas, SG), for example, which are gas mixtures consisting primarily of hydrogen and carbon monoxide have been proven to be a viable alternative fuel for this purpose [4,5]. SG is obtained from coal and biomass gasification, which are abundant resources. In fact, many authors have referenced these alternative fuels as one of the most promising energy sources in both developed and developing countries. However, the low calorific values obtained in this fuel gases (between 1.0 and ~ 2.6 kWh/m^3) difficult the implementation of combustion applications fueled solely with SG [6].

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On the other hand, it has been shown that burners or combustion technologies that include preheating of the reactant streams can improve the stability range and facilitate the oxidation process of these fuel mixtures [7]. The most simple way to design a heat-recirculating burner is stabilizing a pre-mixture flame on the surface of a porous inert media [8]. In this case, part of the heat released during the oxidation of the fuel is absorbed by the porous media, which in turn radiates heat to the load and conducts heat upstream to preheat the fuel-air mixture.

Since 1990, many researchers have been studying this type of burner at high input powers [9]. It has been found that they are capable of burning air-fuel mixtures that would not be flammable in conventional burners. Moreover, low combustion pollutant emissions are obtained. Recently, some studies have shown that these benefits can also be obtained in thermal power range found in home appliances [10,11].

The main purpose of this work is to research the performance of a surface-stabilized combustion burner fueled with natural gas and three equimolar mixtures of synthetic gas and natural gas. We studied the effect of the syngas composition, the equivalence ratio and nominal input power on combustion stability and flue gas composition, mainly CO and NOx emissions. The SG were emulated with H_2 CO mixtures with H_2/CO ratios from 1.5 to 3, or what is the same, 60% H_2 - 40% CO to 75% H_2 – 25% CO. The nominal input powers considered in this work resemble two values found in commercial applications (300 and 500 kW/m^2).

2. Experimental setup

Figure 1 shows a diagram of the experimental setup used to determine the combustion stability, pollutant emissions and the temperature distribution within the porous media. The burner consists of a monolithic honeycomb-type cylindrical structure with parallel channels of square section of 1 mm^2 and a cell density of 18 CPI (cells per inch). The diameter of the porous media is 70 mm and the void fraction is 0.62. The porous material was fabricated from alumina (Al_2O_3) and has a thickness of 25 mm.

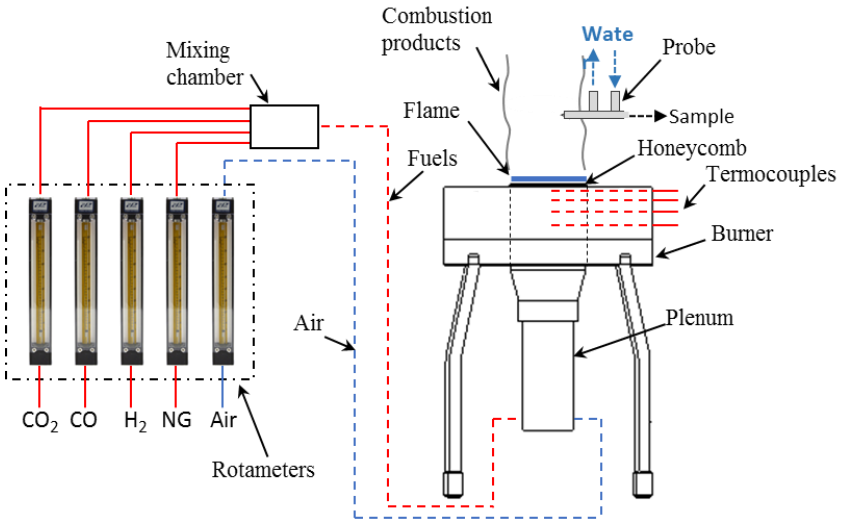


Figure 1. Experimental setup.

In the experimental unit, the oxidizer and the fuel mixture enter to a mixing chamber before reaching the porous media. High purity certified gases (99% purity) were used to emulate the SG. Table 1 lists the volumetric compositions of the NG and the NG-SG mixtures evaluated in this work. Additionally, we include some combustion properties calculated at an equivalence ratio of 1. This combustion properties are the laminar burning velocity (SL), the adiabatic flame temperature (Tad) and the lower heating value (LHV).

Table 1. Volumetric compositions and combustion properties.

	GN	50SG1	50SG2	50SG3
CH_4	94.68	47.34	47.34	47.34
C_2H_6	2.37	1.19	1.19	1.19
C_3H_8	0.81	0.40	0.40	0.40
n-CxHy	0.15	0.08	0.08	0.08
i-CxHy	0.16	0.08	0.08	0.08
CO_2	0.56	0.28	0.28	0.28
N_2	1.27	0.63	0.63	0.63
H_2	--	30.00	33.35	37.50
CO	--	20.00	16.85	12.50
SL(ϕ=1)[a]	0.39	0.61	0.64	0.66
Tad(ϕ=1)[b]	2221	2255	2255	2255
LHV[c]	9.43	6.23	6.21	6.19

[a] SL in m/s. [b] Tad in K. [c] LHV in kWh/m^{3}st.

To register the concentrations of O_2, CO, CO_2 and NOx in the flue gases, we use the same instrumentation and procedure described previously in [12]. Temperature distribution within the burner were registered along the center line using a S-type thermocouple of 33 μm wire diameter at 20 mm from the entrance of the porous media and K-type thermocouples at 5 mm, 10 mm and 15 mm from the entrance of the porous media, as shown in Figure 2. All measurements were performed at steady-state condition.

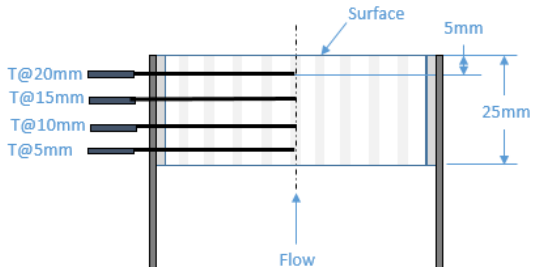


Figure 2. Temperature measurement within the porous media.

3. Results and discussions

3.1. Flame stability

Figure 3 shows the combustion stability diagrams for NG and SG-NG mixtures. The diagrams consist of several operating conditions that were evaluated to find the equivalences ratios – input power combinations that lead to either blow-off or flashback. With this in mind, we defined three operating condition zones: the blow-off zone (equivalence ratios lower than the blow-off limit, BL), the flashback zone (equivalence ratios higher than the flashback limit, FL) and the stable operation zone (equivalence ratios between BL and FL).

As shown in Figure 3, the burner performance is highly affected by the addition of SGs. The operation at high equivalence ratios were characterized by the appearance of flashback. This behavior can be explained by observing the combustion properties presented in Table 1. The addition of SG to the fuel increases the laminar burning velocity; as a consequence, the tendency to obtain flashback increases. As a special case, no variations were found between the operations with SG2 and SG3.

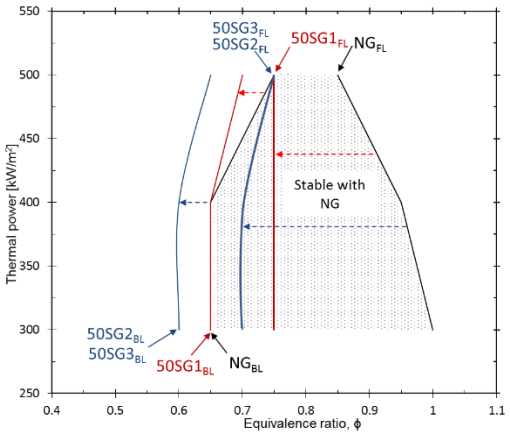


Figure 3. Combustion stability diagram.

3.2. Temperature profile

Figure 4 shows the temperature distribution registered within the burner at some operation conditions. The distances shown in Figure 4 indicate the position along the porous media: 0 mm matches the entrance of the porous media and 25 mm matches the burner exit. Although high variations on temperature profiles were expected, principally due to the high differences on SL and the combustion stability obtained for the blends with respect to NG, the differences were smaller than expected. It seems to be that Tad has a great influence on the temperature profile within the porous media. It is observed from Table 1, that this combustion property does not change considerably with the additions of SGs.

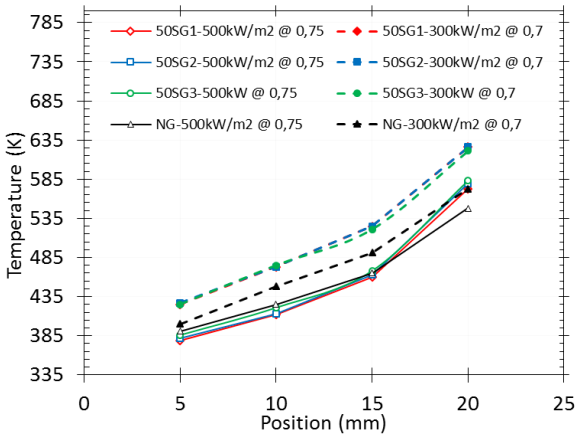


Figure 4. Temperature inside the porous medium.

As expected, the increase of input power decreases the temperature within the porous media (or, what is the same, the preheating temperature) for a given equivalence ratio. This behavior can be attributed to the increase of unburned gases velocity with respect to SL, which causes the flame front to move downstream from the burner surface, as shown in [13].

3.3. Emissions of CO and NOx

Figure 5 shows the CO emissions (air free) for NG and the mixture of NG with the SGs. Generally, the CO increases when the equivalence ratio is close to the FL. In addition, as the hydrogen concentration increases, there are slight decreases in the CO emissions for the different SGs. With respect to this result, some comments can be drawn taking as reference the elementary reactions of Table 2. These reactions belong to the detailed reaction mechanism Gri-Mech 3.0, which has been used to successfully predict the behavior of the fuel mixtures presented here.

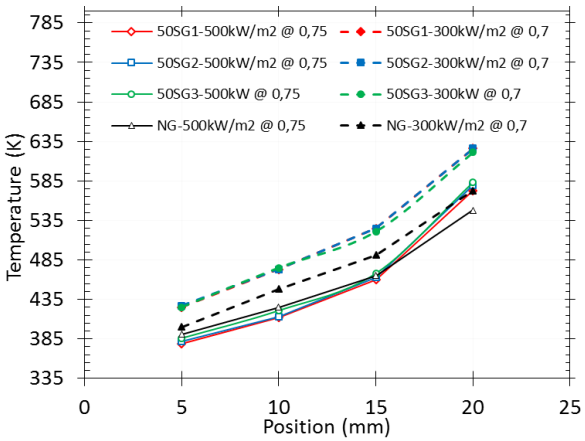


Figure 5. CO emissions.

Table 2. Some elementary reactions present in detailed reaction mechanisms.

Elementary reaction	Ea (cal·mol^{-1})
$CH_4 + O \leftrightarrows CH_3 + OH$ (R1)	8600
$CH_4 + OH \leftrightarrows CH_3 + H_2O$ (R2)	3120
$CO + OH \leftrightarrows CO_2 + H$ (R3)	70
$CO + O_2 \leftrightarrows CO_2 + O$ (R4)	47800
$CO + O + M \leftrightarrows CO_2 + M$ (R5)	2385
$H_2 + O \leftrightarrows H + OH$ (R6)	6260

From Table 2, R4 and R5 suggest that the complete oxidation of CO depends on the oxygen availability. Therefore, CO emissions increase near the FL, where the O_2 availability decreases. On the other hand, it is important to mention that activation energy (Ea, Table 2) of elementary reactions that include OH (reaction 3) are much lower than those that include O or O_2 (reaction 4 and reaction 3), which is valid not only for the oxidation of CO, but also for CH_4 (R2) and H_2 (R7). Huang et al. [14] also found this behavior in synthetic gases. Increasing the H_2 concentration leads to a higher production of OH, therefore, in general, CO emissions decrease in operations with SGs.

Figure 6 shows the NOx emissions for the NG and the SG-NG blends. In general, NOx emissions were found to be less than 5ppm. Moreover, it was found that as the hydrogen concentration increased, there were no important changes in the NOx emissions for the different blends. On the other hand, increasing both the equivalence ratio as well as the input power increases the NOx emissions since the Tad increases.

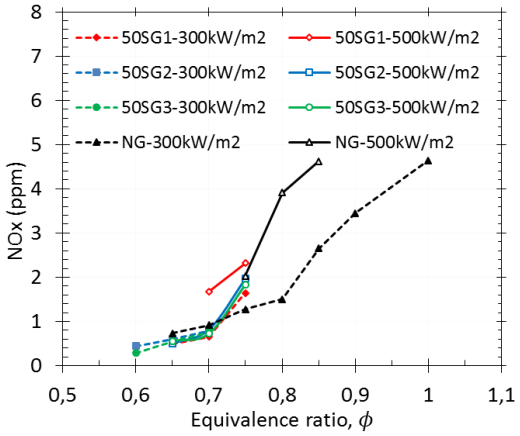


Figure 6. NOx emissions.

4. Conclusions

In this paper, a surface-stabilized combustion burner fueled with natural gas and natural gas – syngas blends were studied. We investigated the effect of the syngas composition, the equivalence ratio and nominal input power on combustion stability and flue gas composition, mainly CO and NOx emissions. The H_2 to CO ratio for the synthetic gases was varied between 1.5 and 3. The following conclusions can be drawn from this study:

- Burner operating conditions considerably change when the NG is replaced by high hydrogen content SGs. Especially, a decrease in the stable operating range was observed. This behavior can be explained by analyzing some combustion properties. The SG concentration in the fuel mixture increases the laminar burning velocity and as a consequence increases the tendency to obtain retro-flame.
- The temperature profiles did not show significant changes when replacing the NG with high hydrogen content SGs.
- As expected, the increase in input power decreases the temperature inside the porous medium (or, what is the same, the preheating temperature) for a certain equivalence factor. This result can be explained by the increase in the velocity ratio of the unburned gases to SL, which causes the front of the flame to move downstream from the burner surface.
- When increasing hydrogen concentration, with the addition of synthesis gases, there are slight decreases in CO emissions for the different SGs, which is explained by the increase in the concentration of OH radicals.
- With respect to NOx emissions, it was found that, as the hydrogen concentration increased, no significant changes occurred in the NOx emissions for the different SGs.

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