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Effect of increasing load on the MILD combustion of COG and its blend in a 30 kW furnace using low air preheating temperature

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Abstract

MILD combustion is a high efficiency technique, applied on industrial furnaces to have low polluting emissions and significant energy saving by high air preheating. The main purpose of this work was the investigation of the behavior of two fuels rich in H2 burning in MILD regime at different furnace temperature levels (1200 K ÷ 1300 K), using air preheating temperature which can be guaranteed by low performance heat exchanger too. Both fuels had very good performance but the one with higher H2 content, which reduces the ignition delays, showed higher capability to keep a well-positioned reaction zone at higher heat transfer to the load and consequently wider flue gases temperature range.

Keywords: MILD combustion; air preheating; furnace temperature; H2-rich fuels; alternative fuels; low LHV fuels; low effectiveness; low polluting emissions

1. Introduction

MILD combustion is an efficient combustion technology, which has been successfully applied to industrial furnaces to have significant energy saving by high air preheating and very low polluting emissions. The main feature of this technique is the use of a proper configuration of the injection system able to guarantee a strong recirculation inside the chamber. The hot flue gases are entrained by the fuel and air jets and they dilute the reactants with consequent temperature increase above the auto-ignition threshold. Therefore, combustion takes place in a wide volume and in diluted way. Thermal gradients and peaks of temperature are reduced, thereby the formation of

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hot-spots, NOx and carbon monoxide emissions are prevented [1]. Moreover, the narrow temperature range allows design, optimization, and adjustment in the process by fine tuning the external parameters [2]. Nowadays, there is an increasing request from industry for new combustion techniques which can be safely used to burn gasified waste or by-product gases as alternative fuels in manufacturing processes. These non-conventional fuels are blends of CH4, CO, H2, N2, and CO2 in variable proportions. The generation of a stable flame can be difficult because of their highly variable calorific value (*LHV*). MILD combustion can be an interesting solution, since there is no need to stabilize a flame front. Achieving maximal heat recuperation efficiency is one of the main reasons of interest in MILD combustion. These results however are only possible in combination with regenerative exchanger or auto-regenerative burners. More frequently, industrial communities are interested in using MILD combustion with limited air temperature, especially if the use of regenerative systems is not possible as retrofit process of existing plants [3].

Nomenclature

ρ	Density (kg/Nm^3)	E	Excess Air
$\dot{q}$	Volumetric flow rate (Nm^3/h)	v	Speed (m/s)
$\dot{m}$	Mass flow rate (kg/s)	$\dot{G}$	Momentum rate (N)
P	Power (W)	T	Temperature (K)
η	Thermal efficiency	S_h	Sensible heat (W)
Imm	Immersion of the water-cooled tubes	ε	Effectiveness
NTU	Number of transfer unit	C	Capacity (W/K)
LHV	Low heating value (kJ/Nm^3 @ 298.15K)	Δ	Difference
K_v	Recirculation ratio	δ	Relative difference

2. Specific Objectives

The UMONS combustion research has been focused on the creation of an experimental database for a furnace working in MILD combustion using different fuels with very variable calorific value, produced by gasification of biomass or wood, or obtained as waste or by-products of industrial processes [4][5][6][7][8]. This work investigates the effect of the decreasing furnace temperature on the combustion characteristics in the MILD regime, using low air preheating temperature easily guaranteed by classical heat exchanger and two different alternative fuels: coke oven gas (COG), and a blend (B50) consisting of 50% coke oven gas and 50% blast furnace gas (BFG) by volume. Table 1 shows their composition and properties with respect to classical natural gas (NG).

Table 1: Composition of the used fuels by volume and their properties compared to natural gas.

	N2	CO2	CH4	H2	CO	Other CxHy	*LHV*	ρ
NG	2.5%	1.21%	89.46%	-	-	6.83%	37105	0.805
COG	2%	1.5%	28.5%	62%	6%	-	17652	0.389
B50	28%	12%	14.25%	32.5%	13.25%	-	10282	0.882

The chamber was designed to work with NG and was deeply tested with this fuel [4][5]. The design of the injection system ensures at the meeting point of the air and fuel jets the minimum recirculation rate K_v, defined as the ratio between the flue gases mass flow rate entrained into the jets and total mass flow rate in inlet:

$$K_v = \frac{\dot{m}_{flue\_entrained}}{\dot{m}_{fuel} + \dot{m}_{air}} \tag{1}$$

If the temperature level and the K_v are sufficiently high to determine the autoignition of the mixture, the conditions of stable MILD combustion are reached. However, it was already observed in other works [8][9] that for classical

CH4 and NG the reaction zone shifts downstream for very reduced chamber temperatures. Here the objective is to understand the sensitivity of the mentioned alternative fuels to different temperature levels. The tested air preheating temperatures was 673 K. The fuel and air mass flow rate were set to get a combustion power at 30 kW and theoretical excess air at 15%. Comparisons were mainly carried out in terms of powers and thermal efficiency, wall, flue gases and recirculation temperatures, flue gases content of CO, NOx, O2, CO2, CH4 on dry basis, and OH* chemiluminescence images of the main reaction zones taken through the available optical access.

3. Experimental facility

Experimental tests were performed on a 30 kW, laboratory scale furnace, designed to only operate in MILD combustion and able to reproduce some of the main features of industrial furnaces (injection system, geometry, variable load). The chamber was already presented in detail in Mosca et al. [8] and is depicted in Figure 1. It is made of stainless steel and equipped with a fiber-made heat insulation layer. It has a square internal section of 0.35 m x 0.35 m and it is 1 m high. Two fuel injectors, with an exit diameter of 4.5 mm or 2.8 mm and a tilt angle of 11° from the vertical axis, are symmetrically located around the air nozzle, whose exit diameter is 24.8 mm. Air can be externally preheated till 1273 K by an electrical preheater. A mixing unit with mass flow meters and controllers and gas bottles are used to get the desired final fuel composition. The presence of the load and its extracted heat can be controlled by changing the immersion of four water-cooled tubes (WCT) in the range 0 to 0.9 m from the top of the furnace. The rear wall of the chamber is equipped with a quartz window, 5 cm wide and arranged along the furnace axis where main reaction zones are supposed to occur. An intensified UV camera is used to take images of chemiluminescent self-emission of OH* radicals. A lateral wall has 8 S-type thermocouples mounted flush with the insulation layer. Temperature of the recirculation zone is measured by a shielded thermocouple, whereas the flue gases one by a suction pyrometer positioned on the top (see Figure 1). Twelve circular lateral holes positioned close to the top extract the gases from the furnace. Analysis of flue gases content (extracted after the exhaust) is performed on dry basis for O2, CH4, CO2, CO, and NOx through paramagnetic, infrared and chemiluminescent gas analyzers.

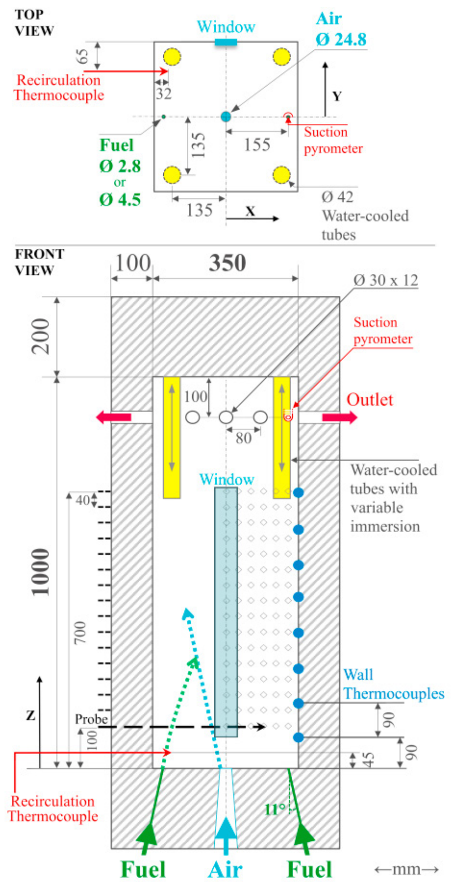

Figure 1: Detailed sketch of the 30 kW chamber. Dimensions are in mm.

4. Experimental procedure

The 30 kW furnace was not designed to work in conventional combustion and its preheating is always performed by a pilot burner fed by natural gas. The following parameters were kept constant during the tests: combustion power at 30 kW, theoretical excess air at 15%, air temperature set-point at 673 K, diameter of the fuel injectors at 4.5 mm (properly chosen to correctly work with both COG and B50 fuels), constant water flow rates set-point for water circuits. Therefore, the immersion of the WCT was the only changing feature affecting the burning conditions. It was increased in step of 0.1 m starting from a position of 0.3 m from the top of the furnace. The WCT have been immersed till the point at which CO levels increased because of main reaction zones very close to the furnace exit (a condition which is not desirable since reacting mixtures could be extracted). Images of OH* self-emissions, which represent a good marker for the main reaction zones, were taken by the intensified UV camera using the same setup. For each case 50 images were collected and corrected, and a final average image was determined.

Table 2 shows the flow rates measured by the flow controllers, the real excess air obtained from the O2 content at the exhaust, the inlet velocities calculated according to the fuel, air and the geometry of the injection system, and the reached immersions of WCT. Thrust of the jets evaluated by momentum rates $\dot{G}$ can be easily deduced. For the sake of completeness, the COG and B50 tests are also compared to the NG ones performed in 2004 by the UMONS combustion team [4][9]. In these old tests real excess air was about 10% (less accurate flow controllers were used), air temperature was 1073 K, water flow rate inside the WCT was 15% lower than the one used in the COG and B50 cases, and fuel injectors with diameter of 2.8 mm were used to guarantee optimal recirculation rates. Despite these differences, the authors still retain useful to report these tests because of the large use of NG in industry.

Table 2: Experimental flow rates, real excess air, speeds, momentum rates, recirculation ratio [10], air temperature and tested immersion of WCT.

	$\dot{q}_{fuel}$	$\dot{q}_{air}$	E	v_{fuel}	v_{air}	$\dot{G}_{fuel}$	$\dot{G}_{air}$	$\dot{G}_{air}/\dot{G}_{fuel}$	K_v	T_{air}	Imm
NG	2.843	33.400	~8.2%	67	75	0.0214	0.900	42.1	3.6	1073	0.3 - 0.4 – 0.5 0.6
COG	6.118	30.490	12.4÷14.8%	58	43	0.0191	0.473	24.8	3.1÷3.7	673	0.3 - 0.4 - 0.5 0.6 - 0.7 - 0.8
B50	10.505	29.553	12.7÷13.1%	100	42	0.1279	0.444	3.5	5÷5.3	673	0.3 - 0.4 - 0.5

5. Results

The obtained experimental data are corrected and analyzed using several homemade automatic tools in Excel-VBA and Matlab. Increasing the immersion of the WCT determines higher heat transfer to the load and a general reduction of all temperatures inside the furnace, as shown in Figure 3 and Table 3. Figure 2 related to OH* emissions shows that two main reaction zones, determined by the intersection of the two fuel jets with the central air one, shift to the top of the chamber in different ways as the WCT exposes higher area to the flue gases. The COG is the fuel which can keep the main reaction zones in a stable position from 0.25 to 0.5 m height in the widest range of flue gases temperatures thanks to its high H2 concentration, which is well known in literature to reduce the ignition delays [11]. B50 also performs well considering the high concentration of inert gases and its low *LHV* (~30% of the NG one). The main reaction zones are more stretched on the chamber height and lifted to the range 0.35 to 0.65 m, because of the increased momentum rate related to the highest mass flow rate to satisfy the 30 kW combustion power, the consequent higher recirculation rate K_v (estimated by the GrandMaison's strong jet/weak jet theory [10]; see Table 2), and the reduced effect of the H2. Hydrogen plays a very important role to speed up the activation of the combustion process and to extend the range of temperature at which the MILD combustion can occur in the correct way in this furnace. In fact, even if the *LHV* of NG is 2.1 and 3.6 times than COG and B50 one respectively, it shows a sudden lift of the main reaction zones; this happens for flue gases temperature about 150 K higher than the COG and B50 cases. Moreover, it is important to remind that in NG tests air preheating was 1073 K. In this condition the autoignition of mixture is significantly facilitated if fuels consisting primarily of methane are used, as already noticed for pure CH4 tests [8]. Lastly, thanks to lower $\dot{G}_{air}/\dot{G}_{fuel}$ ratio, COG and B50 cases exhibit a good vertical symmetry compared to NG (differences on margins are caused by small uncertainties on camera position).

The wall temperature profiles in Figure 3 show an expected stronger reduction of the temperature at the bottom of the chamber as the flue gases temperature decreases, since the main reaction zones are moving up. This is particularly clear for COG which has a stable MILD combustion for wider ranges of exposed area of WCT. The differences ΔT for the flue gases and recirculation temperatures resulting from the increase of the immersion of the load, taking the respective case at 0.3 m as reference, are very similar from a direct comparison among the different fuels (Table 3). The 95% confidence interval for the measurements is less than 2 K. However, from a sensitivity study [9] it has been calculated that the accuracy of the suction pyrometer measuring the flue gases temperature is ~20 K. Around T_{flue} ~ 1200 K MILD combustion of COG and B50 occurs in a way which is not safe considering the geometrical configuration of the 30 kW furnace. Indeed, the main reaction zone is close to the collector holes and the risk to have unburnt gases on the exhaust becomes real. However, tests presented here reached a stable state in terms of temperatures and there were not increased CO levels at exhaust.

The balance of the furnace is easily obtained from the following equation:

$$P_{fuel} + S_{h\_fuel} + P_{air} = P_{flue} + P_{load} + P_{losses} \tag{2}$$

where P_{losses} represents the unmeasured component of the balance (the losses), P_{load} the power to the water-cooled tubes and P_{flue} the one of the flue gases. The power P_{fuel} related to the combustion of the fuel is constant and equal to 30 kW and the fuel sensible heat $S_{\_h\_fuel}$ is negligible. Table 3 reports the main powers and the relative differences δ considering the cases at 0.3 m as reference for the respective fuels. The 95% confidence interval for powers, calculated from the error propagation of measures of mass flow rates and temperatures, is less than 1.0 kW. Losses are very similar for the two alternative fuels and, as expected, they decrease according to the flue gases temperature. They range from 21% to 16% of the combustion power.

The thermal efficiency η of the combustion chamber

$$\eta = \frac{P_{load}}{P_{fuel} + P_{air}} \tag{3}$$

is the simplest parameter to measure the capability of the system to transfer heat to the load. The authors are considering the worst case in which air is externally preheated using an external source. However, it is well known that in MILD combustion it is common practice to recover heat by combustion products. Thermal efficiency mainly depends on the geometry of the system, its materials, the fuel/flue gases composition and the flue gases temperature. Values reported in Table 3 point out that both fuels have good performance. COG always performs better, having the η on average 2-2.5% higher than B50. However, this slight increase means a P_{load} increment of less than 1 kW considering the 30 kW combustion power and the 4 kW air preheating; thereby it is in the range of uncertainty. Air preheating at 673 K by flue gases can be easily carried out using standard gas-gas heat exchangers. Indeed, a rather low effectiveness ε equal to ~35% is required to accomplish this task. For higher values, even at T_{air} = 873 K, recuperative or regenerative systems integrated in the burner are more indicated [12], considering that the capacity ratios is equal to ~0.7, which means higher ε - NTU curves [13].

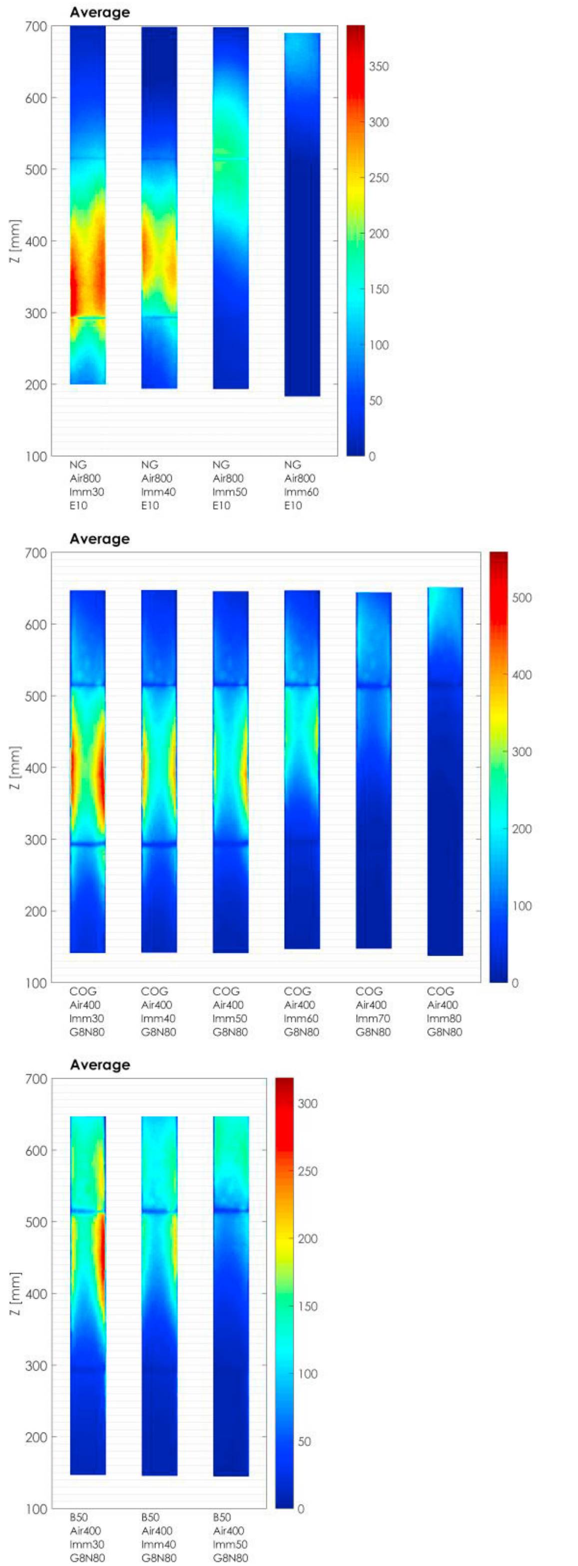

Figure 2: OH* mean images from the lowest (left) to the highest (right) immersion of the WCT. Colours scale is the photons count.

These results also confirm what was observed by Mosca et al. [8] for tests at different T_{air}: COG and B50 performances are very close to the classical fuels such as NG or CH4. Higher differences only appear when there is a lift of the main reaction zones to the top of the furnace, from which WCT are introduced.

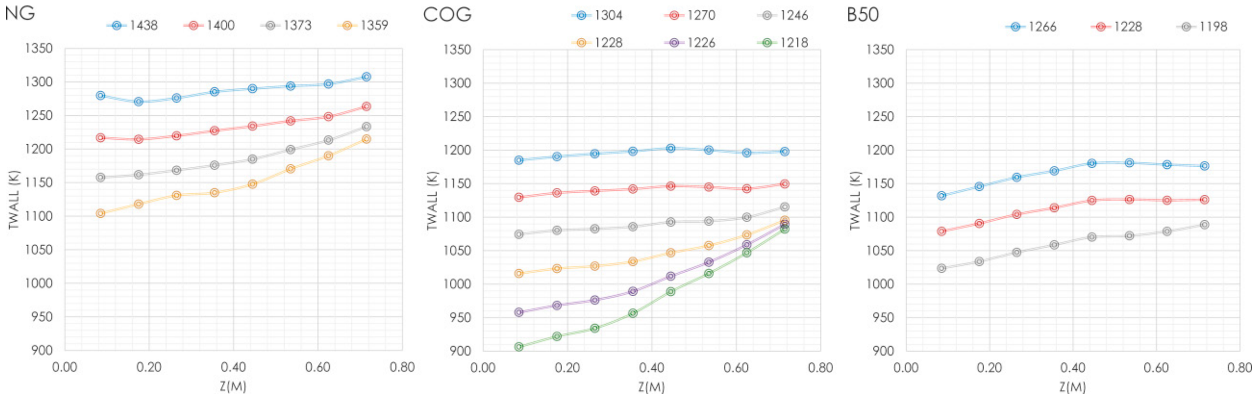

Figure 3: Wall temperature profiles obtained from the 8 S-type thermocouples positioned on a vertical side of the furnace and mounted flush with the wall. Profiles are sorted and painted according to the flue gases temperature.

Table 3: Main powers, differences Δ and relative differences δ taking the case *Imm* = 0.3 m for each fuel as reference.

Fuel	T_{flue} *(K)*	Δ_{Tflue} *(K)*	T_{rec} *(K)*	Δ_{Trec} *(K)*	P_{air} *(kW)*	P_{flue} *(kW)*	δ_{Pflue}	P_{load} *(kW)*	δ_{Pload}	P_{losses} *(kW)*	$\delta_{Plosses}$	η	δ_{η}	*Imm (m)*
NG	1438		1286		10.5	18.9		15.2		10.1		34.4%		0.3
	1400	-38	1225	-61		18.2	-3.8%	17.1	12.1%	8.9	-11.9%	38.6%	12.3%	0.4
	1373	-65	1171	-115		17.7	-6.3%	18.9	24.2%	7.6	-24.5%	42.7%	24.2%	0.5
	1359	-79	1107	-180		17.5	-7.7%	20.2	32.6%	6.6	-34.1%	45.5%	32.4%	0.6
COG	1304		1207		4.2	14.8		13.1		6.4		38.2%		0.3
	1270	-35	1150	-57		14.2	-3.8%	14.6	11.7%	5.4	-15.1%	42.7%	11.7%	0.4
	1246	-59	1093	-114		13.8	-6.5%	15.2	16.6%	5.2	-18.8%	44.5%	16.6%	0.5
	1228	-76	1032	-175		13.5	-8.3%	16.5	26.0%	4.2	-33.6%	48.1%	26.0%	0.6
	1226	-78	978	-229		13.5	-8.6%	17.0	29.8%	3.8	-40.4%	49.5%	29.6%	0.7
	1218	-86	919	-288		13.4	-9.4%	17.2	31.4%	3.7	-41.7%	50.1%	31.2%	0.8
B50	1266		1164		4.1	15.7		12.3		6.2		35.9%		0.3
	1228	-38	1109	-55		15.0	-4.3%	13.6	10.9%	5.5	-10.5%	39.8%	10.8%	0.4
	1198	-67	1055	-109		14.5	-7.7%	14.7	20.1%	4.9	-20.1%	43.1%	20.0%	0.5

Table 4: Main powers related to COG and B50 cases at similar flue gases temperatures. Relative differences δ are calculated taking the corresponding COG tests as reference.

Fuel	T_{flue} *(K)*	P_{flue} *(kW)*	δ_{Pflue}	P_{load} *(kW)*	δ_{Pload}	P_{losses} *(kW)*	$\delta_{Plosses}$	η	δ_{η}	*Imm (m)*	$\delta_{AreaWCT}$
COG	**1270**	14.2		14.6		5.4		42.7%		0.4	
	1228	13.5		16.5		4.2		48.1%		0.6	
	1218	13.4		17.2		3.7		50.1%		0.8	
B50	**1266**	15.7	10.3%	12.3	-16.1%	6.2	14.0%	35.9%	-15.8%	0.3	-24.4%
	1228	15.0	10.8%	13.6	-17.5%	5.5	30.7%	39.8%	-17.2%	0.4	-32.7%
	1198	14.5	8.2%	14.7	-14.3%	4.9	32.8%	43.1%	-13.9%	0.5	-37.0%

A different view of the balances of the two alternative fuels can be carried out considering the conditions at which flue gases temperatures are very close. Table 4 reports this analysis. It appears very clear that B50 is more sensitive to the immersion of the WCT since its flue gases temperature drops as equal as the COG one with steps of 0.1 m instead of 0.2 m. In terms of exposed area of the WCT this means that, taking the respective 1270 K cases as reference, this area must increase by 97% for COG and by 64% for B50 to have a reduction of the flue gases temperature to ~1200 K. On average MILD combustion of B50 has thermal efficiency 7.4% lower than the COG one for similar T_{flue}. The losses result always higher for B50 but the ΔP is very close to the range of uncertainty of the estimated powers.

Concerning the flue gases content, CO averages resulting from the 5 minutes' samples are always lower than 40 ppmv. For these low values, trends of CO data are not relevant since the infrared gas analyser is not able to detect a stable concentration. Figure 4 shows the NOx concentrations corrected at 3% O2 for the discussed cases as a function of flue gases temperature. NOx does not exceed 7 ppmv. These results confirm the environment-friendly behavior of the MILD combustion, which is able to reduce thermal gradients and hot-spots by realizing a combustion distributed in a very wide volume thanks to the high recirculation rates. The uncertainties on the measures with 95% confidence interval are determined by the ISO-GUM approach [14] considering the error on the measure itself, the calibration curve and the calibration bottles. They result 45 ppmv for CO and 4 ppmv for NOx. The increase of the immersion of WCT and the consequent reduction of flue gases temperature always determine lower levels of NOx content. However, it is not easy to understand which is the main route of NOx formation at these very low temperature conditions. Thermal NO could be one of the sources [15], but flue gases temperatures are below 1500 K, thereby it is not possible to identify it as the main mechanism which contributes to NOx production. Other different routes, such as the N2O one, could have a significant role [16][17]. Moreover, for the fuels rich in H2, the NNH route [18] is probably another important mechanism for the NOx formation. Furthermore, Figure 4 shows that there is a different trend of NOx increase as a function of T_{flue} for the different fuels. The lowest slope belongs to the B50, for which the highest recirculation rates are expected. According to the GrandMaison's theory [10], whose results are reported in Table 2, the K_v is about 5, ~50% higher than the COG and NG one. The highest dilution, which can be obtained by an increased K_v or inert gases in the fuel, could explain the lowest increasing rate in terms of NOx. However, values are close to zero and considering the uncertainty of the measures no definitive conclusions can be drawn.

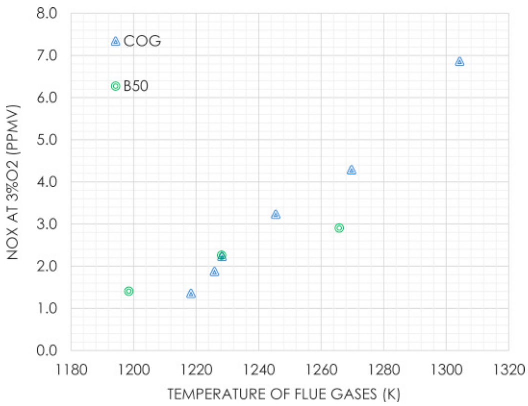

Figure 4: NOx at 3%O2 on dry basis measured at the exhaust.

6. Conclusions

A successful application of MILD combustion using two alternative fuels (COG and a 50%/50% blend of COG/BFG called B50) at very low air preheating temperature (673 K) and for different loads, simulated by water-cooled tubes (WCT) immersed inside the chamber, has been described and analyzed. The experimental tests were performed on a 30 kW laboratory-scale furnace with characteristics similar to industrial furnaces, keeping the inlet excess air at 15% and the same injection system. The immersion of the WCT was increased from the top of the furnace by steps of 0.1 m till the condition at which rising CO levels were recorded. The combustion chamber was also equipped with an optical access, used to take images from the OH* chemiluminescent emissions to track the position of the main reaction zones. Comparisons have been performed in terms of energy balance, thermal efficiencies, thermocouples measurements, OH* self-emission images, and NOx content.

All the tests reached the stable MILD combustion state and extremely low polluting emissions. The decrease of flue gases temperature according to the increased immersion of the WCT determines a reduction of the losses and an increment of the heat extracted by the load, with consequent rise of thermal efficiencies. The performance of the COG is very interesting since it guarantees stable MILD combustion till a maximum exposed area of the WCT ~60% higher than B50 maximum one. Tests show that for B50, rich in inert gases and whose *LHV* is 42% lower than COG one, the exposed area of the load must be on average 30% lower than the one used in the COG case to get similar flue gases temperature in the furnace. The role of H2, able to reduce the ignition delays and to speed up the combustion process, is clearly visible from the reported tests. Images of the main reaction zones, tracked by OH* self-emissions and resulting from the intersection of the two fuel jets with the central air one, depict the ability of H2 to keep these zones in a stable and correct position inside the furnace for different loads and the effects due to high content on inert gases in stretching and shifting them to the top of the chamber. Similar natural gas tests have been reported too to get a direct comparison with a classical fuel used in the industry. Furthermore, for all the presented tests measured NOx and CO concentrations at 3% O2 on dry basis are very low, confirming the environment-friendly behavior of the MILD combustion. Recorded levels are lower than 7 ppmv and 40 ppmv respectively for NOx and CO.

These results prove that a very clean MILD combustion can be successfully reached using low calorific hydrogen-containing fuels with different loads at low air preheating temperature, which can be guaranteed by standard heat exchangers since the required effectiveness is ~35%.

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