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Parametric Study of a Regenerative Burner Working in a Flameless Combustion

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Resumo: *The most used method to produce energy in the world is still the combustion process. Conventional combustion processes consist to burn fuel and air directly to produce heat, generating also emissions of gases causing the greenhouse effect, of CO, CO_2, NO_x, SO_x and other significant atmosphere emissions. The direct burn is widely used in the steel industry mainly in reheating furnaces. However, the most part of heat produced in the reheating process, about 60%, is rejected through the combustion products due to the limitations of the working temperature of the furnace. To heat recovery from the combustion products several methods can be employed such as steam producer, cogeneration, and so on. The problem in use this rejected heat in other process is that cannot be so efficient. The most attractive method is to use this rejected heat to preheat the combustion air to save fuel consumption. This avoids expend high investments in others devices to recovery the heat from the combustion products and their respective maintenance. However, increase the combustion air temperature in conventional combustion yield significant NO_x emissions, becoming the method an environmental problem.*
In the two past decades, another combustion technology has been employed to minimize the emission pollutants. The technology called Flameless Combustion, consists to burn the fuel in the poor oxygen environment through the elevated recirculation of the combustion products or even diluting the air combustion or fuel with some inert, such CO_2 or N_2, for example. This technology has advantage to decrease the environmental impact produced by the pre-heating of the combustion air, such as the reducing the NO_x and CO emissions.
This work proposes to study the behavior of the pilot scale furnace, burning Natural Gas, equipped with a heat exchanger (HE), operating under flameless combustion mode to evaluate the best operational condition. The main objective is simulating the heat treatment from industrial processes and, through this, evaluates the fuel economy using the heat from the combustion products to preheating the combustion air. The pilot scale furnace is equipped with a regenerative burner and the operational conditions to obtain the flameless combustion were established varying its parameters. The HE can operate in various thermal inputs to simulating the heat treatment of the materials.
The operational parameters selected were the excess of air and the switch time between the air injection and suction of the combustion gases, besides of the thermal load of the HE. The heat recover was estimated through the measurements of the temperature in the combustor regenerators. The variation of the excess of air has significant impact over the combustion air temperature, in the pollutant emissions, such CO and NOx. This variation has also an impact over the visual appearance of the flame, while the thermal load of the HE has no significant impact on the operation of the combustion chamber.

Keyword: *Flameless Combustion, Pollutant Emission, Heat Recovery, Regenerative Burner*

1. Introduction

The flameless combustion, also called Flameless Oxidation (FLOX®) (Wünning, 1997), High Air Temperature Combustion (HiTAC) (Tsuji et al., 2003), Moderate or Intense Low-Oxygen Dilution (MILD) combustion (Cavaliere e Joannon, 2004) is a technology able to reduce simultaneously the CO and NOx emissions. When the heat is recoverd from flue gases to pre-heat the combustion air, it's possible to reduce the CO2 emissions, due to the saving fuels. In the last two decades, the crescent numbers of publication have related different strategies to understand the dominating phenomena to obtain the flameless combustion. Studies like those conducted by Flamme (2001), demonstrated that the furnace operating under conventional combustion emits seven times more NO than those working under flameless combustion, at the same conditions, i. e., excess of air coefficient, fuel thermal input, geometric size of the furnace and recovering the waste heat to pre-heating the air combustion.

Nowadays, through the several studies as cited before and others like this present work, it's known that the technology is based on the ignition delay of the fuel with the oxidizer, due to the high recirculation rates in the furnace. The high recirculation rates, in the most cases because of high momentum of the air and/or fuel injection, as mentioned by Mi et al, (2009), Verissimo et al (2011), promotes the better distribution of the temperatures inside of the furnace, increasing the mixture between the fresh reactants and the combustion products. The secondary effect is that the reaction zone is distributed in a large volume, instead of a thin flame front, as occur in conventional flames, avoiding the peaks of the temperatures and, consequently, reducing the NOx emissions. The noise is also reduced, when compared with a conventional combustion.

Another experiments using regenerative or recuperative furnace in pilot and industrial scale obtained the flameless combustion regime with the aim to reduce the pollutant emission. One of them was the industrial scale furnace studied by Blasiak et al (2001) and (2004). The configuration to recover the heat from flue gases was using the pair of the burners situated in opposed side. The burners were operating with 200 kW of fuel thermal input, burning LPG. The study included experimental and numerical parts. They concluded that the better numerical model to describe the experimental results was the RSM/MPDF compared with k-ε/FRED. Rafidi et al. (2006) analyzed the positions of the regenerative burners in a furnace with 2.2m x 2.2m x 3m. The experimental measurements indicate the better uniformity of the temperature in the furnace when it was operating in flameless combustion, instead of the conventional combustion. It's important to mention that the furnace was covered with 300mm thickness of refractory and insulant material. Burggraf et al. (2007) studied the application of the flameless combustion to reheating slabs, burning natural gas or coke oven gas in an industrial furnace. The fuel thermal input in both cases was 1 MW. They could verify the reduction of NOx and the rise of thermal efficiency of the 80% at the furnace when works in flameless combustion. The furnace had 50% of thermal efficiency under conventional combustion mode.

This present work studied the parametric variation of the regenerative burner installed in a pilot scale furnace, burning Natural Gas. It could work in flameless and conventional combustion. The furnace was designed to simulate the heat treatment of the materials. The parameters studied were excess of air coefficient, the switch time of injection and suction of the burner and the thermal load in the heat exchanger.

2. Materials and Methods

Initially, a pilot scale furnace was projected and built to simulating the thermal treatment process. The processes can be simulated through a thermal load using cold air as fluid flow in the heat exchanger, with well controlled flow rate. The dimensions of the furnace are given at the schematic drawing at the Fig. 1. The Fig. 2 shows the imagens of the furnace used in this work.

The operation limits of the heat exchanger were determined by the capability of the blower to flow cold air. To establish the exhaust temperature and the thermal load in the heat exchanger, theoretically, it was employed the Gnielenski method.

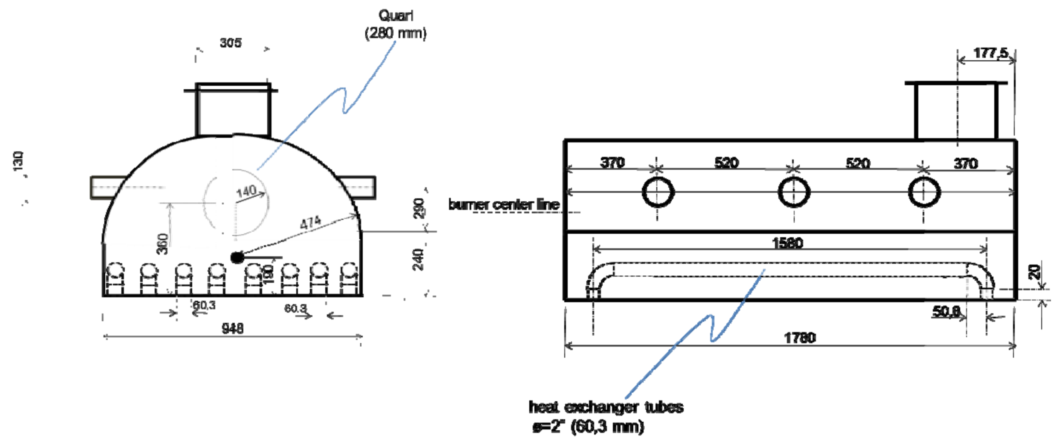


Figure 1 – Schematic representation of the furnace equipped with a heat exchanger.

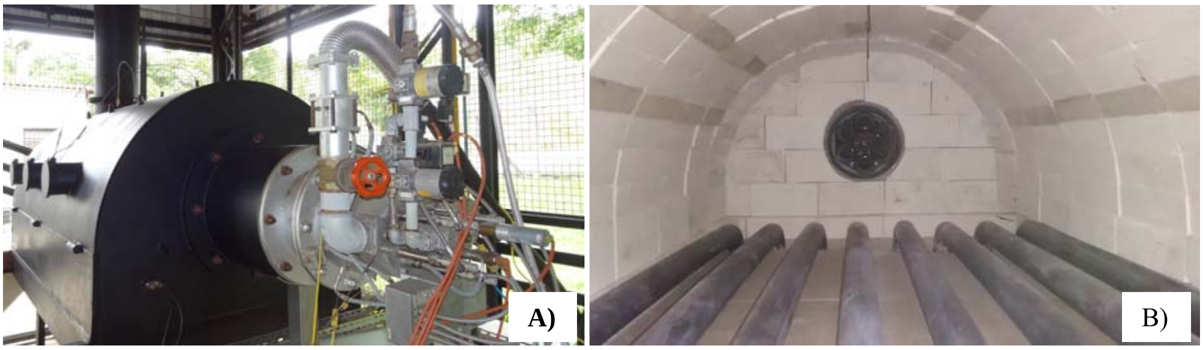


Figure 2 – Pictures of the furnace. A) External view of the furnace. B) Inner view of the furnace. It's possible to see the tubes of the heat exchanger.

Gnielenski's method considers the roughness of the tube, among others parameters, and can work in a wider range of flow rates. To evaluate the thermal load in the heat exchanger was need to consider the characteristic of the flameless combustion. As the temperatures gradients are much attenuated, the entire furnace was considered be at the same temperature. Thus, the temperature inside the furnace is considered constant. Wünning e Wünning (1997), Cavalieri e Joannon (2004), Weber et al., (2005), Zhang et al., (2007), Verissimo et al., (2011) indicate that the temperature inside of the furnace under flameless combustion, burning gas fuel, is between 1100 ºC and 1300 ºC. So, the surface tube was assumed be 1200 ºC.

With these associations the heat exchanger is a problem with of the heat transfer of the tube with constant temperature in its surface. The Gnielenski method is described through the Eq. 1:

$$NU_D = \frac{(f/8)(\mathrm{Re}_D - 1000)\,\mathrm{Pr}}{1 + 12.7(f/8)^{1/2}\left(\mathrm{Pr}^{2/3} - 1\right)} \tag{1}$$

where NU_D is the Nusselt's number, f is the friction factor of the tube, Re_D is the Reynold's number and Pr is the Prandtl's number. Through the NU_D it's possible to determine the thermal load through the Eq. 2,

$$Q = \dot{m}_{air} C_p \Delta T \tag{2}$$

where Q is the heat transfer rate, $\dot{m}_{air}$ is the mass flow rate o fair in the heat exchanger, C_p is the specific heat and ΔT is the difference between the exhaust temperature of the heat exchanger and surround temperature, that was considered be around 25 ºC. The results are shown at the Fig. 3. Note that the increase of the thermal load is directly proportional to the volumetric flow rate.

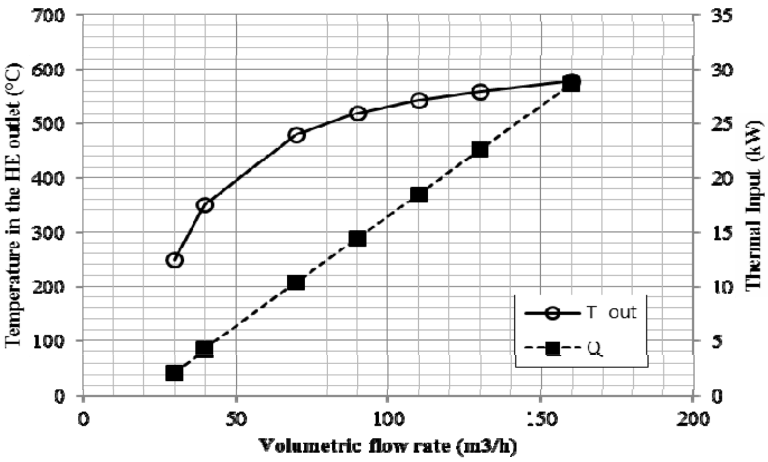


Figure 3 – Temperature and thermal load of the heat exchanger with the volumetric flow variation.

It was used a regenerative burner to recover the heat contained in the exhaust gases to pre heating the combustion air. The burner was manufactured by WS and has six nozzles divided in three for injection and three for suction that switch with pre-programed time. A schematic drawing about the burner working is shown at Figure 4 and the Figure 5 show a picture of the behavior of the flame during the heating up of the furnace. During a pre-determined time, three consecutives superior nozzles inject air inside of the combustion chamber, while at the same time the rest, localized at the inferior part, are making suction of the hot combustion gases, to recover the heat contained in them. After such time, the nozzles that were injecting pass to make suction and vice-versa, closing the cycle. Here, this cycle is denominated *"switch time"*.

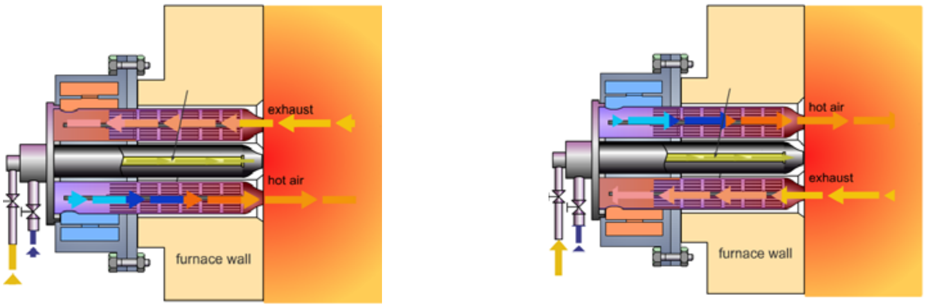


Figure 4 – Schematic drawing about the working of the regenerative burner (WS, 2013).

The fuel flow rate was measured using a flowmeter with variable tube. To measure the combustion air flow rate it was used a micro venture located close to the burner intake. The air flow rate of the heat exchanger it was used a vortex flowmeter manufactured by Yokogawa. The measurements of the different points of temperatures of the furnace and to monitoring the flow temperatures were used thermocouple type K. To collect the sampling of the thermocouples were used a data logger manufactured by NOVUS, model field logger 512k, that converts the analogic to digital signal. Two thermocouples were positioned at the nozzles to monitoring the air combustion temperature and the exhaust temperature, as shown at Figure 5. The T1 thermocouple is positioned in the nozzle above the burner, while the T2 thermocouple is positioned below the nozzle of the burner.

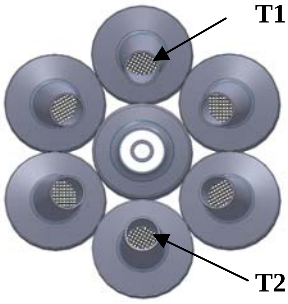


Figure 5 – Thermocouples located at the nozzles of the burner.

The specifications of the analyzers are related at the Table 1. The sampling of the gases for the measurement of exhaust mean O_2, CO_2, HC, CO and NOx concentrations was achieved using a stainless steel water-cooled probe. The analytical instrumentation included a magnetic pressure analyzer for O_2 measurements, a non dispersive infrared gas analyzer for CO_2 and CO measurements, a flame ionization detector for HC measurements and a chemiluminescent analyzer for NOx measurements. The exhaust gases flowed to drying system before to be determined its concentration by the gas analyzers.

Table 1 – Specifications of the gas analyzers.

Manufactured by	Model	Pollutant	Sensibility	Precision	Repeatability
Sick	SIDOR	CO	100 ppm fs*	1 %	1%
Sick	SIDOR	CO_2	50 ppm fs*	1%	1%
Rosemount	400A	UHC	4ppm on 1% fs	1%	1%
Sick	SIDOR	O_2	0,01%	1%	1%
Rosemount	951A	NOx	0,1 on 10ppm fs	0,5%	1%

*fs (full scale).

3. Test conditions

The conditions of the burner operation are given at the Tab. 2. Basically, the runs were based on the switch time, excess of air and the variation of the thermal load in the heat exchanger. To verify the effects of the burner operation, all of parametric conditions were modulated. The fuel thermal input was fixed at 70 kW. The air excess coefficient was varied with the flow rate of the combustion air. The switch time was varied with 8, 10 and 12 seconds. The variation of the air temperatures inlet combustion and also the exhaust temperatures are given at the Fig. 6.The temperature of the combustion air for short intervals of the switch time is lower than those with longer.

Table 2. Test conditions.

Run	Switch time (s)	λ	Thermal Input (kW)	HE Thermal Input (kW)
1	10	1.6	70	0
2	10	1.7	70	0
3	10	1.8	70	0
4	10	2.0	70	0
5	10	2.1	70	0
6	10	2.2	70	0
7	10	2.3	70	0
8	10	2.4	70	0
9	10	1.8	70	0.14
10	10	1.8	70	2.18
11	10	1.8	70	6.26
12	10	1.8	70	10.33
13	10	1.8	70	16.45
14	10	1.8	70	25.60
15	10	1.8	70	28.27
16	8	1.6	70	0
17	8	1.7	70	0
18	8	1.8	70	0
19	8	2.0	70	0
20	8	2.1	70	0
21	8	2.2	70	0
22	8	2.3	70	0
23	8	2.4	70	0
24	12	1.6	70	0
25	12	1.7	70	0
26	12	1.8	70	0
27	12	2.0	70	0
28	12	2.1	70	0
29	12	2.2	70	0
30	12	2.3	70	0
31	12	2.4	70	0

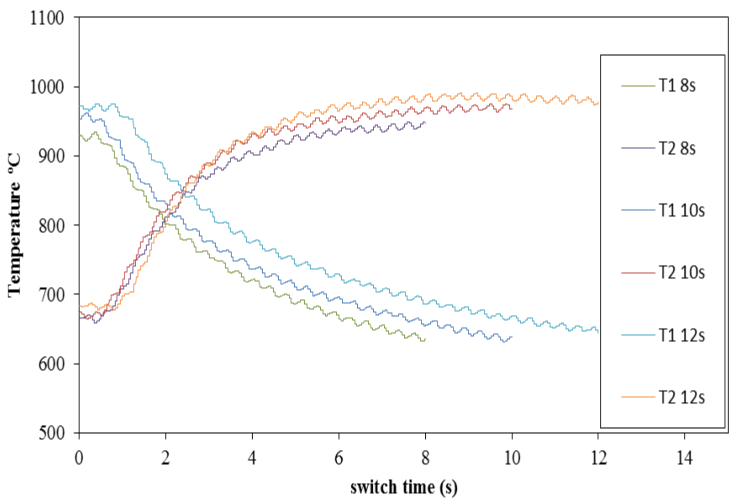


Figure 6 – Temperatures at the nozzles with the switch time variation.

The variation of the thermal load in the heat exchanger was made through the variation of the air flow rate, as was previously calculated in the Figure 3.

4. Results and Discussion

The flameless combustion mode is not obtained instantaneously, being necessary to heat up the furnace with a conventional combustion until reach to auto ignition temperature. To ensure that the interior of the furnace is in auto ignition temperature, the thermocouple was placed at the coldest point of the furnace. In this case, the auto ignition temperature was 870 ºC. The difference between a conventional combustion and flameless combustion is shown at Fig. 7. The images were obtained through of the visor located at the burner's head. However, another visor was built at the bottom of the furnace to visualize all the combustion process.


A)


B)

Figure 7 – Difference between the conventional combustion and flameless combustion.

However, one can observe the differences of non-visible-flame and visible-flame when the quantity of air inside of combustion chamber is varied, as one can see at the Fig. 8. Note that a flame appears and become visible from λ = 2.0 onwards. In the last picture, it's possible to see a yellowish flame, what suggest the soot formation.

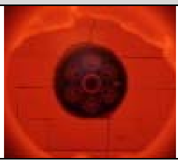
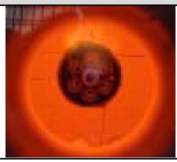
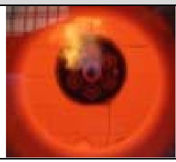
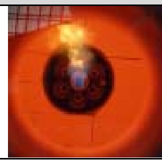
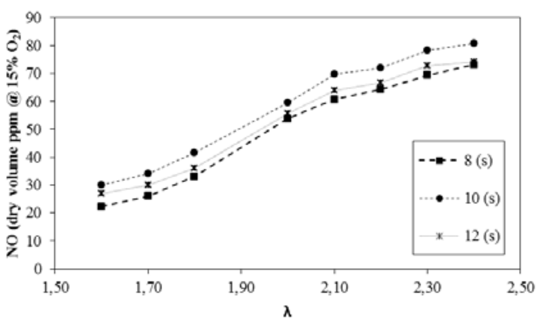
λ	*1.6*	*1.8*	*2.0*	*2.2*	*2.3*	*2.4*
Switch 10s						

Figure 8 –Visibility of the flame with the variation of excess of air.

In order of the Fig. 8, it's very important to say that to obtain the flameless combustion is necessary to dilute the fresh reactants, in this case, with the combustion products. However, if the dilution is not enough, the flame become visible, the temperatures' gradient inside of the furnace increase and, consequently, the burner working out of the flameless combustion mode. In the Fig. 9 show the pollutant emission with the variation of the excess of air. Note that the NO emissions increase with the excess of air increase; while the CO remain without significantly change, indicating that the burner is out of flameless combustion for high excess of air, namely from λ = 2.0.



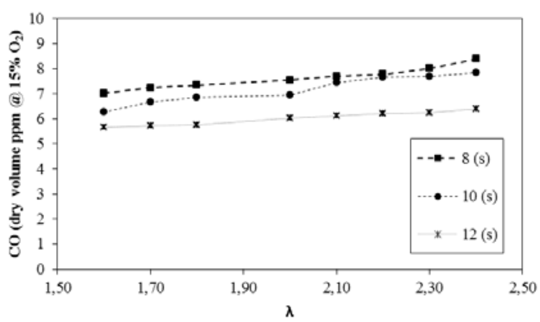


Figure 9 – NO and CO emissions with excess of air coefficient variation.

As mentioned before, a heat exchanger was used to simulate the heat treatment of materials. In the present case, the HE worked with thermal load from 2.5 kW until 28.27 kW. The result of the NO emissions, for the switch of 10s and 80% of the excess of air is shown at Fig. 10. Note that has no variation of the pollutant emissions. One of the reasons is due to the operation working under low NO emissions, another is the low thermal input imposed in the HE. It's important to observe that what we know until now, the most appropriate mechanism to describe the NO emissions is via N_2O as intermediate. This mechanism is valid for high excess of air and temperatures between 1000 and 1300K. To explain the NO formation in process with temperatures relatively low, Löffler et al (2000) and Yang and Blasiak (2005) used numerical simulation witch explain the NO formation through the N_2O intermediate. The simulations were made considering the excess of air between 9% and 25%, with pre-heated air around 100 ºC. The conclusion of the cited authors is that the better results is taken when a model consider the N_2O as intermediate reaction to predict the NO formation, especially in the reaction zone.

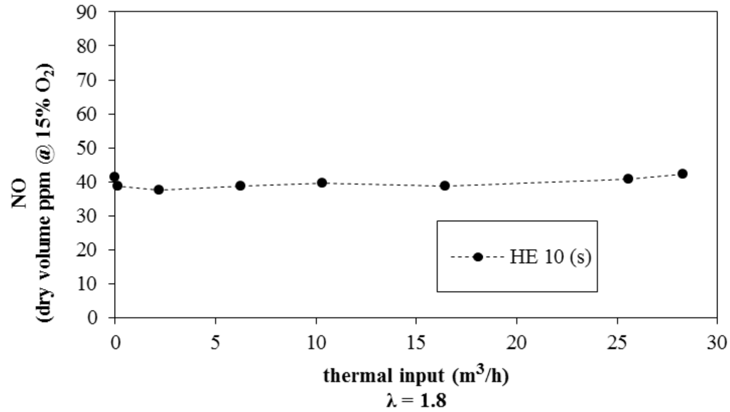


Figure 10 – NO emissions with variation of the thermal input in the heat exchanger.

The heat recovery through the combustion air can be calculated using the Eq.2. The Eq. 3 is used for correct nomenclature for the combustion air regenerated.

$$Q_{air,reg} = \dot{m}_{air}\rho_{air}C_p\left(T_{air,reg} - T_{sur}\right) \tag{3}$$

Where $\dot{m}_{air}$ is the air flow, ρ_{air} is the air density, C_p is the specific heat of air, $T_{air,reg}$ is preheating air while using the regenerative burner, and T_{sur} is the surround temperature. Analyzing the Eq. 3 one can see that the heat in the air is directly proportional to the $\dot{m}_{air}$ and $T_{air,reg}$. The measurements of the air combustion temperature and the heat contained in the air combustion, through the regeneration, are given in the Tab. 3. The measurements were taken following the operational conditions from the Tab. 2. It's important to note that the heat regenerated increases with the air excess and the temperature, as discussed, but not all the operational conditions are in flameless combustion mode.

Table 3 – Temperature inlet and heat recovery from the combustion products.

		$T_{air,reg}$ (K)			$Q_{air,reg}$ (W)		
		Switch Time (s)			Switch Time (s)		
λ	$\dot{m}_{air}$ (kg/s)	8	10	12	8	10	12
1.6	0.03828	1062.15	1067.15	1089.15	11572.44	11600.87	11723.71
1.7	0.04067	1053.15	1074.15	1096.15	12240.05	12367.12	12496.39
1.8	0.04306	1046.15	1081.15	1103.15	12913.63	13137.87	13273.45
2.0	0.04785	1037.15	1062.15	1084.15	14284.09	14465.54	14620.14
2.1	0.05024	1033.15	1057.15	1065.15	14966.45	15150.49	15210.49
2.2	0.05263	1026.15	1052.15	1046.15	15620.97	15831.58	15783.66
2.3	0.05503	1021.15	1047.15	1027.15	16290.03	16511.79	16341.93
2.4	0.05742	1015.15	1042.15	1008.15	16942.91	17185.07	16878.62

The results reveal that the highest heat recovery is reached when the burner operating with switch time of 10s and with 140% of excess of air. However, in this condition the NO emission is elevated, when compared with the rest of the results, besides in this condition the burner is not working in flameless condition. In the situation of the flameless combustion, the most appropriate condition is when the burner is working until λ=1.8, which the best results is for switch time at 12 seconds.

5. Conclusions

A combustion system was studied under conventional combustion and flameless combustion mode. The runs show that the system can work under flameless combustion regime for low excess of air bellow of λ=1.8. When the combustion system is operating under flameless combustion, the NO and CO emissions is low as well. However, for high excess of air, the system operates in conventional combustion, due to the reactants not be well diluted with the combustion products, besides recovery more heat from the combustion products. When the system is operating with the heat exchanger, it was not observed any variation of the pollutants emissions for the thermal loads studied here.

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