Still Furnace Optimization

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Abstract. *Aiming better uniformity of the heat transfer fluxes inside still furnaces, an experimental work was carried out in a pilot scale furnace. The methodology used was based in the modification of the mixture processes between fuel and air in order to smoother the reaction rates along the flame and, therefore, the gas temperature profiles and the heat transfer fluxes on the wall. The mixture process was altered changing the angle between the nozzle sprays` and making the use of three concentric air streams (primary, secondary and tertiary). Also, measurements of the CO, NOx and particulate material were carried out searching for a good compromise among the better solutions for heat transfer fluxes which would result in acceptable levels of emissions for these pollutants. The reference for comparisons was an atmospheric industrial burner commonly used in still furnaces that was tested in the same furnace. The better results in terms of heat transfer fluxes revealed that the lower possible amount of air must be supplied to the secondary air flow. The amounts of primary and tertiary air flows must be carefully divided so the primary air flow rate does not reach the blow out limit. The addition of swirl always resulted prejudicial for the main objective. Finally, the angle between nozzle spray's must be reduced to the minor possible value that do not yield a significant coalescence of the spray's drops*

Keywords*: optimization, still furnaces, heat transfer fluxes*

1. Introduction

Nowadays in Brazil there are several situations where the still furnaces work on their limit, constituting bottle necks for refinery throughputs.

In general, these operational limits do not come from limitations in the mass flow rates of air and fuel, neither from the exhaust systems capability. In fact the limits referred in this article are related with the non-uniformity of the heat transfer fluxes to the coils inside which the process fluids are flowing (liquid or gaseous) to be heated. These coils are disposed uniformly over or between the internal walls in combustion chamber of the furnaces, constituting the so called "furnace radiation zones".

The flames, generally vertical, produced by the burners, have inevitably non-uniformity properties distribution (like temperature, chemical species concentrations, local emission and absorption radiation coefficients). As a result some peaks in the heat transfer fluxes over the coils will exist, as a consequence of the mainly heat transfer mechanism inside these furnaces being the radiation one.

These peaks generate two undesirable facts: (1) high skin temperatures, what are a risk for the integrity of the tubes; and (2) over-heating of the fluid flowing inside them; these phenomena generating a progressively coke formation over the internal wall of the tubes, increasing the pressure loss of the fluid flow. In the limit condition, a significant reduction of the mass flow rate of the process fluid will occur.

In summary, for remotion of the bottle neck to increase the production of these furnaces will consist in the attainment of the more uniformity heat transfer fluxes distribution over the coils. After words it will be possible to increase the power of the burners.

In order to obtain a greater uniformity of the heat transfer fluxes over the coils, the solution proposed in this work was the modification in the mixing process between fuel and air to soften the reaction rate along the flame.

To achieve this objective, a new air distribution box for the burner was developed in order to have not only two air streams (the common arrangement of the present still furnace burners), but three air streams. Also a spray angle of the nozzles was explored combined with these air streams configurations.

Finally, it is important to notice that the solutions obtained were confronted with pollutant emissions they produced. The better solutions must be those in which a compromise can be established.

2. Methodology and Experimental Setup

This research work was strictly experimental [IPT (2004)]. The main purposes of research, based in the previous discussion presented at the introduction, were: (1) to act on the air flow supplied to the burner; and (2) to act on the angle between the sprays produced by the nozzle. The problem of the heat flux picks on the walls of a still furnace is strictly accomplished to the fact that in the same regions that these picks appear there are high conversions rates of the fuel in combustion products. High reaction rates will produce high energy liberation rates, mainly in the form of heat. As a consequence, locally high heat fluxes will be produced, normally near the root of the flame. In the subsequent regions, as the fuel was strongly consumed near the initial region, the rate of reaction tends to become gradually weak, and the heat fluxes over the wall will suffer an intense attenuation in their values.

The fuel utilized was the Brazilian oil type 1A, whose average composition in mass base is: 87 % of carbon; 11 % of hydrogen; 1 % of sulfur; and 1 % of nitrogen.

Based on these phenomena, it would be ideal to gradually supply air to the flame, in order to initially reduce the rate of reaction, therefore reducing the heat fluxes in this initial region. To reach these objectives a new burner was designed and built, in which there were three independent air compartments, concentric to the fuel spray. Specifically, the first air stream joins the spray at the root of the flame and is called primary air; the second air stream circumscribe the first one and is called secondary air; and finally the third air stream is supplied far from the other two, and is called tertiary air.

The bare actuation on the three suggested air streams is not enough to give good results in terms of heat fluxes distribution. To achieve better results it is also mandatory to act on the spray angle produced by the nozzle. Hence, three nozzles with different angle between the sprays, 30°, 40° and 50°, were designed and built. Figure 1 illustrates, schematically, the combination of these features upon the experiment.

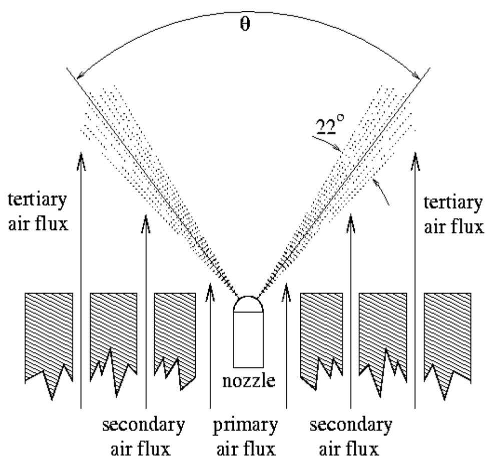

Figure 1. Schematic draw of the air streams and the angle between the sprays, θ.

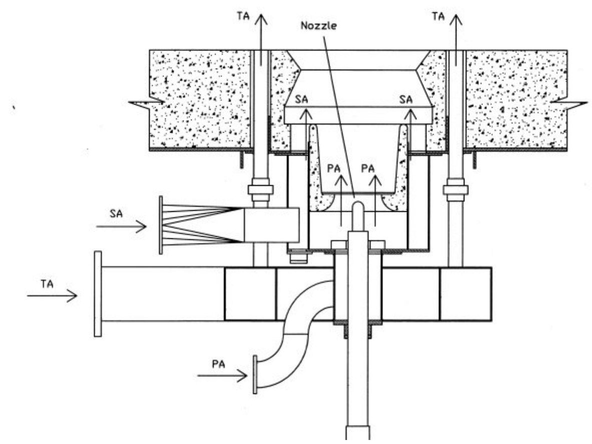

Figure 2. Schematic draw of the air boxes of the constructed burner. In the figure, PA, SA and TA mean primary, second and third air streams, respectively.

Combining the air flow rates control for the three air streams with the angle θ between the sprays it is possible to control more efficiently the reaction rate. It is also important to notice that great values of θ are not desirable regarding the achievement of good heat fluxes distribution, once for this kind of configuration the fuel will be strongly consumed in significantly short distances from the burner port.

Figure 2 shows the burner fitted with the three air streams. During the experiments, the three air flow rates were independently controlled, therefore the air partition supplied to the flame could be adjusted to the goal of each experiment.

The proposal of this methodology can also be understood by means of the burn-out coefficient. This coefficient takes in account the mass fraction of the fuel burned up to a position z along the longitudinal axis of the furnace. On the situations where there are heat flux picks near the burner, the burn-out coefficient reaches high values also near the same region. When the proposed method of air staging is used, the rate of fuel oxidation is reduced and, consequently the burn-out coefficient is attenuated [Van Dongen (1983)]. Figure 3 illustrates this phenomenon.

Figure 4 shows the pilot test furnace utilized in the experiments for the heat fluxes measurements, which were calculated from the variation of the water temperature in each module (see Figure 4). For each module the water mass flow rate, $\dot{m}$, and its inlet, T_i, and outlet, T_o, temperatures are known. As the internal superficial area, A, of each module is known, the net heat flux, $\dot{q}''$, for a generic module j is,

$$\dot{q}''_j = \frac{\dot{m}_j C_{p,a}\left(T_{o,j} - T_j\right)}{A_j} \tag{1}$$

where $C_{p,a}$ is the water specific heat at average temperature between T_o and T_i. The measurement of the water mass flow rates was made through calibrated orifice plates. The temperatures measurements were made using T thermocouples.

The results obtained for each operational condition must be compared not only with the maximum net heat flux and its distribution along the longitudinal axis of the furnace, but also with the total heat transfer rate inside the furnace. One condition will be better than an other if there is a reduction in the heat flux pick value (or it remains invariable) combined with an increase in the total heat transfer rate (or it remains invariable). Calling $\dot{Q}_t$ the total heat transfer rate and $\dot{q}''_{\max}$ the heat flux pick, the relation $\dot{q}''_{\max}/\dot{Q}_t$ will express exactly the uniformity. The minor this parameter, the better will be the new operational condition. The value of $\dot{Q}_t$ is calculated as,

$$\dot{Q}_t = \dot{m}_t C_{p,a}\left(\overline{T}_o - T_i\right) \tag{2}$$

where $\dot{m}_t$ is the total water mass flow rate and $\overline{T}_o$ is the average water outlet temperature. All water outlet flows (see Figure 4) go to a common exit duct, where $\dot{m}_t$ and $\overline{T}_o$ are measured.

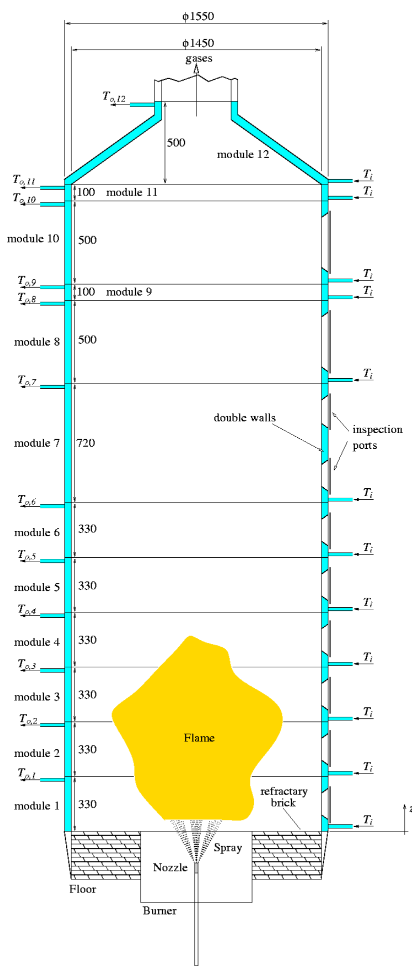

Figure 4. Schematic draw of IPT pilot test furnace.

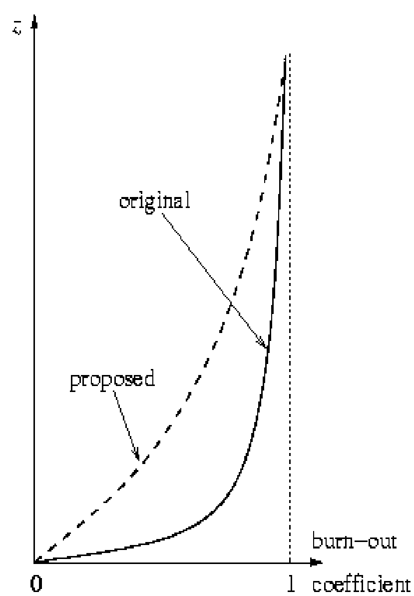

Figure 3. Idealized comparison of the burn-out coefficient in the original condition (not staged flame) and proposed condition (staged flame).

Other important variables to be considered are those related with the pollutant concentrations at the exit section. In this research work, the concentrations of CO, NO_x and Particulate Material (PM) where measured with an appropriate probe placed at the exit gases duct (see Figure 4). The importance to measure these variables is justified by the fact that the better operational condition in terms of heat fluxes distribution must also be followed by adequate pollutant emissions.

Table 1 shows the operational conditions of the experiments realized. In this table, $\dot{m}_f$ means fuel (oil) mass flow rate; $\dot{m}_s$ is the atomization steam mass flow rate; *ALR* is the ratio between $\dot{m}_s$ and $\dot{m}_f$; $\dot{m}_a$ is the total air mass flow rate; *PA*, *SA* and *TA* are the percentages of total air mass flow rate for the primary, secondary and tertiary air streams, respectively; θ is the angle between the sprays (see Figure 1); λ is air coefficient. Generalizing the code name for the tests by P-A-F-E-X, it follows that: P identify air stream partition (there were 12 tested partitions); A identify the angle between the sprays (30˚, 40˚ or 50˚); F identify the fuel mass flow rate; E identify, qualitatively, the air excess, high (H) or low (L), the parameter λ being its quantitative value; and X identify the presence, with the letter S, or not, of swirl in the burner. The tests numbered named 7-50-70-L and 7-50-70-H refer to an aspirated (atmospheric) commercial burner for comparison with the results for the other tests, made with the burner shown in Figure 2. The values chosen for the air partitions obey a natural way in the search for better conditions in terms of heat fluxes distribution. The partition number 1 was chosen as reference condition. It is in accordance to the practiced partition in the industrial still furnaces operating with aspirated burners (partition number 7).

Table 1. Operational conditions of the experimental tests.

Test	$\dot{m}_f$ [kg/h]	$\dot{m}_s$ [kg/h]	*ALR*	*PA* [%]	*SA* [%]	*TA* [%]	$\dot{m}_a$ [kg/h]	θ [deg]	λ	Heat release [kW]
1-50-70-L	70.0	28.9	0.41	50	50	0	1021.1	50	1.0834	797.5
1-30-70-L	70.1	35.3	0.50	50	50	0	999.5	30	1.0747	797.8
1-50-70-H	70.3	29.6	0.42	50	50	0	1227.0	50	1.2494	800.1
2-50-70-L	70.1	29.1	0.41	30	70	0	1030.9	50	1.0823	798.8
2-50-70-H	70.3	29.0	0.41	30	70	0	1223.5	50	1.2330	800.4
3-50-70-L	70.1	28.9	0.41	30	40	30	989.9	50	1.0797	798.2
4-50-70-L	70.1	28.8	0.41	20	20	60	1066.2	50	1.1328	798.4
40-30-70-L	70.2	34.5	0.49	20	20	60	1061.4	30	1.1084	798.9
4-30-77-L	77.4	35.0	0.45	20	20	60	1201.0	30	1.1218	881.5
4-30-70-H	70.1	32.3	0.46	20	20	60	1200.0	30	1.2528	798,4
4-30-70-L-S	70.0	37.0	0.53	20	20	60	1083.0	30	1.1273	796.7
4-30-70-H-S	70.5	34.5	0.49	20	20	60	1195.0	30	1.2562	802.9
5-50-70-L	70.0	29.8	0.43	60	40	0	1028.3	50	1.0890	796.7
5-50-77-L	77.0	34.2	0.44	60	40	0	1190.5	50	1.1193	876.9
5-50-70-H	70.2	29.6	0.42	60	40	0	1216.5	50	1.2428	799.5
5-50-70-L-S	70.3	35.0	0.50	60	40	0	1023.0	50	1.1218	800.6
5-50-70-H-S	70.4	34.5	0.49	60	40	0	1198.0	50	1.2494	801.8
5-30-70-L-S	70.5	35.0	0.50	60	40	0	1029.0	30	1.1164	802.9
5-40-70-L-S	70.2	34.5	0.49	60	40	0	1057.0	40	1.1273	799.5
6-30-70-L	70.1	34.8	0.50	36	12	52	1077.3	30	1.1236	798.0
6-40-70-L	70.3	31.6	0.45	36	12	52	1080.5	40	1.1358	800.1
6-30-77-L	77.2	35.0	0.45	36	12	52	1187.0	30	1.1164	879.2
7-50-70-L	70.5	34.0	0.48	------------------------				50	1.1137	801.2
7-50-70-H	70.4	33.5	0.48	------------------------				50	1.2492	801.2
8-50-70-L	70.1	35.5	0.51	20	80	0	1065.0	50	1.1218	798.4
8-30-70-L	70.2	34.0	0.48	20	80	0	1087.0	30	1.1384	799.5
9-50-70-L	69.8	35.0	0.50	40	60	0	1043.0	50	1.1164	794.9
9-30-70-L	70.1	34.5	0.49	40	60	0	1061.0	30	1.1263	798.4
10-30-70-L	70.6	35.0	0.50	30	20	50	1058.0	30	1.1328	804.1
11-30-70-L	70.6	34.5	0.49	40	20	40	1019.0	30	1.1273	804.1
12-30-70-L	70.1	34.0	0.49	44	20	36	1063.0	30	1.1273	798.4

3. Results

The results for the heat fluxes measured along the furnace axis are shown by the Figures 5 to 7 and 9 to 11. For all results shown it is clear the strong heat transfer rates for the first modules of the furnace and the decreasing of the heat fluxes as z values become greater. Also, for all results recuperation occurs, although small, near the end of the furnace (module 12, see Figure 4). The behavior is due to the shape factor of the last module that sees almost all the internal volume of the combustion chamber.

Figure 5 shows the heat fluxes results for the reference air partition (1-50-70-L and –H, blown burner) and that for an aspirated burner (7-50-70-L and -H). It is clear form the results shown that there is similar qualitative behavior for the four experiments. Despite the quantitative differences it is possible to conclude that the air partition chosen for the blown burner partition (1-50-70) adequately represents the operation practice of the refineries. Also the results show that the total heat exchanged with the furnace wall is greater for the proposed burner than for the aspirated one. Finally the results prove that low air excess flames have always greater heat fluxes than those for high air excess ones in the regions near the flame root (low z values).

Figure 6 show the comparison between the reference air partition (1-50-70) and all the other partitions with primary and secondary air streams only. The results shown are for both low and high air excess, and for a fixed angle between the sprays, $\theta = 50°$. Again it is easy to see that the results for partitions with high air excess have a smaller heat flux pick than their low air excess pair. Hence, for all cases, except for those with swirl, the increase in the air excess reduces the total heat transfer rate to the walls. This behavior can be understood by two factors [Hottel and Sarofin (1967)]: (1) the reduction of the absorption/emission coefficients of radiation along the flame; and (2) the gases temperature reduction in the combustion chamber. On the other hand, the results for swirl addition don't have the same trend, although they always have worsened the results compared with the reference condition. The air partitions 2, 8 and 9 have greater secondary air flow rates than the reference condition (partition 1) and partition 5. As it can be seen in Figure 6 their results are worse than those obtained for those partitions. The explanation here refers to the fact that when a great part of the air is supplied to the second stage the reaction rate is increased near the root of the flame. In other words, more air in the second stages leaves to more intense mixture processes of fuel and air in the early regions of the flame, therefore increasing the heat fluxes in these regions. The swirl effect on the heat fluxes distribution has an analogous explanation, since it also promotes a strong mixture processes. Regarding the objective of this work, these results indicate that swirl and high secondary air flow rates are prejudicial.

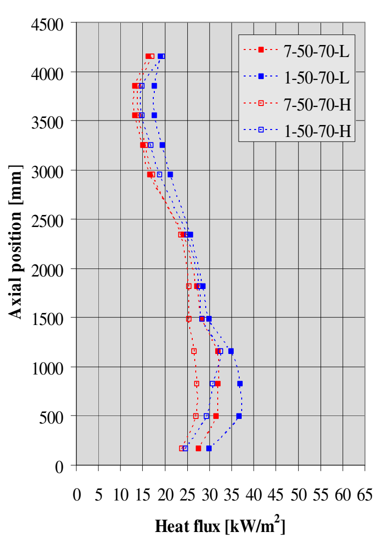

Figure 5. Comparative results for the reference partition (1-50-70) and the aspirated burner (7-50-70).

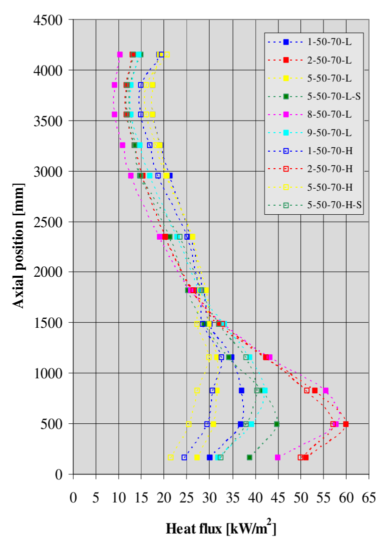

Figure 6. Comparison between all partitions using only two air streams (primary and secondary).

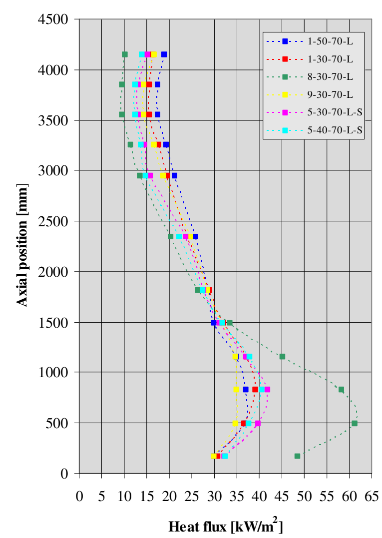

Figure 7. The influence of θ for some partitions working with primary and secondary air streams.

Figure 7 presents the influence of θ for some partitions with primary and secondary air streams only. These experiments were not realized for high air excess, since its influence was already established for the previous tests. As the results show there is not significant influence of θ over the condition of two air streams. Again the addition of the swirl worsens the results confirming the expectations.

Figure 8 resumes the results of Figure 6 showing the classical experiment regarding two air streams. Here a new parameter, $\dot{q}''_{max}/\dot{Q}_t$, is shown against the primary air ratio, $\dot{m}_{pa}/\dot{m}_a$. The curves in this Figure allow the quick conclusion that increasing primary air ratio is a good choice for the objective target. The same Figure also evidences two important asymptotes: the first for primary air fraction lower than 0.3 and the second for the same parameter higher than 0.6. Consequently it can be said that the quantity of experiments carried out with two air streams was enough for the complete characterization of the phenomenon. It is important to notice that all tentative to increase the primary air fraction beyond 0.6 always resulted in the flame blow-out.

Summarizing the results for two air streams (Figures 5 to 8) it is possible to say that:

1. the reference condition was satisfactory for comparison with the results obtained for the other partitions tried;
2. it is better to operate the burner with low than high air excess;
3. increasing the secondary air ratio is prejudicial to the heat fluxes distribution, although it is good to increase the total heat transfer between the gases and the furnace walls;
4. addition of swirl acts in the same way of the secondary air ratio;
5. the influence of the angle between the sprays it is not significant.

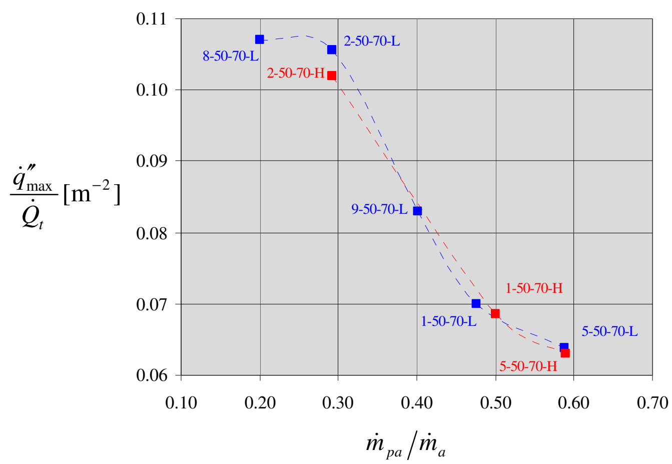

Figure 8. Performance parameter results for partitions with only two air streams.

In the sequence the influence of the three air streams was explored. The results are shown in Figures 9 and 10.

Figure 9 shows the results for the first two air partitions with three air streams (3 and 4) compared with the reference one. In this Figure it is also shown the influence of $\theta = 30°$ and $\theta = 50°$ and the swirl addition. It is interesting to notice that when maintaining $\theta = 50°$, partitions 3 and 4 caused worse results for heat fluxes than the reference condition. Here is important to pay attention in the fact that partitions 3 and 4 are opposite regarding the quantity of air supplied for the tertiary air stream: 30 % for partition 3 and 60 % for partition 4. Hence, independently of the magnitude of air supplied to the third stage, the influence of θ is still dominant. To understand this just see Figure 1. High values of θ maintain the mixture process of air and fuel near the flame's root, therefore resulting in an increase of heat release in this region. Following the idea to stretch the reaction zone along the axial axis of the furnace, it was used $\theta = 30°$. In the same Figure partition 4 with $\theta = 30°$ is shown. The results confirmed the expectations where the heat fluxes distribution became more uniform with a reduction in the heat flux pick. Finally, the gain obtained with three air streams and a small value of θ was lost when swirl was imposed as can be seen for the 4-30-70-L-S curve, although for 4-30-H-S the result is lightly better than the reference partition.

At this point it was clear the way to follow: to decrease θ; to decrease the amount of air to the second stage, maintaining the stability of the flame; to increase the quantity of air to the first stage up to the blow-out limit; and to use the remaining air in the third stage.

Figure 10 shows exactly the exploration of these concepts. Partition 6 use the minimum value for the secondary air ratio where the stability of the flame was not compromised (see Table 1). For partitions 10, 11 and 12, the primary air ratio was gradually increased and the third one decreased while the second was fixed at 20 %, up to the blow-out limit. The results shown that the ideas previously explored were correct. Except for partition 6-40-70-L, all the others were better than the reference one for the heat fluxes distribution. It is important to notice that the blow-out was reached with 60 % of primary air fraction when using only two air streams. Here, with three air streams this blow-out limit was found at 36 % of primary air fraction, therefore this limit is dependent on the type of air partition used. As a disadvantage, the increase of the primary air ratio leaves to a decrease in the total heat transfer rate for the furnace walls, hence a compromise must be established in order to achieve a particular application.

Summarizing, the results for three air streams will be better than the use of two if:

1. the angle between the sprays is reduced. In this work 30° gave better results than 50°;
2. a reduction is applied in the secondary air ratio up to the stability limit of the flame;
3. the primary air ratio was the maximum for what there is not a blow-out of the flame;
4. depending on the application, a compromise between the primary and tertiary air fractions must be taken,

always looking for a reduction in the heat flux pick while there is not a significant reduction on the total heat transfer rate inside the furnace.

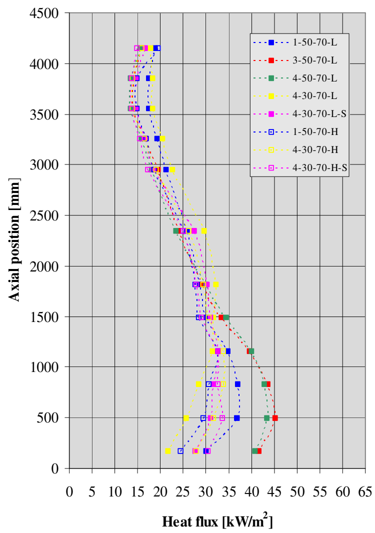

Figure 9. Results for the first two air partitions with three air streams (3 and 4) compared with the reference one.

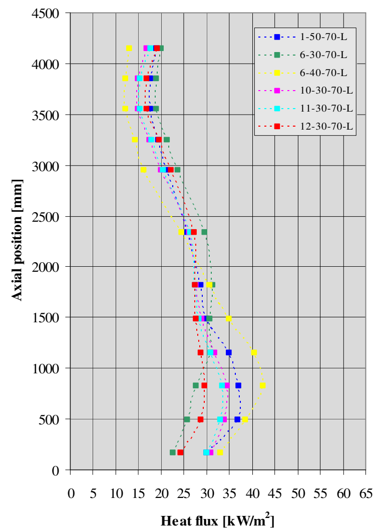

Figure 10. The best results for three air streams with θ = 30°.

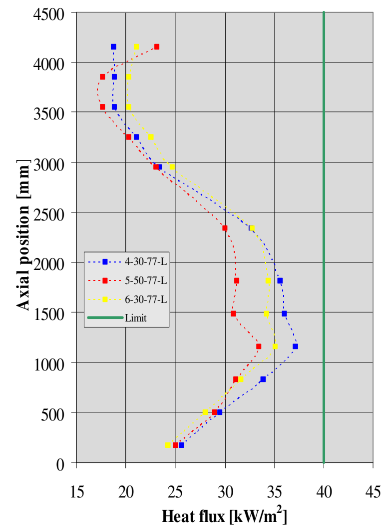

Figure 11. Results of partitions 1, 4 and 6 for low air excess with an increase of 10 % in the heat release.

Nowadays there is a limit of 40 kW/m^2 in the heat flux pick regarding the still furnaces in operation [Serfaty (2003)]. Figure 11 shows the results of partitions 1, 4 and 6 for low air excess with an increase of 10 % in the heat release. The results make clear that this increase of the heat release is still allowable, since the pick is under this suggested limit. It must be appointed that partitions that make use of three air stages are more sensitive for an increase of fuel flow rate (see the curves for partitions 4 and 6) than those that make use of two air stages (partition 1). Figure 12 shows the classification of all partitions explored in terms of the performance parameter, $\dot{q}''_{max}/\dot{Q}_t$. As can be seen the first three positions are for partitions that make use of three air stages and operate with 30° for the angle between the sprays.

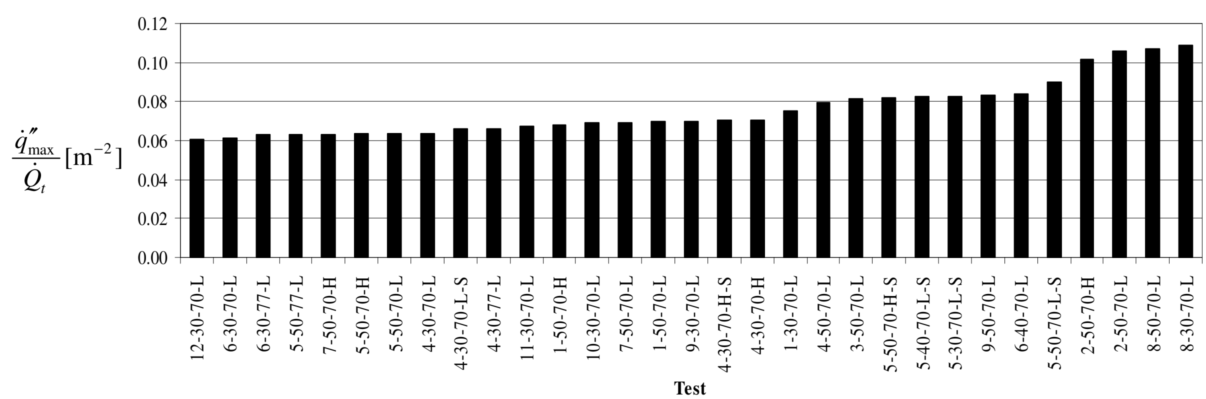

Figure 12. Classification of all partitions tested.

For the closure of the results topic pollutant emissions rates are shown. These measurements were done under the idea that an optimization of one process must consider the most important phenomena involved, the pollutant emissions being one of these. Among the main pollutants there were elected to be analyzed carbon monoxide (CO), nitrogen oxides (NO_x) and particulate material (MP).

The results are shown in Figures 13 to 15. The partitions analyzed were those more significant in terms of heat fluxes distributions. The first aspect that must be arising refers to partitions 1 and 7. For the previous heat flux study, partition 1 was that chosen for a blown burner as being similar for the aspirated burner (partition 7). For heat fluxes distribution it was proved the agreement between then. Here, this agreement repeats for CO and MP emissions. The same was not true for NO_x. The authors have their hypothesis for this behavior, however the space limitations of this paper is prohibitive for this explanation. Regarding the other partitions (4, 5 and 6), the ones for heat fluxes distributions operating with three air streams (4 and 6) were the worst for MP and CO emissions (as CO is related with MP). This can be understood if one takes in account that when increasing the third stage air ratio there is a delay in the oxygen supply for a complete combustion of the fuel. As a result a decrease of the coque particles oxidation rate will produce more MP and, consequently, more CO.

A deeper analysis could be made regarding this topic, however the space limitation of the paper must be respect.

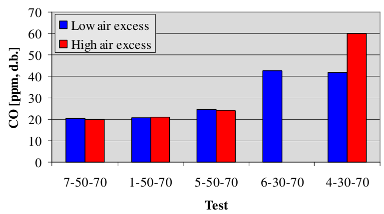

Figure 13. Carbon Oxide emissions.

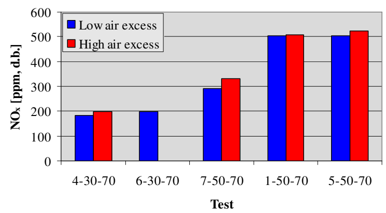

Figure 14. Nitrogen Oxides emissions.

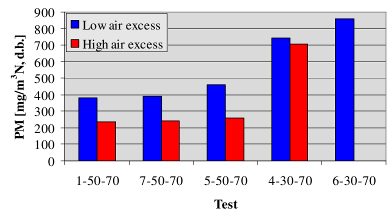

Figure 15. Particulate Material emissions.

4. Conclusion

Based in the objective proposed, the main conclusions are:

- the operational conditions of still furnaces was satisfactorily reproduced using a blown burner with two air streams, whose partition obey 50 % of the total for each one;
- it is better to operate the furnace with low excess air than high, as it results in a higher value of the total heat transfer rate inside the furnace;
- using only two air streams, the greater was the secondary air ratio, the worse will be the heat fluxes distribution with an elevated pick near the atomization nozzle;
- the swirl addition always worsen the heat fluxes distribution;
- the operating condition of the burner with two air streams is practically independent of the angle between the sprays produced by the atomization nozzle;
- the operating condition of the burner with three air streams is highly dependent of the angle between the sprays produced by the atomization nozzle. Among the values tested: 30°, 40° and 50°, the best results were obtained for 30°;
- the three air streams is more efficient than the two stream one in the production of uniform heat fluxes distribution;
- all the partitions that gave the best heat fluxes distributions were found to penalize the CO and MP emissions;
- solutions for reduction of CO, MP and, eventually, the NO_X emissions should be study in future works for the complete optimization of burners to be applied in still furnaces;
- for that partitions having the best heat fluxes distributions it was proved to be possible to increase the heat release by 10 % without reaching the limit for heat flux pick nowadays imposed for the security operation of the still furnaces.

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6. References

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