ANALYSIS OF THE COMBUSTION AIR PREHEATER FROM THE ALUMINUM MELTING FURNACES

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Abstract
This paper presents solutions and the equipment for preheating combustion air from scrap aluminum melting furnaces through flue gas heat recovery. For sizing convection pre-heaters, there has been developed a mathematical model which has been transcribed into a computer program in C + +. A constructive version of the pre-heater was drawn up and a recovery heat exchanger was manufactured and mounted on an aluminum melting furnace. Both the functional parameters values and the reasons causing the pre-heater worning out, as well as the steps taken for sizing and the achievement of a new air pre-heater able to bear the operating conditions of the aluminum melting furnace are shown.

Keywords*: pre-heater, combustion air, furnace, aluminum scrap*

1 INTRODUCTION

The preheating of the combustion air in the alumnium melting furnaces is generally made by using radiation or convection preheating heat exchangers. It was found that the preheating devices can improve the practical efficiency of aluminum melting furnaces by 4-7% for every 100 °C the combustion air is increased in temperature [1]. Also, preheating devices offer the faster return the investiments for preheating combustion air. Customers are realizing a 19-25% reduction in the fuel usage with these heat exchangers and ROIs are averaging 26 months [2]. The newest operational system of using the regenerative burners has several disadvantages: higher costs, greater space for their mantling and additional cost for their maintenance [3,4]. Radiation air pre-heaters used in these furnaces are generally dr.Schack type. They are made of two concentric tubes where the flue gas flows through the inner tube and the combustion air flows in parallel through the section of the two tubes. The parallel flow is preferred due to the high temperature of the flue gas of over 1000 °C [1,3]. The parallel flow submits the refractory steel inner tube to lower temperatures which means a longer life for it, but this also leads to approx. 7-8%, lower temperatures of combustion air preheating, meaning a lower efficiency of recovery in comparison with the countercurrent flow [3,5,6,7].

The convection air pre-heaters used in these furnaces are usually cross flow type in countercurrent with vertical pipes between the air chambers and flue gas flowing perpendicularly on the tubes [3].

Due to the high temperatures of the flue gas of over 1000 °C, as well as of the components resulted from the flows of fluorine, chlorine based gases, etc., used in the process of scrap melting or from the reactions of the cast aluminum or magnesium oxidation and engaged by the flue gas, the life of the metallic recovery heat exchangers is extremely short [3]. As a consequence, there are studies to find solutions for improving the metallic convection recovery heat exchangers, as well as for replacing the refractory steel grades with ceramic materials (for instance the recovery heat exchangers made of silicon carbide). Such a recovery device, made of Field tubes modules, has been tested and there has been reached a combustion air preheating temperature of 815 °C, for the exhaust flue gas temperature of 1205 °C [8]. For these ceramic recovery heat exchangers there are still sealing, mechanical strength or thermal shock resistance problems.

Improving the construction solution of the metallic convection pre-heaters could be made on the grounds of an exhaustive analysis of the causes leading to their worning out. In the same time, the numerous construction possibilities should be analyzed, by sizing them by means of a computer program [7].

For the convection air pre-heater sizing we use our own computer program. The mathematical model and the calculation algorithm are presented in this paper [7].

The C++ transcribed mathematical model was used for sizing of the air pre-heater required by the Contractor of the modernization of an aluminum melting furnace on the base of the following design parameters:

-recovery heat exchanger type: bundle of tubes performed from refractory AISI 304 steel, outer diameter 76 mm, available;

-maximum natural gas flow: 1000 m^3N /h;

-maximum temperature of the flue gas at the recovery heat exchanger entrance: 950 ºC;

-maximum temperature of the hot air at the entrance of the burners: 480 ºC.

In the same time, the Contractor settled that the combustion air temperature regulation is perform to exhausting into the atmosphere of certain quantity of air from the maximum available flow of 12000 m^3N /h.

Information related to the dust contain of the flue gas were required from the Beneficiary and therefore there has been decided the designing of the recovery heat exchanger with the inner pipes flue gas flow for different thicknesses of the deposition layers. In the same time, while building the entrance and exit chamber of the flue gas, these were endowed with detachable taps for inside cleaning of the pipes. As well, information was required from the Beneficiary of the furnace regarding its working regime, finding that the natural gas flow drops from the maximum value of 1000 m^3N /h, after reaching the preset temperature in the furnace, in order to maintain it at a constant value. As a consequence, after several tens of running it, the cross countercurrent or parallel flow construction option for the pre-heater was chosen (shown in figure 1).

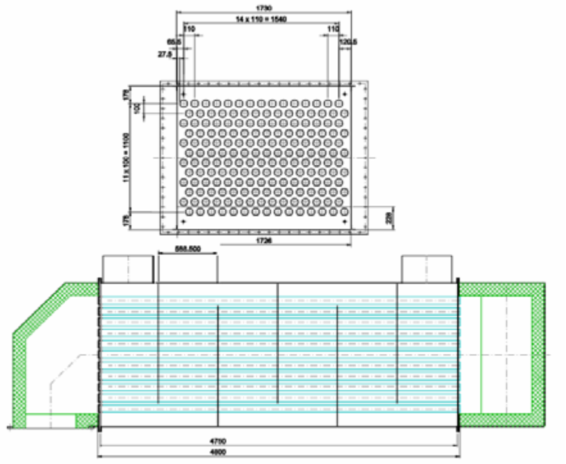

Fig.1 View of the cross countercurrent air flow pre-heater

Simulations of different natural gas flows, different air excess coefficient, on the air and flue gas side, respectively, and of thickness of the deposition layers on the inside of the tubes were undertaken on the same construction option, but with eight countercurrent passes (the length of the tubes is the same in everyone passes), as well as on a mix option of it, with the parallel flow on the first passes and countercurrent on the following ones.

Figure 2, shows the chart of the temperature variation of the combustion air preheating, TAE, in °C, as per the natural gas flow DC in m^3N /h and the different thickness of the deposition layer, GF, considered 0.0000; 0.0005; 0.0001 and 0.00015 m, if operating with an air excess coefficient of 1.05 at the burners and for the flue gas from the recovery heat exchanger and with a difference of air excess coefficient of 0.1 between the air in the recovery heat exchanger and the one entered the burners, in the case of an eight countercurrent flows passes recovery heat exchanger.

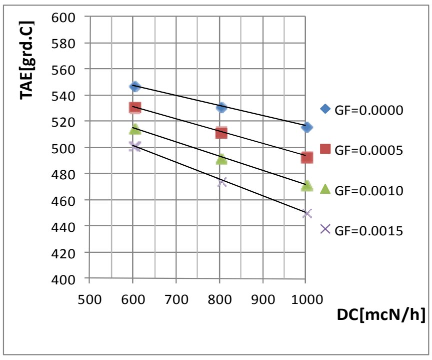

Fig.2 Variation of the combustion air preheating, TAE, in °C, depending on the natural gas flow, DC, in m^3N /h and on the thickness of the deposition layer, GF, in m, for the cross countercurrent flow recovery heat exchanger

Also, there were calculated the air flows for which the preset maximum temperature at the burners entrance of 480°C is not over passed while considering the temperature loss of 10°C between the pre-heater exit and burners entrance. In the case that the maximum air quantity is exhausted into the atmosphere, with the recovery heat exchanger without deposition layer, GF=0.0000m, the air flows will be of 7911 m^3N /h instead of 6000 m^3N /h for the fuel flow of 600 m^3N /h and it reaches 11905 m^3N /h instead of 10000 m^3N /h for a fuel flow of 1000 m^3N /h. Thus, a maximum efficiency is reached with an air preheating temperature at the recovery heat exchanger exit in the range of 460-490 °C, the lower air temperature values are for the maximum fuel flows (DC=1000 m^3N /h) and higher depositions (deposition layer GF = 0.0015 m) and the higher values are for the lower fuel flows (DC=600 m^3N /h) and without depositions (GF = 0.0000 m).

In the same time, there was calculated that for the cross countercurrent recovery heat exchanger option the temperature of the pipes could reach maximum values of 700 °C. As a consequence, in order to drop the temperature of the pipes, trials were made also for the mix flow recovery heat exchanger, with parallel flow in the first passes from the combustion air inlet and cross countercurrent flow in the last passes at the combustion air exit from the recovery heat exchanger.

Figure 3 shows, in the case of the recovery heat exchanger with the first three passages with parallel flow and the following five with countercurrent flow, the preheating temperature variation of the combustion air, TAE, in °C, depending on the natural gas flow, DC, in m^3N /h and on the thickness of the deposition layer, GF, considered 0.0000; 0.0005; 0.0001 and 0.00015 m, in the case of an air excess coefficient of 1.05 in the burners and for the combustion air and flue gas in the recovery heat exchanger.

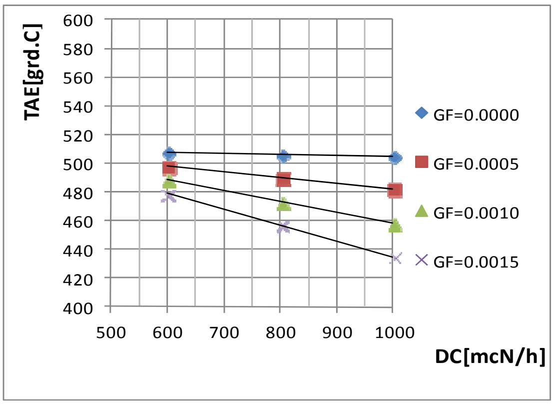

Fig.3 The combustion air preheating temperature, TAE, in °C, depending on the natural gas flow, DC, in m^3N /h and on the thickness of the deposition layer, GF, in m, for the mix recovery heat exchanger with cross parallel flow for the first three passes and countercurrent flow for the next five

For the cross flow recovery heat exchanger with parallel flow in the first three passes and countercurrent flow for the next five, the temperature of the pipe wall reaches maximum 565 °C, which gives greater safety during a longer operation life against the cross countercurrent recovery heat exchanger.

In the same time, the maximum efficiency is reached through air preheating temperature at the exit of the recovery heat exchanger in the range of 460-490 °C, as in the case of the cross countercurrent recovery heat exchanger, except when using natural gas flows greater that 800 m^3N /h at maximum depositions of 0.0015 m during functioning.

Therefore, there was proposed to the Contractor to use the cross parallel flow scheme for the first three passes and countercurrent flow for the next five and the Contractor did not agree arguing this would change the initial offer we placed.

2 EXPERIMENTAL RESULTS

Cross countercurrent pre-heater heat exchanger schematically shown in fig no.1, was manufactured and mantled on the aluminum scrap melting furnace. Figure 4 is a view of this air pre-heater while mounting it on the aluminum scrap melting furnace.

Fig.4 View of the air pre-heater while mounting it on the aluminum scrap melting furnace

After the Contractor started running the modernized furnace, he reported exceeding air preheating temperatures at the inlet of the new burners which are mounted by him. It has been found that the Contractor installed a lower flow air fan than indicated by our paper which did not assure the necessary flow for air exhausting into the atmosphere under specific operation conditions. Also, the Contractor installed 4 new burners, mounted two by two on the side walls with parallel air and natural gas flows, respectively, which collide above the liquid bath at a small distance from the flue gas exhausting hole. This incorrect solution, without considering the CFD simulation, increased the flue gas exhausting temperature [9]. At approx. one month after starting operating the furnace this stops because of lack of combustion air. While dismantling the inlet flue gas chamber of the recovery heat exchanger, the following are found:

-The tubesheet, from the flue gas entrance side of the recovery heat exchanger is damaged (see figure 5 and figure 6);

-The pipes of the bundle of the recovery heat exchanger from the flue gas entrance side were submitted to higher temperatures than the accepted ones, on a maximum length of 110 mm;

-The ceramic fiber covering the turning loop of the exhaust flue gas from the furnace to the recovery heat exchanger is burned and shows the characteristics of burning at approx. 1250 °C as well as its fastening anchors;

-The deposition layer thickness is under 0.0001m and it is on the inside of the pipes on a length of only 0.7m towards the flue gas entrance side.

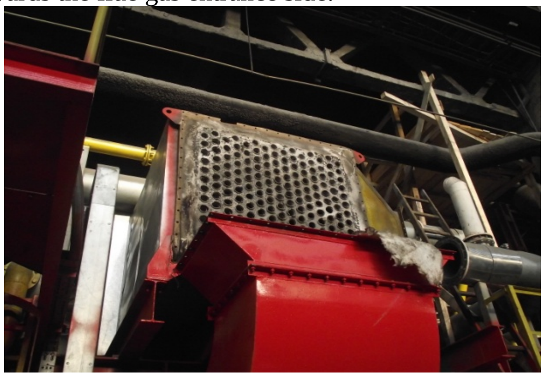

Fig.5 View of the air pre-heater, from the flue gas entrance side towards the damaged tubesheet

Fig.6 View of a part of the damaged tubesheet

3 RESULTS AND DISCUSSIONS

From the metallographic analysis and the chemical composition reports made by an authorized lab the followings resulted.

From the sample microstructure (figure 7), of the heat treated area of the tubesheet we find intergranular rust aspects and isolated areas of intergranular rusty cracks in the austenitic matrix, pressure corrosion areas under the conditions of high temperature exposure in aggressive environment.

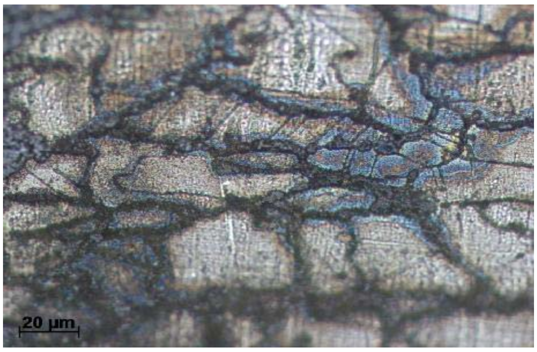

Fig.7 The sample microstructure of affected area from the tubesheet, by heat (x500)

From the sample microstructure (figure 8) of heat affected zone of the tube with a length of 100 mm we ascertain on the outer surface the depth of the corrosion of approx. 0.10 ÷ 0.15 mm. of the twinned polyhedra austenitic matrix and some carbide points. Enlarging X 500 titan nitride type inclusions are observed (figure 7).

Fig.8 The sample microstructure of the heat affected zone with a length of L=100mm (x500)

From the sample microstructure (figure 9) of the heat affected zone of the tube with a length of 25 mm we find that the inner surface is highly intergranular corrosive, which is as characteristic of the oxide environment exposure, highly aggressive and at high temperature.

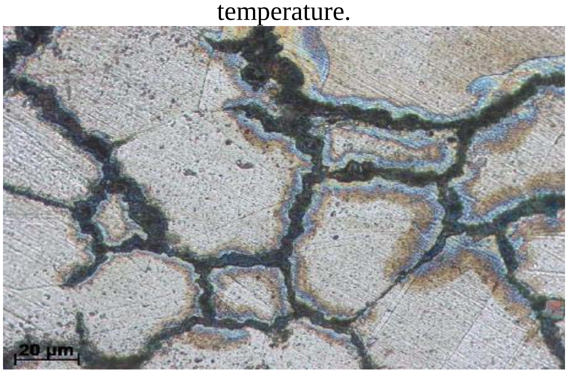

Fig.9 The sample microstructure of the heat affected zone with a length of L=25mm (x500)

Consequently, the repairing of the cross countercurrent flow recovery heat exchanger is decided.

The repairing of the cross countercurrent flow recovery heat exchanger meant the replacement of the tubesheet from the flue gas entrance side and of a 110 mm of the pipes.

In the same time, there was decided the use of the cross parallel flow scheme for the first four passes and the countercurrent flow for the next five, with varying distance between baffles (length of the pipes in one of the passes of combustion air) so that constant and high speeds of the combustion air should be reached and allowed by further use of the same air fan.

For such a recovery heat exchanger, named a mix, trials were run for various distance between baffles and under different natural gas flows, excess coefficients for the air and flue gas, respectively, and at different thickness values of the depositions on the inside of the tubes.

The input data and the obtained results on the computer, while running the sizing program for the functioning of the mix pre-heater heat exchanger, for instance, with a natural gas flow of 700 m^3N /h in a complete burning with an air excess coefficient of 1.15, the flue gas flow results of 8336.5 m^3N /h and the thickness of the deposition layer is considered of maximum 0.001m are synthetically shown in table 1, 2 and 3. In table 1 the input data and parameters with constant values for the mix recovery heat exchanger are shown. Table 2 presents the results for the first four zones for which the flow is parallel and table 3 shows the results for the following five zones in terms of the countercurrent flow.

Table1.The input data and parameters with constant values for the mix recovery heat exchanger with cross parallel flow for the four passes and countercurrent flow in the following five

No.	Parameter	U.M.	Value
1	Natural gas flow	m^3N /h	700
2	Combustion air flow	m^3N /h	7636.5
3	Flue gas flow	m^3N /h	8336.5
4	Efficiency	-	0.98
5	Air excess coefficient	-	1.15
6	Environment temperature	ºC	40
7	Tube outside diameter	m	0.076
8	Tube wall thickness	m	0.003
9	Number of flue gas passes	-	1
10	Vertical length of the tubesheet	m	1.70
11	Horizontal length of the tubesheet	m	1.45
12	Tube pitch (vertical)	m	0.010
13	Tube pitch (horizontal)	m	0.011
14	No. of tubes on one row (vertical)	-	15
15	No. of tubes on one row (horizontal)	-	12
16	Distance to the wall (vertical)	m	0.010
17	Distance to the wall (horizontal)	m	0.010
18	Pressure	bar	1
19	Thickness of the scum layer	m	0.001
20	Deposition layer conductivity	W/m*K	0.1
21	Steel conductivity	W/m*K	50

Table 2.The results and the data regarding the different values parameters for the first four zones with parallel flow of the mix recovery heat exchanger

No.	Parameter	U.M.	ZONE I	ZONE II	ZONE III	ZONE IV
1	Inlet air temperature	ºC	30	96	162	223
2	Outlet air temperature	ºC	96	162	223	281
3	Inlet flue gas temperature	ºC	950	901.3	851.2	801.7
4	Air heating value	W	185159.2	187613.1	184230.8	168873.4
5	Inlet flue gas heating value	W	3376173	3186158	2993977	2803526
6	Outlet flue gas heating value	W	3187235	2994716	2805987	2631206
7	Outlet flue gas temperature	ºC	901.3	851.2	801.7	755.4
8	Average temperature difference	ºC	852.6	747.0	635.3	526.1
9	Average gas temperature	ºC	925.6	876.1	826.3	778.2
10	Average air temperature	ºC	73.0	129.0	191.0	252.0
11	Distance between baffles	m	0.300	0.350	0.400	0.450
12	Flue gas flow section	m^2	0.692	0.692	0.692	0.692
13	Air flow section	m^2	0.161	0.188	0.215	0.242
14	Flue gas speed	m/s	14.67	14.07	13.46	12.87
15	Air speed	m/s	16.65	16.58	16.75	16.85
16	Flue gas convection coefficient	W/ m^2/K	21.81	21.74	21.65	21.51
17	Air convection coefficient	W/ m^2/K	59.56	59.89	61.00	61.97
18	Thickness of the gas layer	m	0.063	0.063	0.063	0.063
19	Gas radiation coefficient	W/ m^2/K	8.80	8.58	8.39	8.07
20	Gas transfer coefficient	W/ m^2/K	30.61	30.32	30.05	29.58
21	Overall heat transfer coefficient	W/m/K	3.98	3.96	3.96	3.95
22	Overall heat transfer coefficient	W/ m^2/K	17.35	17.29	17.30	17.24
23	Heating exchange surface	m^2	12.38	14.45	16.51	18.57
24	Air pressure loss	N/m^2	1058.5	1092.1	1167.2	1224.6
25	Gas pressure loss	N/m^2	31.99	30.71	29.49	28.24

Table3.Results and data of the parameters with different values for the last five zones with countercurrent flow of the mix recovery heat exchanger (units of measure are identical to the one in the table 2)

No.	Parameter	ZONE V	ZONE VI	ZONE VII	ZONE VIII	ZONE IX
1	Inlet air temperature	281	321	360	398	439
2	Outlet air temperature	321	360	398	439	480
3	Inlet flue gas temperature	628	658	688	720	755
4	Air heating value	117490.8	115347.6	113137.7	122892.5	2629839
5	Inlet flue gas heating value	2161585	2272077	2375765	2498666	2503570
6	Outlet flue gas heating value	2041696	2154375	2260318	2373265	123743.1
7	Outlet flue gas temperature	596	628	658	688	720
8	Average temperature difference	311.6	299.5	286.5	278.9	273.0
9	Average gas temperature	612.5	643.0	671.4	703.1	738.1
10	Average air temperature	301.0	343.5	384.8	424.2	465.0
11	Distance between baffles	0.60	0.60	0.60	0.65	0.65
12	Flue gas flow section	0.692	0.692	0.692	0.692	0.692
13	Air flow section	0.322	0.322	0.322	0.349	0.349
14	Flue gas speed	10.84	11.21	11.56	11.95	12.38
15	Air speed	13.81	14.84	15.83	15.49	16.40
16	Flue gas convection coefficient	20.43	20.65	20.86	21.11	21.34
17	Air convection coefficient	53.43	57.16	60.85	60.37	63.80
18	Thickness of the gas layer	0.063	0.063	0.063	0.063	0.063
19	Gas radiation coefficient	5.85	6.41	6.97	7.60	8.31
20	Gas transfer coefficient	26.29	27.07	27.84	28.71	29.65
21	Overall heat transfer coefficient	3.54	3.67	3.80	3.86	3.99
22	Overall heat transfer coefficient	15.46	16.03	16.58	16.83	17.40
23	Heating exchange surface	24.77	24.77	24.77	26.83	26.83
24	Air pressure loss	698.3	894.0	1096.8	1047.5	1242.0
25	Gas pressure loss	23.9	24.7	25.5	26.3	27.3

For the mix cross flow recovery heat exchanger with parallel flow for the first four passes and countercurrent flow in the following five, the temperature of the tube wall reaches maximum 571 °C, which gives it a greater safety and longer life in comparison with the cross countercurrent flow recovery heat exchanger.
In the same time, the maximum efficiency is reached by air preheating temperatures at the mix recovery exit point in 460-490 °C range.

A view of the new air pre-heater, from the exhaust gas entrance towards the tubesheet is shown in figure 10. Both the tubesheet and the side entrance taps of the air, the lower tap next to the tubesheet from the parallel flow zone and the higher tap from the countercurrent flow zone are covered with a metallic sheet for transportation purposes.

Fig.10 View of the repaired pre-heater from the flue gas entrance zone towards the tubesheet, covered by a metallic sheet for transportation purposes

After installing this recovery heat exchanger on the furnace, experiments will be undertaken in order to establish the functional parameters and its expected life term.

4 CONCLUSIONS

For the convection air pre-heater heat exchanger sizing we use our own mathematical model transcribed into a computer program in C + +. Simulations of different natural gas flows, different air excess coefficient, on the air and flue gas side, respectively, and of thickness of the deposition layers on the inside of the tubes were undertaken on the same construction option, with eight passes on a cross countercurrent flow recovery heat exchanger, as well as on a mix option of it, with the parallel flow on the first passes and countercurrent on the following ones. The Contractor decided to use the cross countercurrent flow recovery heat exchanger and 4 new burners, mounted two by two on the side walls with parallel air and natural gas flows, respectively, which collide above the liquid bath at a small distance from the flue gas exhausting hole.

The choice of the materials W1.4878 has been made as per the flue gas temperature (given by the Contractor in the project subject as 950°C) and as per the combustion air temperature in different operation regimes of the furnace, resulting a maximum tube wall temperature 700°C. This material has specified as heat treatment range 1020 ÷ 1120°C, without showing any micro structural change.
The lab results as well as the pictures shown, indicate a structural change, the occurrence of rust at the crystal limit and the burning of the sample material taken from the front tubesheet and from the welded tubes within.In conclusion, it follows that the flue gas temperature was much higher than the one in the project and over the indicated heat temperature.
Consequently, the repairing of the cross countercurrent flow recovery device is decided. The repairing of the cross countercurrent flow recovery heat exchanger meant the replacement of the tubesheet from the flue gas entrance side and of a 110 mm of the tubes. In the same time, there was decided the use of the scheme with cross parallel flow in the first four passes and cross countercurrent flow for the next five, with varying distance between baffles, so that constant and high speeds of the combustion air should be reached and allowed by further use of the same air fan. After installing this recovery heat exchanger on the furnace, experiments will be undertaken in order to establish the functional parameters and its expected life term.

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