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CONTRIBUTION TO IMPROVING THE DURABILITY OF THE REFRACTORY LINING OF THE STEEL LADLES

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The paper presents experimental results obtained in the iron and steel industry with an own conception burner for drying and heating the steel ladles masonry, using, as a solution to intensify the combustion, the oxygen enrichment of combustion air. The main goal is to reach the maximum temperature of 1200 ºC inside the refractory lining, according to the request of the refractory materials manufacturers. The results obtained in ArcelorMittal Galati confirm the correctness of the adopted solutions, the burner allowing to reach the required heating speed and to respect the thermal parameters of diagram, that contribute to the significant increase of the durability of the ladles wear layer.

Keywords: ladle, durability, refractory lining, burner, oxygen, temperature

1. Introduction

The modern processes of the liquid steel treatment in the ladle impose the prior preheating the ladles refractory lining at high temperatures (1150 – 1200 ºC), to diminish as much as possible the cooling process of the hot steel at the contact with the ladle masonry. The technological process of drying-heating the layers which compose the refractory lining has a special importance to ensure the durability of material at the prolonged contact with the liquid metal. The diagrams are designed so that the thermal conditions be achieved to totally eliminate the

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refractory material moisture, as well as a high temperature inside the lining to reduce the heat loss of the liquid steel into environment.

Generally, the methods of combustion intensifying are air combustion preheating (by recovery the physical heat of waste gas resulted from the process) and the oxygen enrichment of air. By the both methods it is obtained a significant increase of the flame temperature and, implicitly, of waste gas resulted from the combustion process, so that the transfer of thermal energy by radiation and convection from gases to the first layer, which composes the refractory lining (the wear layer), is much improved. Further, the heat is transferred by thermal conductivity in all lining layers (intermediate and permanent layer), ensuring a global heating of the refractory lining, superior in terms of heat compared to the conventional heating processes.

Worldwide they are known the self-recuperative burners, which have embedded the metal heat recuperator in the burner construction, which ensures a very high heat exchange between waste gas and the combustion air, the air reaching temperatures of over 600 ºC. Conceived and achieved by the British company Hotwork Development Ltd. [1], this burner type is limited at thermal power values of maximum 400 kW. The energy efficiency of the self-recuperative burners is diminished with the increase of their thermal powers, because the heat recuperator sizes would be very large to obtain a heat transfer as effective. Therefore, in case of the steel ladles of high capacity (of over 65 t), that require combustion installations with thermal powers of over 1000 – 1500 kW, the self-recuperative burners have a very diminished efficiency. Generally, the high capacity ladles are placed horizontally and the heating installation is installed on a mobile wagon, equipped with a refractory lined vertical wall (with a ladle cover role), a conventional burner and a waste gas / combustion air exchanger [2]. But the horizontal position of ladle is not recommended in case of the new built ladle and subjected to drying (especially, for refractory linings of dolomite blocks).

A high degree energy recovery (up to 0.90) in the heating process of steel ladles masonry can be achieved [3 – 5] by use the self-regenerative burners. The thermal power of this burner type varies in the range 300 – 4000 kW. The regenerative heat exchanger uses balls and cylinders of refractory ceramic material. Made by the British company Hotwork and then by the French companies Stein-Heurtey and Hotwork France (after its license), the burners operate in tandem. The combustion air is preheated at temperatures that can reach 900 – 1000 ºC. As the high thermal powers self-recuperative burners, the self-regenerative burners involve the horizontal position of ladles subjected to drying and, so, are not advisable in case of drying processes of new built ladles masonry.

The other method of combustion process intensifying, noted above, is oxygen enrichment of combustion air. Effects of this method application are significant: decrease of heating duration, optimal using of oxygen, increase of refractory lining durability, uniform heating of lining, decrease of energy costs, reduction of CO_2 and NO_x volumes. Literature presents the Pyre Tron burner [6] of the British company Air Liquide, having maximum flexibility in the proportion of oxygen in combustion air, allowing to obtain flame temperatures in a very large range, depending on needs. On the other hand, the burner (of acceptable sizes regardless of its thermal power) placing is easily on the ladle cover and this can be vertically placed.

Also, the burners with oxygen enrichment air of the Japanese company Chugai Ro Ltd. [7] are recommended for rapid heating processes and at high temperatures of the steel ladles.

If in terms of energy effects the burners operating with oxygen enrichment air are superior compared to the self-recuperative and self-regenerative burners, presented above, not the same thing can be said about the efficiency of the technological heating process. Thus, in case of self-recuperative and self-regenerative burners, a part of waste gas energy resulted from the process is recovered by preheating the combustion air at high temperatures and is reintroduced into system. In case of burners operating with oxygen enrichment air, used in the heating process of ladles, waste gas heat is not recovered, although their energy content is much higher than that of waste gas produced in the combustion process of self-recuperative and self-regenerative burners. By placing of some heat recuperators above the exhaust holes of the hot gases would increase very much the weight of ladle cover. Certainly, there is also the possibility to energy recovery in this case with condition of horizontal position of the ladle and placing the recovery system on a mobile wagon [8]. As previously noted, the horizontal position of the ladles is not suitable for those new built.

The aim of research presented in this paper is to achieve an own conception installation with oxygen enrichment air, designed for drying and heating processes of high capacity steel ladles masonry (180 t). The burner was designed and achieved for the Converters Steelwork in ArcelorMittal Galati, taking into account the technological and material concrete situation of the plant. It is estimated that, by using the new combustion installation to achieve the drying-heating diagrams required by the manufacturers of refractory materials, that compose the wear layers, it will obtain a significant increase of the refractory lining durability.

2. Refractory materials of the composition of steel ladles lining and technical specifications of the manufacturers

Currently, in the Converters Steelwork of ArcelorMittal Galati the steel ladles are built in several ways, two of which being the most used. A mode of masonry construction consists of using magnesia bricks bonded with magnesium spinel, as a wear layer (which comes in direct contact with slag and molten steel), with thickness of 187 mm, silica – alumina bricks as a permanent layer (made on the inner surface of the ladle metal shell), with thickness of 80 mm in the upper area of ladle and 120 mm in the lower area and granulated dolomite bonded with tar as an intermediate layer (between the wear layer and the permanent), with thickness of 50 mm. The second mode of masonry construction is composed of dolomite blocks as a wear layer, with thickness of 150 mm, high-aluminous refractory concrete B90A as a permanent layer, with thickness of 80 mm in the upper area and 120 mm in the lower area and granulated dolomite bonded with tar as an intermediate layer, with thickness of 50 mm [9].

Between the ladle refractory lining layers, that on which it is focused the entire attention during the drying-heating process, is the wear layer. Therefore, the refractory materials, which influence the parameters of the drying-heating diagrams used in the two ways of ladles masonry construction, are magnesia bricks bonded with magnesium spinel, made in Tremag Tulcea and dolomite blocks, made even in ArcelorMittal Galati, at the Bricks Plant.

The magnesia bricks manufacturer requires compliance with a heating diagram with the total duration of 30 hours, characterized by a heating in the first stage up to 1000 ºC in 25 hours (with the speed of 40 ºC/ h), continued by a maintaining at this temperature for 2.5 hours and the final heating from 1000 ºC to 1200 ºC in 2.5 hours (with the speed of 80 ºC/ h). The measurement point of temperature would be placed, according to the technical specification of manufacturer, 50 mm from the inner surface of the ladle shell, i. e., practically, in the permanent layer, at 450 mm from the bottom of ladle.

Literature recommends [10] for the magnesia masonry a drying-heating diagram with the duration of 30 hours, but with a linear increase with the heating speed of 40 ºC/ h, constant kept up to the end of process. The constant maintaining at 1000 ºC, required by the Romanian manufacturer, has not a motivation based on textural-structural transformation inside the magnesia bricks, but only the need of the heat transfer homogenization and the stabilization of dimensional variation of material in the entire volume of masonry. The need to heat up to 1200 ºC is imposed by getting a denser refractory mass, with low porosities, which does not allow the liquid steel infiltration during its stationing in the ladle. Using the magnesium spinel ($MgO{\cdot}Al_2O_3$) as a binder, aims, inter alia, to diminish the effects of masonry dilatation, the coefficient of linear dilatation of spinels being with about 40% lower than the magnesia on the entire temperature range 20 – 1600 ºC [11].

The manufacturer (ArcelorMittal Galati-Bricks Plant) requires compliance with a drying-heating diagram with the total duration of 16 hours, achieved in four stages, according to table 1.

Table 1

Drying-heating diagram of dolomite blocks

Temperature range (ºC)	20 - 450	450 - 800	800 - 1060	1060 - 1145
Heating speed (ºC/ h)	215.0	87.5	38.5	26.1
Duration (hours, min.)	2.00	4.00	6.45	3.15

Literature recommends [10] a more compressed diagram, with the total duration of only 12 hours, having only two heating stages, according to table 2.

Table 2

Drying-heating diagram of dolomite blocks recommended by Didier

Temperature range (ºC)	20 - 450	450 - 1175
Heating speed (ºC/ h)	215.0	72.5
Duration (hours, minutes)	2.00	10.00

The very high speed of the beginning process (215 ºC/ h) is imposed, inter alia, by the need to avoid the unwanted phenomenon of dolomite hydration, which modifies the thermal and structural characteristics of this material [12]. This can occur, in significant measure, at temperatures of below 450 ºC, in conditions of a low heating speed.

The explication of difference between technological requests of the two manufacturers of dolomite blocks (ArcelorMittal Galati and Didier) must be search, primarily, in the recognition of lower performances of the current combustion installations which equip the ladle preparation sector of the Romanian iron and steel industry and, implicitly, the impossibility to answer the requests imposed by the drying-heating technology of this refractory material type. Therefore, it is preferably to reach rapidly the temperature of 800 ºC, and then the heating is conducted slowly up to 1145 ºC, with a speed obviously much lower and in a greater time range. In this way, the heating in the range 800 – 1145 ºC, during 14 hours, allows a good temperature homogenization inside the refractory material.

Corresponding to the drying-heating diagram of magnesia bricks, the measurement point of the masonry temperature is placed 50 mm from the inner surface of the ladle shell and 450 mm from the bottom of ladle.

3. Own conception technical solutions adopted to design the combustion installation

3.1. Technical requests imposed to the combustion installation

Because the technological conditions imposed by the magnesia bricks and dolomite blocks manufacturers for the drying-heating process of ladles masonry of 180 t in Arcelor Mittal Galati were impossible to achieve with the installations existing in the plant, it was imposed to made a new burner with advanced characteristics, capable to answer to the following requests:

- the flame developed through combustion to be radiant by self carburizing, with a preponderantly central jet of natural gas, surrounded by annular flame jets produced by the mixture between natural gas radial distributed and the primary combustion air;
- the combustion efficiency to be very high, as that, by achieving an intimate mixture between fuel and combustion air (distributed in three mixture stages), the transformation of fuel chemical energy in thermal energy to take place in maximum proportion;
- the real flame temperature would reach values of over 1700 ºC, achieving by processes of combustion intensifying, noted previously;
- pollutants emissions in waste gas (CO, NO, NO_x) to be below the maximum levels allowed by the law.

Considering the superiority, in terms of energy effects, of the process of combustion intensifying by using oxygen enrichment of combustion air [9], as well as the easily installing this burner type on the cover, the ladle position being vertically, it was adopted this intensifying variant.

3.2. Description of the constructive and functional solution adopted to design the burner

To design the new combustion installation destined to the vertical drying-heating stand of the steel ladles of 180 t, they are adopted the hourly flow rate of natural gas of 250 m^3_N/ h and the maximum flow rate of oxygen (available at the supply source of the stand area) of 150 m^3_N/ h.

To achieve the imposed technical requests, noted above, it was considered the need to ensure a preponderantly central jet of natural gas (80% from the total flow rate of fuel) through an axial central orifice with the diameter Ø 20 mm. The remaining fuel (20%) is radial distributed through 24 orifices Ø 8 mm. The fuel radial distributed meets a part of the instilled air amount (primary air), swirled with more propellers welded on the body of natural gas pipe and, in this annular cylindrical area it is produced the first mixture stage between fuel and air. The secondary combustion air passes through an annular concentric route and exits through oblique slits made in the head of piece, on its inner surface, which ensure a rotary motion of air in opposite direction compared to the primary air motion. In this area, it is produced the second mixture stage between the ignited fuel and the secondary air. To cool the combustion chamber of the burner, made from 15SiNiCr250 refractory steel, a peripheral stream of tertiary air is instilled. This enters in the combustion chamber and participates in a third stage of mixture at the fuel combustion. The tertiary air role is, excepting the cooling of the combustion chamber, to lengthen the flame.

The phased distribution of combustion air in the combustion process is one of the well-known methods of reducing the nitrogen oxides concentration in waste gas [13].

The introduction of technical oxygen to increase the volumetric proportion of oxygen in the combustion air is achieved by the injection in the entry connection of air in the burner body. The oxygen addition occurs simultaneously with the reduction of the combustion air flow rate. By diminishing the nitrogen volume in air, that is an inert element, which does not participate at the combustion reaction of methane from the fuel, the flame temperature increases significant due to the reduction of cold nitrogen in waste gas.

In Fig. 1 it is presented the constructive scheme of the burner for achieving the drying-heating process of the steel ladles masonry in Arcelor Mittal Galati.

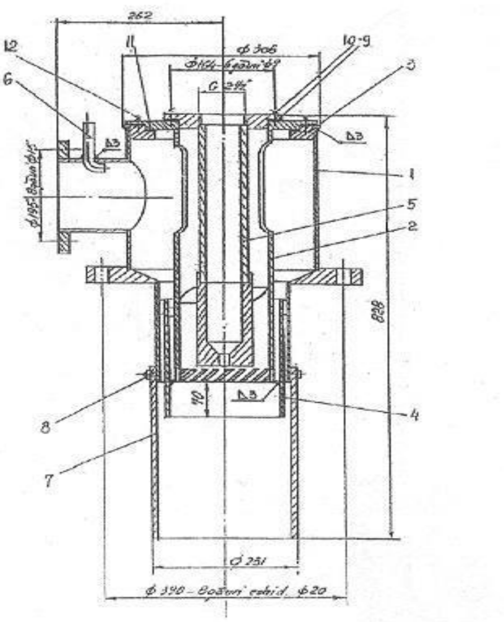

Fig.1. Constructive scheme of the burner for drying-heating process of steel ladles in ArcelorMittal Galati: 1 – burner body; 2 – primary air pipe; 3 – sealing piece; 4 – secondary air pipe; 5 – natural gas pipe; 6 – oxygen pipe; 7 – combustion chamber; 8 – fastening system of the combustion chamber; 9,11 – gasket; 10,12 – fastening system.

Burner body (1) is made by stainless steel. The role of the two air pipe, primary (3) and secondary (4) is to ensure proper mixing between natural gas – air. Combustion chamber (7) is made by refractory steel. Sealing burner is provided by gaskets (9) and (11) with fastening system (12)

In table 3 they are presented the main technical and dimensional characteristics of the burner designed for drying and heating installation of steel ladles of 180 t.

Table 3

Technical and dimensional characteristics of the burner

Name	Unit	Value
A. Technical characteristics		
Nominal flow rate of natural gas	m^3_N/ h	250
Nominal pressure of natural gas	mbar	75
Maximum flow rate of oxygen	m^3_N/ h	150
Maximum pressure of oxygen	bar	1.5
Coefficient of air excess	-	1.02
Nominal flow rate of combustion air - at the operation without additional oxygen - at the operation with oxygen enrichment of combustion air (30%)	 m^3_N/ h m^3_N/ h	 2428 1190
Maximum temperature of the flame	ºC	1890
B. Dimensional characteristics		
Length	mm	828
Diameter	mm	300
Net mass	mm	85.56

4. Experimental methodology

The burner experimentation was carried out directly in industry at the Converters Steelwork in ArcelorMittal Galati on a drying and heating stand of steel ladles of 180 t. The new burner was installed on a ladle metal cover, lined with super aluminous refractory concrete. The cover has four equidistant holes Ø 200 mm for waste gas exhausting from the ladle. Two steel ladles built in the two most used modes were dried and heated with the new burner.

The following parameters of the process were measured:

- hourly flow rate of natural gas, with a calibrated gas meter;
- natural gas pressure, with AFRISO FZM 15 digital manometer, with measuring range of 0 – 150 mbar;
- hourly flow rate of oxygen, with a calibrated oxygen meter;
- oxygen pressure, with AFRISO FZM 15 digital manometer;
- refractory masonry temperature, determined manually with a Chromel-Alumel thermocouple, with the measurement range of 0 – 1200 ºC, installed in the posterior area of ladle, with the measurement point placed 50 mm from the inner of the ladle, according to the requests of the refractory bricks manufacturers;

- waste gas temperature at the exit from the ladle, determined with a Pt-Rh-Pt thermocouple, with the measurement range of 0 – 1800 ºC, placed into one of the exhaust holes of gases from the ladle cover;
- inner surface temperature of the refractory masonry, measured with a Rytek type radiation pyrometer, with the measurement range of 800 – 1800 ºC;
- waste gas chemical composition, determined with an AFRISO-MAXILYZER type gas analyser, with built-in printer for CO, NO, NO_x, CO_2 and O_2, the sampling performing with the capture probe introduced through one of the waste gas holes of the ladle cover.

5. Experimental results and discussions

In table 4 it is presented the technical data sheet of the drying-heating process of a steel ladle of 180 t new built in the first mode of masonry construction used in ArcelorMittal Galati (magnesia bricks as a wear layer).

Table 4

The technical data sheet of the drying-heating process of a ladle built with magnesia bricks

Duration hours, minutes	Temperature, ºC			Flow rate, m^3_N/ h			Observations
	Inside the masonry	Waste gas	Inner surface of the ladle masonry	Natural gas	Combustion air	Oxygen	
0.00	20	-	-	150	1457	-	Beginning the drying
1.00	80	200	-	150	1457	-	
2.00	130	270	-	130	1262	-	
3.00	170	300	-	100	971	-	
4.00	195	350	-	100	971	-	
5.00	230	375	-	100	971	-	
6.00	260	400	-	150	1457	-	
7.00	300	440	-	150	1457	-	
8.00	330	480	-	180	1748	-	
9.00	390	550	-	190	1845	-	
10.00	430	625	-	210	2039	-	
11.00	485	660	-	170	1651	-	
12.00	530	695	-	155	1505	-	
13.00	550	720	-	155	1505	-	
14.00	580	740	-	155	1505	-	
15.00	600	770	-	152	1476	-	
16.00	630	780	-	170	1651	-	
17.00	695	840	-	170	1651	-	
18.00	745	890	-	220	2136	-	
19.00	780	945	-	200	1942	-	

20.00	810	980	925	200	1942	-	
21.00	850	1025	970	200	1942	-	
22.00	880	1060	1000	227	2204	-	
23.00	920	1105	1050	227	1374	50	Beginning the oxygen supply
24.00	990	1150	1100	221	1400	30	
25.00	1000	1175	1110	221	1400	30	
26.00	1000	1175	1110	227	1442	30	
27.00	1000	1170	1105	230	1461	30	
27.45	1000	1175	1110	238	1108	150	
28.00	1060	1200	1150	238	1108	150	
29.00	1145	1300	1245	250	1190	150	
30.00	1200	1375	1305	(250)*	(1190)*	(150)*	Stopping the burner
Total consumption (m^3_N)				5,400	46,120	500	

Note: The natural gas, air and oxygen flow rates noted with *) correspond to the moment of burner stopping at the end of process.

Based on the data from table 4, in Fig. 2 it is presented the diagram of drying-heating process of ladle, containing the time evolution of temperature value measured inside the masonry (50 mm from the ladle metal shell) compared to the recommended values of manufacturer, on the inner surface of ladle masonry, as well as the evolution of waste gas temperature at the exit from the ladle through the cover holes.

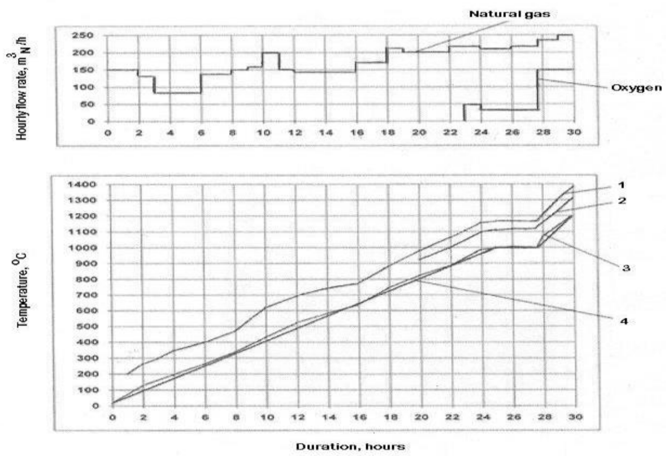

Fig. 2. Diagram of the drying-heating process of a ladle built with magnesia bricks as a wear layer 1 – waste gas temperature at the exit from the ladle; 2 – temperature on the inner surface of ladle masonry; 3 – temperature inside the masonry measured in the point indicated by manufacturer; 4 – temperature inside the masonry according to the diagram required by manufacturer.

Also, it is showed the variation during the process of the hourly consumptions of natural gas and oxygen used to enrich the combustion air.

The final masonry temperature in the measurement point indicated by manufacturer, of 1200 ºC, was reached after 30 hours of combustion installation operation. The heating speed of 40 ºC/ h up to the constant maintaining at 1000 ºC, according to the diagram imposed by manufacturer, was easily maintained, in conditions of the burner operation without contribution of supplementary oxygen. The slightly non-uniformity of the increasing slope of masonry temperature is due to the absence, at the date of experiments, of the automatic control equipment of the process. The continuation of the heating process over 1000 ºC was possible only with oxygen addition in the combustion air. The volumetric proportion of oxygen in air was maintained at the value of 30%.

Analyzing the graphs from Fig. 2, it can be observed that the waste gas temperature at the exit from the ladle is higher with about 150 ºC than the temperature measured inside the masonry, reaching 1375 ºC at the end of process.

The total natural gas consumption during the drying-heating process is 5400 m^3_N and the total oxygen consumption is 500 m^3_N.

In table 5 it is presented the technical data sheet of the drying-heating process of a steel ladle of 180 t new built in the second mode of masonry construction used in ArcelorMittal Galati (dolomite blocks as a wear layer).

Table 5

The technical data sheet of drying-heating process of a ladle built with dolomite blocks

Duration hours	Temperature, ºC			Flow rate, m^3_N/ h			Observations
	Inside the masonry	Waste gas	Inner surface of the ladle masonry	Natural gas	Combustion air	Oxygen	
0	20	420	-	250	2428	-	Beginning the drying
1	275	720	-	240	2330	-	
2	450	900	-	245	2379	-	
3	515	960	-	245	2379	-	
4	590	1000	-	245	2379	-	
5	690	1075	975	245	2379	-	
6	800	1160	1100	245	2379	-	
7	845	1260	1175	245	2379	-	
8	855	1270	1190	245	2379	-	
9	880	1290	1200	245	1632	10	Beginning the oxygen supply
10	970	1350	1295	230	1496	20	
11	1000	1400	1340	230	1496	20	
12	1025	1425	1355	235	1530	20	

13	1085	1450	1400	235	1496	30	
14	1100	1480	1425	235	1428	50	
15	1150	1570	1480	240	1122	150	
16	1200	1640	1550	(240)*	(1122)*	(150)*	Stopping the burner
Total consumption (m^3_N)				3,850	31,611	300	

Note: The natural gas, air and oxygen flow rates noted with *) correspond to the moment of burner stopping at the end of process.

Fig. 3, based on the data from table 5, shows the diagram of the drying-heating process of ladle, containing the time evolution of temperature value measured and, respectively, required by manufacturer, of the inner surface temperature of ladle masonry and of waste gas temperature at the exit from ladle. Also, it is presented the evolution during the process of the value of hourly flow rates of fuel and supplementary oxygen.

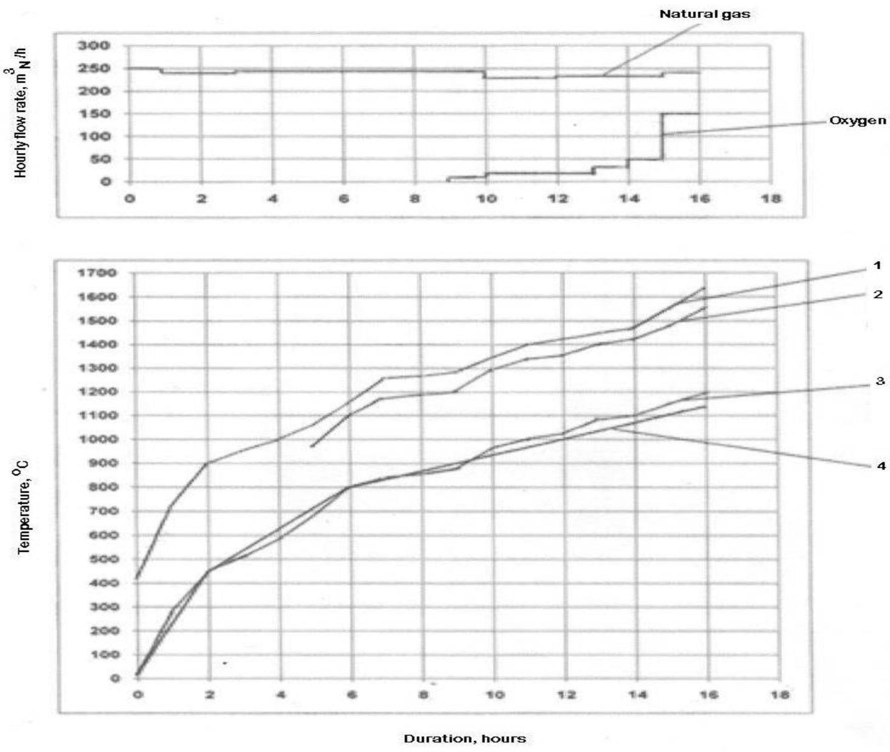

Fig. 3. Diagram of the drying-heating process of a ladle built with dolomite blocks as a wear layer: 1 – waste gas temperature at the exit from the ladle; 2 – temperature on the inner surface of ladle masonry; 3 – temperature inside the masonry measured in the point indicated by manufacturer; 4 – temperature inside the masonry according to the diagram required by manufacturer.

Analyzing the experimental data presented in table 5 and graphically represented in Fig. 5, it results that, in case of drying-heating process of the ladle built with dolomite blocks as a wear layer, respecting the diagram imposed the burner operation at its nominal capacity without supplementary oxygen up to the temperature of 880 ºC inside the masonry. Then, it was necessary the oxygen enrichment of air to maintain the increasing slope imposed by the heating diagram and to reach the final temperature of 1200 ºC in the recommended time range.

From the experimental data results that waste gas temperature at the exit from ladle is higher with about 400 ºC than the temperature measured inside the masonry, reaching 1640 ºC at the end of process. The high difference between waste gas temperatures resulted in the drying-heating process of dolomite blocks and magnesia bricks and the temperatures measured inside the refractory lining of the ladles built with these materials, of about 400 ºC and, respectively, 150 ºC, in conditions of obtaining the same final temperature values inside the ladle masonry (1200 ºC), confirms that there is a significant difference between the values of the coefficients of heat transfer by thermal conductivity of the two refractory lining types. Thus, the thermal energy distribution and, implicitly, the heat accumulation in the dolomite masonry mass are achieved more difficult comparable with the same distribution and accumulation in the magnesia masonry mass.

The total consumption of natural gas during the process was 3,850 m^3_N and the total consumption of supplementary oxygen was 300 m^3_N.

6. Technical parameters of the drying-heating process and the refractory linings durability of ladles

The use of the new burner in the drying-heating process of the steel ladles led to significant modifications of the process parameters and the increase of the refractory linings durability of ladles, compared to the results of the reference combustion installation. Thus, though the reference fuel consumption is higher for the two main masonry construction modes of the ladles (7,500 m^3_N compared to 5,400 m^3_N, in case of ladles with magnesia bricks and, respectively, 5,900 m^3_N compared to 3,850 m^3_N, in case of the ladles with dolomite blocks), the maximum heating temperature cannot exceed the value of 1050 ºC, while, using oxygen enrichment of air (in a volumetric proportion of 30%), the final temperature of process reaches 1200 ºC.

In table 6 they are presented, by comparison, the technical parameters of process and the ladles durability for the two variants of masonry construction obtained by the modification of the combustion installation [9].

Table 6

Technical parameters of the process and the ladles masonry durability

Name	Unit	Value	
		Refractory lining with magnesia bricks	Refractory lining with dolomite blocks
Refractory material mass built for one steel ladle	kg	15,100	12,300
Number of steel casting of a cycle - during the experiment - reference situation	 - -	 59 45	 62 40
Liquid steel amount casting in ladle - at one discharge - at the total cycle for: · dried and heated experimental ladle · reference situation	 t/ charge t/ cycle t/ cycle	 170 10,030 7,650	 170 10,540 6,800
Total natural gas consumption during the drying-heating process - during the experiment - reference situation	 m^3_N/ charge m^3_N/ charge	 5,400 7,500	 3,850 5,900
Electricity consumption of the air fan - during the experiment - reference situation	 kWh/ charge kWh/ charge	 202.5 225	 135 140
Oxygen consumption during the test	m^3_N charge	500	300
Duration of the drying-heating process - during the experiment - reference situation	 hours hours	 30 30	 16 16
Final heating temperature - during the experiment - reference situation	 ºC ºC	 1200 1050	 1200 1050

7. Economic effects

7.1. Calculus of specific consumption of the refractory materials

Knowing the mass of magnesia bricks (15100 kg) and dolomite blocks (12300 kg) which constitute the wear layer of refractory lining of ladles built in the first and, respectively, the second mode of masonry construction, as well as the steel amounts casted in the two ladle types during the experiment and, respectively, in the reference situation (10,030 t and 10,540 t, respectively, 7.650 t and 6,800 t), they are calculated the specific consumptions of magnesia bricks and dolomite blocks in table 7. Considering the prices of the two refractory natural types (€900/ t magnesia bricks and €350/ t dolomite blocks) [9], they are calculated the specific consumptions values, being indicated in the same table.

Table 7

Specific consumption and the value of refractory materials used at the masonry construction of the ladles wear layer

	Specific consumption of refractory materials, kg/ t steel		Specific consumption value of refractory materials, €/ t steel	
	Magnesia bricks	Dolomite blocks	Magnesia bricks	Dolomite blocks
Experimental ladles	1.51	1.17	1.36	0.41
Reference situation	1.97	1.81	1.77	0.63
Economy	0.46	0.64	0.41	0.22

7.2. Calculus of the specific consumptions of natural gas and electricity

The total natural gas and electricity consumptions for the cycle of using the ladles wear layer has been presented in table 6, both for the experimental ladles and for the reference situation. The electricity consumptions include the consumption at the combustion air fan and the indirect consumption necessary to produce the technical oxygen (0.65 kWh/ m^3_N). The average price of natural gas is €250/ 1000 m^3_N and the average price of electricity is €90/ MWh [9].

The calculus results of energy consumption value (natural gas and electricity) corresponding to a cycle of using the wear layer of ladles, as well as the cumulated specific consumptions value of energy, are presented in table 8.

Table 8

Calculus the value of cumulated specific consumptions of energy

	Type of material in the wear layer	Value of energy consumption €/ cycle		Value of cumulated specific consumption	
		Natural gas	Electricity	€/ cycle	€/ t steel
Experimental ladles	Magnesia bricks	1350	47.5	1397.5	0.14
	Dolomite blocks	962.5	29.7	992.2	0.09
Reference situation	Magnesia bricks	1875	20.3	1895.3	0.25
	Dolomite blocks	1475	12.6	1487.6	0.22
Economy	Magnesia bricks	-	-	497.8	0.11
	Dolomite blocks	-	-	495.4	0.13

According to the data from table 8, it results that the value of cumulated specific consumption of energy (natural gas and electricity), in case of masonry construction with magnesia bricks, is diminished from €0.25/ t steel to €0.14 / t steel, resulting an economy of €0.11/ t steel and, in case of masonry construction with dolomite blocks, is reduced from €0.22/ t steel to €0.09/ t steel, resulting an economy of €0.13/ t steel.

Analyzing the distribution of energy consumption values between the two components (natural gas and electricity), it can be observed that, in case of experimental ladles, the values of electricity consumptions increased over twice, explicable by the supplementary consumption of oxygen. But, it is important to decrease the values of natural gas consumptions at the experimental ladles, even more as the final lining temperature of these ladles (1200 ºC) is obviously higher than the final temperature obtained in the reference situation (only 1050 ºC). Moreover, the increase in value of electricity consumptions is compensated by the significant reduction of the value of natural gas consumptions, so that the value of the cumulated consumption of energy indicates economies in the two modes of ladles masonry construction.

7.3. Calculus of the net economies resulting by the increase of ladles durability

According to the data from table 6, the durability of the experimental ladles lining increased obviously from 45 to 59 casting/ cycle at the ladles with magnesia bricks and from 40 to 62 casting/ cycle at the ladles with dolomite blocks, leading to the significant increase of the steel amounts casted in the two ladle types. Considering that the layers' masses of magnesia bricks and, respectively, dolomite blocks are not modified, it results that, by reporting to greater steel amounts, the specific consumption of refractory materials and, implicitly, their values are diminished.

This economic advantage is obtained by amplifying the energy requests of the combustion installation, that makes the drying and heating ladles lining. To highlight clearly the efficiency of using the new combustion installation achieved and applied industrially it is necessary to summon the consumption values of natural gas and refractory materials (from table 7) and the consumption values of natural gas and electricity (from table 8) corresponding to the reference and experimental ladles. Subtracting from the total value of the material and energy consumptions of the reference ladles, the total value of the same type consumptions of the experimental ladles, it is obtained the net economy value due to the innovative solution. The results of these calculations are presented in table 9.

According to the data from table 9, the cumulated values of refractory materials and energy consumptions economies are €0.52/ t steel, for the ladles built with magnesia bricks and, respectively, €0.35/ t steel, for the ladles built with dolomite blocks.

Table 9

Calculus of efficiency applying the technical solutions

	Refractory lining type	Specific consumption value of the refractory material €/ t steel	Value of the energy consumption at the ladle drying and heating €/ t steel	Total value of consumptions €/ t steel
Experimental ladles	Magnesia bricks	1.36	0.14	1.50
	Dolomite blocks	0.41	0.09	0.50
Reference situation	Magnesia bricks	1.77	0.25	2.02
	Dolomite blocks	0.63	0.22	0.85
Economy	Magnesia bricks	0.41	0.11	0.52
	Dolomite blocks	0.22	0.13	0.35

The values of these economies are not high, but it must be considered that there is an obvious difference between the maximum limits of temperature reached in the experimental ladles masonry (1200 ºC) and the reference ladles masonry (1050 ºC).

8. The impact on environment

During the drying-heating experimental process they are carried out determinations of waste gas composition, corresponding to the both masonry construction types of ladles [14]. The CO concentration in waste gas is in the range 19 – 31 mg/ m^3_N, below the maximum limit of 100 mg/ m^3_N allowed by the MAPPM Order no. 462/ 1993 [15].

The concentration of nitrogen oxides NO and NO_x has values comprised in the range 210 – 265 mg/ m^3_N, at the operation without oxygen enrichment of air and 200 – 246 mg/ m^3_N, at the operation with oxygen enrichment of air, in conditions in which the maximum limit allowed by law is 350 mg/ m^3_N [15]. Determinations of the pollutants concentration in waste gas resulted in the drying-heating processes achieved with the reference combustion installations indicate high exceeding of the maximum limit allowed for CO (160 – 200 mg/ m^3_N) and values close to the maximum limit allowed for NO and NO_x (310 – 350 mg/ m^3_N).

9. Conclusions

1. The combustion installation for drying and heating the steel ladles masonry of 180 t was conceived, achieved and industrial tested at the Converters Steelwork in ArcelorMittal Galati.
2. The main aim of research presented in the paper is the increase of maximum heating temperature of the refractory lining of new built steel ladle up to 1200 ºC by techniques of intensification of the combustion process.
3. The installation is based on intensification solutions of combustion by oxygen enrichment of combustion air of 30% to ensure energy conditions need to reach the final temperature of 1200 ºC (the measurement point being situated inside the masonry 50 mm from the metal shell, in the posterior area of ladle) and to achieve the heating speeds required by the refractory materials manufacturers.
4. The own conception burner is characterized by the distribution of a preponderantly central jet (80%) of natural gas, surrounded by annular jets of flame produced by the mixture between the radial distributed fuel and the primary combustion air. They are provided three mixture stages between fuel and air, the secondary and tertiary air coming later in contact with the ignited fuel. Thus, the flame is radiant by self-carburizing and the phased contact system between fuel and air ensures low emissions of nitrogen oxides. The oxygen for enrichment of air is injected in the air stream in the supply connection area.
5. The industrial experimentation of the burner confirmed the correctness of selection the solutions of combustion intensification, the diagrams of drying and heating ladles masonry being achieved according to the requests of the refractory materials manufacturers.
6. Due to respect the drying-heating diagrams, the durability of the wear layer of ladles (magnesia bricks or dolomite blocks) increased significantly from 45 and, respectively, 40 steel castings/ cycle, up to 59 and, respectively, 62 castings/ cycle.
7. At the technical advantage of the new heating system, represented by the difference between the maximum temperature values inside the masonry (1200 ºC compared to 1050 ºC), it is added the economic advantage constituted by the cumulated material and energy economies between €0.35 – €0.52/ t steel.
8. The new system of combustion intensifying in the drying-heating process of the steel ladles, according to the authors' design, was applied for the first

time in the Romanian iron and steel industry and is used at all drying and heating stands at the Converters Steelwork in ArcelorMittal Galati.

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