The application of fuel burning pulsating resonance during drying and heating processes of steel-teeming ladles

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Abstract
The results of the experimental-industrial tests of the fuel burning pulsating resonance system at the posts of drying and heating of steel-teeming ladles are given in the paper. The high performance and efficiency of the system were established. Reduction of the natural gas saving was 2.7 ÷ 26.1% when ladles drying, and 19.5 ÷ 37.8% when heating.
Keywords: PULSATION, BURNING, NATURAL GAS, STEEL-TEEMING LADLE, DRYING, HEATING

Introduction

In ferrous metallurgy in addition to the basic metallurgical industries a number of ancillary areas are also significant consumers of fuel. Among these consumers the ladle preparation is stood out, namely the processes of drying and heating of ladle linings. Often these processes use scarce and expensive natural gas in a large amount.

Problem state

The application of a number of methods and devices for drying and heating of the steel-teeming ladles is possible (see. Fig. 1).

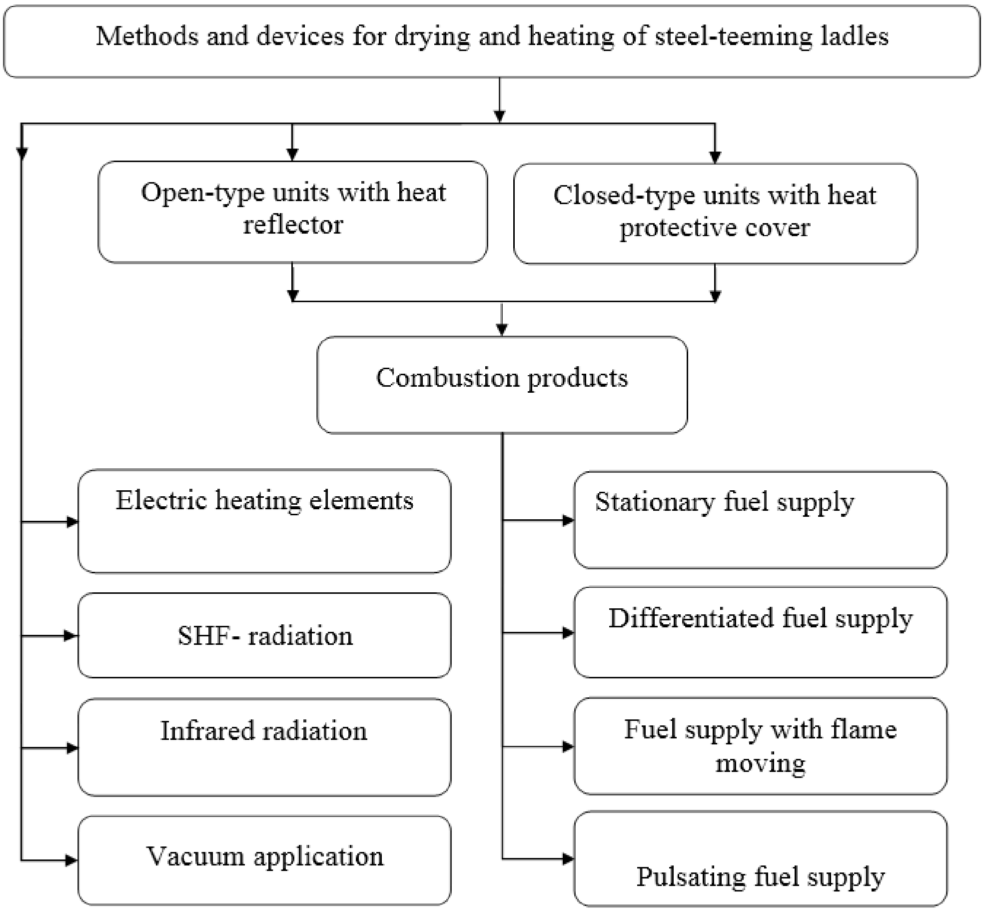

Figure 1. Methods and devices for drying and heating of steel-teeming ladles

More than 80% of the steel teeming ladles drying and heating processes are carried out with the combustion products. The differentiated supply, fuel supply with flame moving, pulsation and other methods are applied to eliminate thermal defects of ladle linings and more efficient use of fuel heat in addition to the stationary fuel supply.

However, drying and heating of combustion products has a number of drawbacks:

- low coefficient of fuel power usage (30%);

- contamination of workplaces and environment with harmful components (oxides of sulfur, nitrogen, carbon) of fuel combustion;

occurrence of thermal defects on the ladle linings.

In order to eliminate thermal defects of the lining the application of "soft" mode of drying and heating of ladles with adjustable fuel supply is proposed [1]. When drying the temperature of the lining external surface in this case as opposed to "hard" mode does not exceed the evaporation temperature of water, which helps to reduce thermal lining defects.

The introduction of additional structural elements (insert pieces) to the workspace of ladles leads to intensification of heat transfer between the flow of combustion products and lining, which increases the utilization coefficient of fuel combustion power [2, 3]. The disadvantage of this method is the complexity of the devices design for drying and heating of steel-teeming ladles.

A number of other design and technological solutions aimed at improving the processes of drying and heating of steel teeming ladles with using fuel are known [4-6].

In the paper [4], the use of the cyclic modes for drying and heating of steel teeming ladles is proposed. The application of cyclic modes improves coefficient of fuel power utilization and reduces the risk of local overheating of the lining. The disadvantage of the cyclic mode is the impossibility of reducing the duration of the drying and heating processes.

A method of combined heat supply mode into the workspace of the ladle is known, which is also the alternation supply of the combustion products and the heated air [5]. This method of supplying heat allows eliminating lining overburning, however, it requires significant fuel consumption.

When ladles drying and heating processes according to the method proposed in [6], recuperative and regenerative burners have been used. They allow reducing fuel consumption due to heating fuel and air by combustion products. It does not provide uniform heating of the lining and reducing the duration of drying and heating.

The electrical heating elements [7], SHF radiation [8], infrared radiation [9] and vacuum application [10] can be used as an alternative to the combustion products.

Widespread use of electric heating elements that improve thermal efficiency coefficient of drying and heating processes up to 50% holds back a little service life of heating elements and complicated technology of their production.

Drying and heating of the ladle lining by means of SHF-radiation ensures uniform heating of the lining entire volume, which eliminates the occurrence of thermal defects therein and improves coefficient of processes efficiency up to 60%. At the same time disadvantage of this method is a significant decrease in the efficiency coefficient of drying process as removing moisture from the lining, because a major component which absorbs microwave radiation is water. When using SHF-radiation an emergency organization to protect staff from the influence of microwave radiation is required.

In paper [10], the results of experimental studies of the vacuum use in the drying and heating processes of steel-teeming ladles are shown. The duration of processes, and accordingly, fuel expenditure are reduced by 30%. A significant drawback of this method includes reduction in hardness of the lining, which worsens its quality.

In general, alternative technologies listed significantly complicate the drying and heating processes as compared to conventional processes using fuels and in some cases require the application of expensive custom equipment. At the same time, alternative solutions are energy-intensive technologies.

Research problem statement

In order to reduce the consumption of natural gas it is advisable to use fuel burning pulsating resonance [11], from introduction of which we should expect:

- more thorough heat treatment of the inner surface of the ladle working volume by eliminating stagnant zones insufficiently washed with products of combustion;
- intensification of heat exchange between combustion products and the ladle lining;
- improved fuel efficiency due to the reduction of unburnt fuel.

There are three options of excitation of the fuel burning pulsating resonance mode: pulsations excitation on the gas pipeline, on the air pipeline and share excitation of pulsations on the gas and air pipeline.

The objective of this work was to evaluate the applicability of the burning fuel pulsating resonance for drying and heating processes of steel-teeming ladles through the introduction of the developed system and evaluation of its performance in industrial conditions.

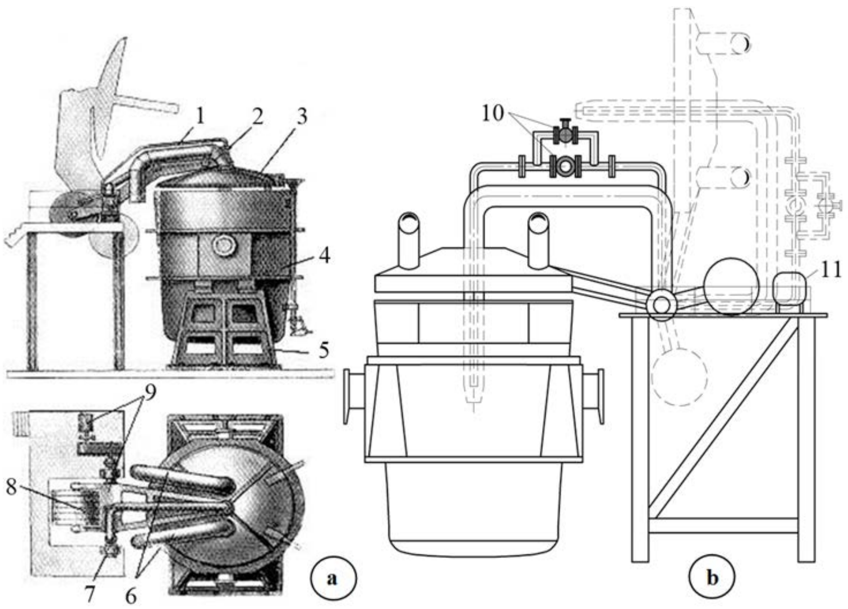

Figure 2. Stand for ladle drying

a – general view; b – arrangement scheme of the pulsating unit; 1 – gas pipeline; 2 – burner; 3 – cover; 4 – ladle; 5 – supports; 6 – exit flue for combustion products; 7 – air piping; 8 – counterweight; 9 – cover swing mechanism; 10 – pulsating unit; 11 – power supply and control

The researches were preceded by the development of hardware for fuel burning pulsating resonance on the drying and heating stands of steel-teeming ladles, the assembly of pulsating devices on the gas pipelines of drying and heating stands, the acoustic analysis of the ladles working volume and selection of standard ladles for comparison with experimental data.

Research on the drying post

The research was carried out in the Electric Steel Melting Shop No2 JSC "Oskol Electric Steel Works." General view of the stand for the drying of steel-teeming ladles and the arrangement scheme of pulsation unit is shown in Fig. 2.

The stand consists of supports on which the ladle is mounted and swing cover with the burner.

On the stand, the burner of "pipe in pipe" type is installed. The pulsations of the gas flow are created by pulsating unit mounted on the gas pipeline and executed in the form of mechanical pulsator with cylindrical interrupter of the gas flow. The pulsator is driven by DC electric motor that is connected to the network via resistor.

By rotating pulsator, the passage section of the pipeline supplying the natural gas is overlapped with predetermined frequency, which leads to periodic compression and rarefaction of natural gas flow and formation of elastic oscillations.

The scheme of hardware of fuel burning pulsating resonance when drying the steel-teeming ladles is shown in Fig. 3.

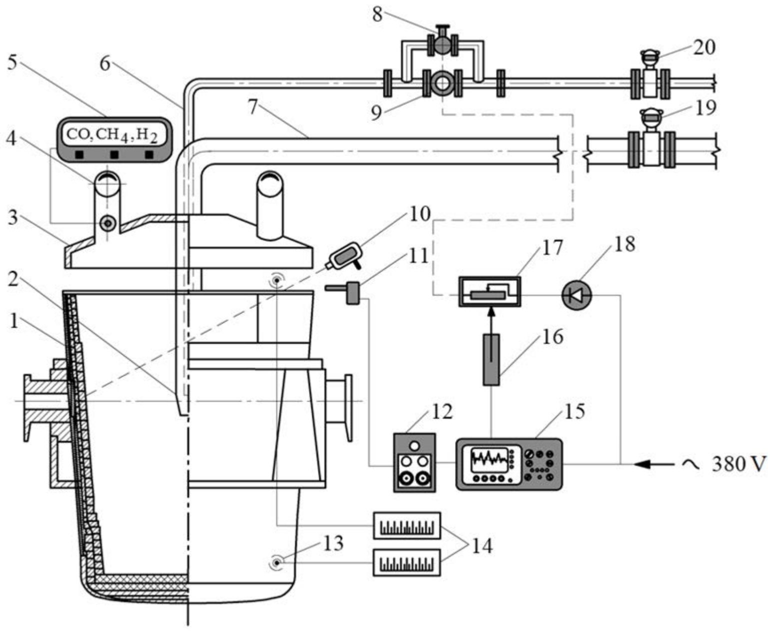

Figure 3. The scheme of hardware of fuel burning pulsating resonance when drying the steel-teeming ladles

1 – ladle; 2 – burner; 3 – cover; 4 – exit flue for combustion products; 5 – chromatograph; 6 – gas pipeline ; 7 – air piping; 8 – bypass; 9 – pulsating unit; 10 – thermal radiation pyrometer; 11 – acoustic probe; 12 – preamplifier; 13 – thermocouple; 14 – potentiometers; 15 – spectrum analyzer; 16 – actuating mechanism; 17 – resistor; 18 – rectifier; 19, 20 – flowmeters

An acoustic probe that sends a signal to the preamplifier, from which the amplified signal is routed to the spectrum analyzer, determines required frequency of interruption of gas flow for the resonance.

The frequency at which the maximum amplitude of the oscillations is determined by spectral analysis and thus the number of electric motor revolutions, which is necessary to obtain a resonant frequency, is determined:

$$n = 60 \cdot \omega / 2 \cdot \pi, \text{ r/min}, \qquad (1)$$

where ω - circular frequency of the gas flow interruption, Hz

The pulsator by-pass in combination with a valve mounted thereon allows adjusting the amplitude of pulsations by changing the amount of gas passing through the pulsator. When the valve on the bypass is closed gas completely passes through the pulsator. Opening of valve bypasses some part of gas to bypass and reduces pulsator gas flow, which decreases the degree of gas condensation before the pulsator and accordingly reduces the pulsations amplitude.

Thus, the amplitude of the pulsations is adjusted by the position of the valve in the bypass, which allows changing the ratio of gas consumption passing through the pulsator and the bypass. The pulsations frequency is adjusted by changing the electric current voltage supplied to the pulsator's drive by altering resistance of the resistor with actuating mechanism.

The temperature of the ladle lining surface was determined with pyrometer at 500-700 mm below the upper edge of the ladle. The ladle shell temperature was measured by contact thermocouple. This allowed us to control drying processes of the ladle in accordance with the technological instructions.

Chemical unburning was evaluated according to the content of carbon monoxide (CO) in the combustion products, which was determined by chromatography.

Drying of the ladle lining was carried out after the complete replacement of the working layer. The test results are shown in Table 1.

Table 1. The results of tests during drying process of steel-teeming ladles

Test No	Ladle No	Pulsations frequency, Hz	Lining temperature, °C	Shell temperature, °C	Total natural gas consumption, m^3	Natural gas saving, %
-	H	-	~900	75	2570	-
1	36	45÷55 18÷25	~900	77	2370	7.8
2	31	18÷25	1050÷1060	78	2500	2.7
3	2	18÷25	~1100	75	2295	10.7
4	5	18÷25	1050÷1120	79	2230	13.2
5	12	18÷25	1050÷1120	80	2215	13.8
6	25	18÷25	~900	87	2020	21.4
7	36	18÷25	~900	74	1900	26.1
8	30	18÷25	~900	76	2200	14.4

Changes in the supply of the natural gas during the experiments are presented in Fig. 4.

Drying of the first test ladle (No 36) had been taking place according to the schedule for five hours corresponding the technological instruction, i.e. according to the schedule of the standard ladle (H). At the end of the fifth drying hour the pulsating unit for fuel burning was on and began searching for the resonance mode. The frequency of pulsations when searching of the resonance mode was changed in the range of 15 ÷ 60 Hz. At the same time bypass remained open. With open bypass resonant mode was not detected requiring bypass overlap.

When completely overlaped bypass the significant resonance effect in the frequency range of 45 ÷ 55 Hz was found, however, work in this frequency range was not possible due to the resonant excitation of the drying post structures.

A second less intense peak of the resonance frequency (subharmonic) was detected before completion of the drying process in the range of 18 ÷ 25 Hz . The definition of this range occurred at the beginning of the tenth hour of the ladle drying. At the same time decreased in the sixth hour fuel consumption was increased to the standard, since the delay of ladle lining heating was observed.

Drying of the second test ladle (No 31) was carried out on the standard schedule in the pulsating resonance mode with a frequency range of pulsations 18 ÷ 25 Hz.

Due to incorrect installation of the ladle relative to the cover (eccentricity was about 300 mm) the resonance effect was slightly weakened.

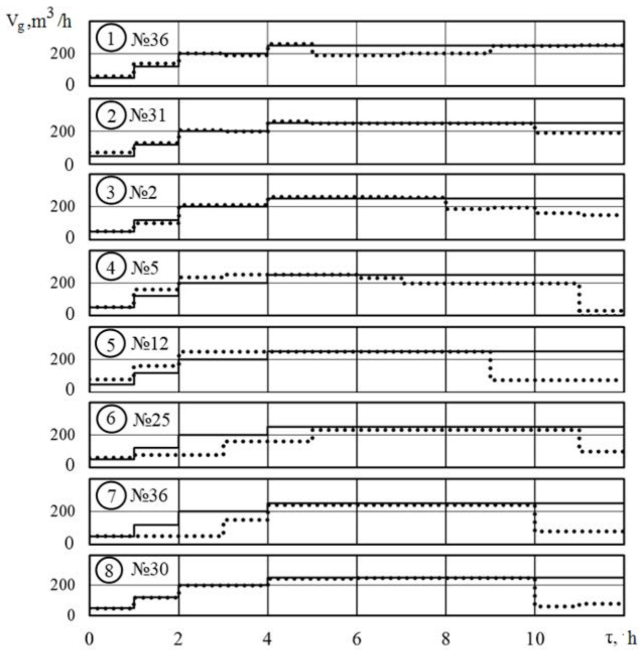

Figure 4. Changes in the supply of natural gas (V_g) during the ladles drying when fuel burning pulsating resonance

1…8 – numbers of the tests; ———— standard mode; .... test mode

Nevertheless, after seventh hour of ladle drying the temperature on the lining on distances of 500-700 mm from ladle edge was 1050-1060°C, that was significantly above the standard (900°C). The ladle shell temperature reached the standard value (75°C) after ten hours of drying. All this allowed us after the tenth hour and to the end of drying to reduce the gas consumption in relation to the standard consumption.

Drying of the third test ladle (No 2) during the first seven hours was carried out by the standard schedule of fuel supply in pulsating resonance mode with frequency range 18 ÷ 25 Hz . .

During this period the flame stability was studied. Artificial flameout was produced by supplying excess air followed by reduction of the combustion process.

The high stability of the flame was established, which was not inferior to the flame in the normative drying mode. Enough solid and stable flame was maintained at a greater deviation from the stoichiometric ratio "fuel-air". On the eighth hour of drying the tests related to the flame stability were stopped.

After eight hours of drying temperature of the ladle lining was 1040°C. The lining temperature after ten hours was 1100°C. Exceeding of the standard temperature (900°C) allowed reducing the gas flow rate after the eighth and the tenth hour of the ladle drying, respectively, maintaining pulsating resonance mode of fuel combustion.

In subsequent tests (No4÷8) the search of the optimal drying mode was carried out.

When drying of the fourth and fifth tests ladles (No 5 and No 12) the fuel consumption was increased in the first drying hours. The lining temperature was 1050÷1120°C at the end of the drying process on both ladles, the lining temperature had reached the standard value (900°C) considerably earlier than twelve hours of drying and, therefore, the drying cycle could be shortened to 9-11 hours. However, the actual reduction of the drying time was not possible, since it would lead to violation of the technological process organization in the lining of the shop. In particular, reducing of the drying time violates the work cycling of refractory lining area that creates a shortage of time for refractories burning and has a negative impact on their durability.

To keep the standard drying time the fuel supply for the ladle No 5 (after seventh hour of drying) and for the ladle No 12 (after the ninth hour of drying) was reduced. At the same time, the fuel burning pulsating resonance mode was maintained.

In the next two test ladles (No25 and No36) for maintaining the drying time within the standard value the gas supply during the initial drying period was slightly reduced. However, the rate of the lining temperature increase was significantly faster than standard, which required reducing the fuel consumption at the end of drying: for the ladle No 25 at the twelfth, and for the ladle No 36 at the eleventh hour to avoid overheating (over 900°C).

Drying of the last test ladle (No 30) was carried out in the resonance mode (18÷25 Hz) at the standard gas consumption up to the tenth hour of the drying inclusively. The gas consumption was reduced after the tenth hour of drying to exclude overheating.

In general, the test of fuel burning pulsating resonance mode on the drying stand of steel-teeming ladle allows us to note the following:

-work of pulsation unit on the gas pipeline stand provides the gas consumption and gas consumption change in accordance with the technological instruction;

- practically confirmed possibility of pulsating resonance frequencies search in an industrial conditions when a negative impact of temperature, acoustic interference and equipment inertia;

- sufficiently high efficiency of pulsation unit and the ability to stable maintaining required resonant frequencies of gas pulsations during the drying process have been established;

- more intensive course of the drying process, thereby reducing process time and thus decreasing the fuel consumption have been noted;

- saving of natural gas at the fuel burning pulsating resonance mode in comparison with the standard indicators was 2.7÷26.1 %;

- Test results allow us to recommend an experimental implementation of fuel burning pulsating resonance mode.

Research on the heating post

Research of fuel burning pulsating resonance during the heating of steel-teeming ladles in MSP-2 were held on the post No 1 of intense ladles heating for melting.

The scheme of hardware for fuel burning pulsating resonance is shown in Fig. 5.

The ladles after long idle hours were selected for tests, i. e. ladles heating was carried out from cold state.

The ladle was laid on movable trolley in horizontal position and moved to the deflection (refractory) wall with raised burner of GOP-9 type. The burner axis is located at a distance of 1/3 of the ladle diameter from the bottom edge.

In accordance with the technological instruction when the ladle has more than 6 idle hours without heating, the duration of the heating should be not less than 6 hours.

The search of resonance frequencies was performed similar to the tests on the ladles drying stand. The resonance frequencies range on the heating stand is slightly different from the resonant frequencies on the drying stand due to changes in the acoustic characteristics of the stand. Setting the resonance frequencies led to the working frequency range 18÷30 Hz.

The changes in gas consumptions during the tests are shown in Fig. 6.

The test results are presented in Table. 2.

Table 2. The results of tests on the heating post of steel-teeming ladles

Test No	Ladle No	Pulsations frequency , Hz	Lining temperature, °C	Shell temperature , °C	Total natural gas consumption, m³	Natural gas saving, %
-	H	18÷30	700	93	2000	-
1	38	18÷30	879	89	1550	22.5
2	9	18÷30	910	97	1610	19.5
3	19	18÷30	750	82	1335	33.3
4	8	18÷30	737	77	1245	37.8
5	12	18÷30	777	84	1425	28.8

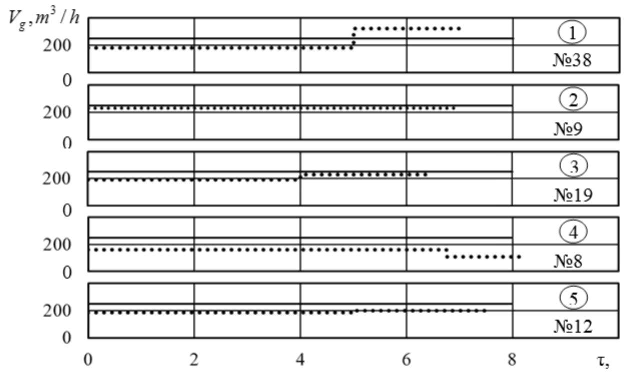

Figure 6. Changes in the supply of natural gas (V_g) during the ladles heating when fuel burning pulsating resonance

1…8 – numbers of the tests; ———— standard mode; .... test mode

Considering the more intensive heating when fuel burning pulsating resonant mode the gas consumption on heating the first test ladle (No 38) was reduced by 28% compared to the standard mode. After fifth hour of drying in the rate of heating the significant ladle underheating was established, which required increasing the gas flow rate over the standard by 30%. After seven hours of drying, the process was complete with the ladle overheating: 879°C instead of the standard value 700°C.

On the second test ladle (No 9) during the seven hours the consumption of natural gas was maintained by 8% lower than the standard rate. However, after seven hours of heating the significant overheating of ladle lining was obtained: 910°C instead of 700°C.

On the subsequent test ladles (No 19, No 8 and No 12), reduction in gas consumption was due to the need of excluding the significant ladles overheating over standard values. The final temperature of the ladles lining surface was 750°C, 737°C and 777°C respectively.

In general, the results of the tests of the fuel burning pulsating resonance system in the ladle heating post allowed, besides the above mentioned features of the system in the drying post, note the following:

- high excitability of the resonance frequencies in the ladle due to a small extent and volume of the gas pipeline area between the pulsating unit and the burner compared to the drying stand, where a large distance between the pulsator and the burner slows excitation of resonant frequencies due to the pulsations dissipation of the gas flow;
- significant increase of the heating intensity compared to the drying as a result of less high end lining temperature (777÷910°C instead of 900÷1120°C) and the absence of moisture vapor;
- the feasibility of use the fuel burning pulsating resonance mode at the posts of intensive ladles heating for melting was established, i.e. pulsating resonance mode allowed forcing the heating resonant pulsation of the flame along with an increase in gas consumption;
- natural gas saving is 19.5÷37.8%, that allows recommending fuel burning pulsating resonance mode on the heating stands to experimental implementation.

Conclusion

1. Experimental-industrial research had shown a high efficiency of developed fuel burning pulsating system when drying and heating of steel-teeming ladles. Reducing the consumption of natural gas; and therefore, its savings were 2.7÷26.1% when drying ladles, and 19.5÷37.8% when heating.

2. As a result of the test of fuel burning pulsating resonance mode on the ladles drying stand was found that work of the pulsation unit on the gas pipeline of the stand provided the gas consumption and the gas consumption changes in accordance with the technological instruction. In practice, the ability to search the pulsating resonance frequencies in industrial conditions despite the negative impact of temperatures, acoustic interferences and equipment inertia was confirmed. Sufficiently, high efficiency of the pulsating unit and the ability to stable maintaining the required resonance frequencies of the gas pulsations during the drying process was established. The intensive course of the drying process allowed reducing the process time and thus shortened fuel consumption.

3. Test results of fuel burning pulsating resonance system in the ladle heating post indicate the feasibility of using the fuel burning pulsating resonance mode at the posts of intensive heating of ladles for melting, since the pulsating resonance mode allows us to force the heating for melting by the flame resonance pulsation along with an increase in the gas consumption.

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