Розроблено спосіб пульсаційно-резонансного спалювання палива в процесах сушіння і розігріву сталерозливних ковшів з метою економії палива. Метод дослідження ґрунтується на збудженні пульсацій при спалюванні палива з частотою, яка дорівнює частоті власних коливань в робочому обсязі ковша, що призводить до резонансу пульсацій. Це дослідження проводилося з метою визначення способу ефективного спалювання палива й підтвердження зменшення споживання палива в процесі пульсаційно-резонансного спалювання.

В результаті дослідно-промислових випробувань на протязі 8 операцій сушіння та 5 операцій розігріву ковшів встановлена можливість забезпечення нормативним вимогам у відповідності до технологічних інструкцій на 80–100 %. Підтверджено можливість пошуку пульсаційно-резонансних частот у промислових умовах, попри негативний вплив високих температур, акустичних перешкод та інерційності апаратури. Встановлено працездатність пульсаційного блоку і можливість стабільної підтримки в процесі сушіння необхідних резонансних частот пульсацій газу. Відзначено більш інтенсивне протікання процесу сушіння, що дозволяє зменшити тривалість процесу і, відповідно, скоротити витрату палива. Виявлено високу збудливість резонансних частот у ковші при розігріві внаслідок невеликої протяжності та об'єму ділянки газопроводу між пульсаційним блоком та пальником порівняно зі стендом сушіння. Інтенсивність розігріву помітно вища порівняно із сушінням внаслідок менш високої кінцевої температури футеровки (777–910 °С замість 900–1120 °С) і відсутності випарів вологи. Застосування пульсаційно-резонансного режиму спалювання палива на постах інтенсивного розігріву ковшів під плавку дозволяє форсувати розігрів резонансною пульсацією факела. При пульсаційно-резонансному спалюванні помітно зростає корисне використання теплоти палива, що призводить до підвищення к. к. д. процесів сушіння і розігріву та до відповідної економії палива. Зниження споживання природного газу склало при сушінні ковшів 2,7÷26,1 %, а при розігріві – 19,5÷37,8 %. Наведені дані вказують на енергетичну ефективність пульсаційно-резонансного спалювання і доцільність впровадження способу спалювання в процесах сушіння і розігріву ковшів

Ключові слова: ківш, сушка, розігрів, спалювання, пульсація, резонанс, баланс, паливо, економія

UDC 669.184:662.612
DOI: 10.15587/1729-4061.2020.201077

AN EFFECTIVENESS ANALYSIS OF THE PULSED RESONANT FUEL COMBUSTION IN THE PROCESSES OF STEEL-CASTING LADLE DRYING AND WARMING

Yu. Gichov
Doctor of Technical Sciences, Professor*
E-mail: iurii.gichov@gmail.com
M. Stupak
Postgraduate Student*
E-mail: st.misha@i.ua
*Department of Industrial Power System
National Metallurgical Academy of Ukraine
Gagarina ave., 4, Dnipro, Ukraine, 49600

Received date 04.03.2020
Accepted date 20.04.2020
Published date 30.04.2020

1. Introduction

Among major fuel consumers in steelmaking are foundry bays for the preparation of steel-casting ladles, namely, for the processes of ladle drying and warming, which in some cases use scarce and expensive natural gas.

The cost of natural gas for drying, for example, a single ladle with a capacity of 160 tons, is up to 3,000 m^3; for warming – up to 2,000 m^3. As the ladle capacity increases, the consumption of natural gas increases accordingly.

One of the areas in fuel economy is to devise efficient techniques to burn fuel, thereby providing better combustion with less underburning and better utilization of the heat generated from fuel combustion. Such technologies include pulsed combustion.

Interest in pulsations is due to their positive impact on the characteristics of technological and energy processes. The use of pulsations in most cases begins with the impact on the combustion process of fuel by exciting the fluctuations in the gas and air flows participating in the combustion. The most effective manifestation of pulsations should be expected under resonance modes, that is, when the frequency of forced oscillations, which cause pulsations, coincides with the natural frequency of oscillations within the working volume of a firebox, a furnace, or a technological unit.

Given this, it is a relevant task to develop and implement an economical pulsed resonant fuel combustion technology in the processes of steel-casting ladle drying and warming.

2. Literature review and problem statement

In the total volume of processes of steel-casting ladle drying and warming, taking into consideration all drying and warming techniques, more than 80 % involve fuel combustion products. At the same time, the drying and warming with combustion products have a series of drawbacks: a low fuel heat utilization rate, the pollution of workplaces and the environment, the occurrence of thermal defects in the ladle lining, and so on.

To eliminate these deficiencies, it is recommended to regulate the supply of fuel, providing a "soft" mode of heat treatment. It is proposed to introduce additional partitions into the ladle cavity that could intensify the heat exchange [1–3], which, however, does not resolve the issue. It is possible to use the pulsed mode of fuel combustion [4], as well as the use of heat recovery [5], regenerative burners [6–8], and so on. However, according to our analysis, all these techniques were not used to dry and warm the steel-casting ladles and their application is problematic.

The above technical solutions do not fully eliminate the shortcomings in the ladle drying and warming by combustion products.

An alternative to fuel combustion products is found in electric heating elements, microwave radiation, infrared radiation, application of a vacuum, as well as other technical solutions. The alternative technologies significantly complicate the processes of ladle drying and warming in comparison with conventional techniques and, in some cases, require the use of non-standard expensive equipment. The alternative technologies are rather energy-intensive.

Given this, using the pulsed fuel combustion is of interest [9], including mechanical engineering [10–12] and rocket engineering [13], which could significantly reduce the fuel underburning and increase the intensity of heat output from combustion products, which indicates the prospects and demand for a given direction. However, all the studies carried out do not concern the drying and warming of steel-casting ladles. This work highlights the pulsed resonant combustion technique [14], at which the most effective pulsation frequencies (the most effective in reducing the underburning and in the intensification of heat release) are achieved at minimal energy costs for the generation of pulsations.

To assess the feasibility of using the pulsed resonant fuel combustion, it is necessary to have the appropriate equipment for the process, to confirm the possibility of finding the pulsed resonance frequencies under industrial conditions, taking into consideration high temperatures, acoustic interference, and the equipment inertia. This information has not been revealed in the scientific literature.

3. The aim and objectives of the study

The aim of this study was to assess the effectiveness of the pulsed resonant fuel combustion in the processes of steel-casting ladle drying and warming.

To accomplish the aim, the following tasks have been set:

– to adapt the pulsed resonant fuel combustion at existing steel-casting ladle drying and warming benches and to design the appropriate equipment for the processes;

– to conduct an experimental-industrial study at the drying and warming posts and to compare the results on the drying and warming of regular ladles based on conventional technologies without pulsation;

– to analyze the thermal balances of steel-casting ladle drying and warming processes based on the results from the experimental-industrial study in order to determine the energy efficiency of the pulsed resonant fuel combustion in comparison with a conventional combustion technology without pulsations.

4. The equipment and adaptation of the pulsed resonant fuel combustion method

The study method is based on the initiation of pulsations when burning fuel at a frequency equal to the frequency of natural fluctuations within the working volume of a ladle, which leads to the resonance of the pulsations. The principal diagram of the bench for the pulsed resonant fuel combustion in a steel-casting ladle is shown in Fig. 1.

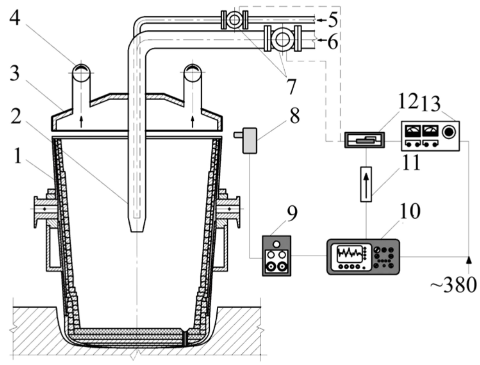


Fig. 1. The principal diagram of a bench for drying the steel-casting ladles through the pulsed resonant fuel combustion: 1 — ladle; 2 — burner; 3 — cover; 4 — gas pipeline to discharge combustion products; 5 — gas pipeline; 6 — air pipeline; 7 — pulsation unit; 8 — acoustic probe; 9 — preamp; 10 — spectrum analyzer; 11 — controlling element; 12 — rheostat; 13 — straightener

The spectrum of oscillation frequencies in a ladle is recorded by acoustic probe 8. The signal from the probe is transmitted through preamp 9 to spectrum analyzer 10, where the working frequency of natural oscillations is selected. Based on the magnitude of a working frequency, controlling element 11 sets, through rheostat 12, the predefined DC voltage on the electric motors in the pulsation unit. This enables the pulsators' rotation at a speed corresponding to the oscillation natural frequency within the working volume of the ladle.

5. Experimental and industrial study of the pulsed resonant combustion

The study was carried out at 160-ton steel-casting ladles. The general view of the bench for drying steel-casting ladles and the arrangement scheme of the pulsation unit are shown in Fig. 2.

The bench includes the racks that host the ladle and a turning cover with a burner. The pulsations of gas flow are created by a pulsation unit installed on the gas pipeline, fabricated in the form of a mechanical pulsator with a cylindrical gas flow interrupter [15].

A schematic of the equipment to enable the pulsed resonant fuel combustion at the drying post is shown in Fig. 3.

The lining of the ladle was dried after the complete replacement of the working layer. The test results are given in Table 1 (H – regular ladle).

Testing the pulsed resonant fuel combustion at the bench of steel-casting ladle drying makes it possible to note the following:

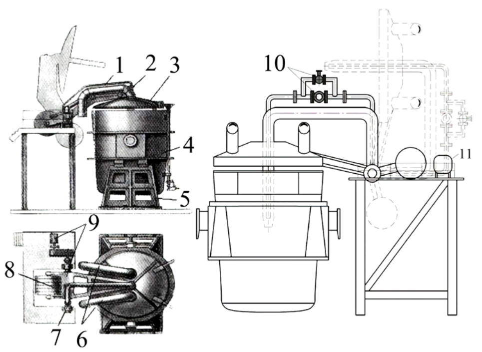
– the possibility to search for the pulsation resonance frequencies under industrial conditions has been confirmed, despite the negative impact exerted by high temperatures, acoustic interference, and the equipment inertia;

– the pulsation unit has been found to operate rather sufficiently; the possibility to steadily maintain the necessary resonance frequencies of gas pulsations during the drying process has been established;

– a more intensive course of the drying process has been noted, which shortens the process length and reduces fuel consumption accordingly;

– the savings of natural gas under the pulsed resonant fuel combustion mode amounted, in comparison with the normative indicators, to 2.7÷26.1 %;

– the test results allow us to recommend the pulsed resonant fuel combustion mode for the experimental introduction.



a *b*

Fig. 2. A steel-casting ladle drying bench: *a* — general view; *b* — pulsation unit arrangement scheme; 1 — gas pipeline; 2 — burner; 3 — cover; 4 — ladle; 5 — rack; 6 — gas pipelines to discharge combustion products; 7 — air pipeline; 8 — counter-load; 9 — cover turning mechanism; 10 — pulsation unit; 11 — power and control unit

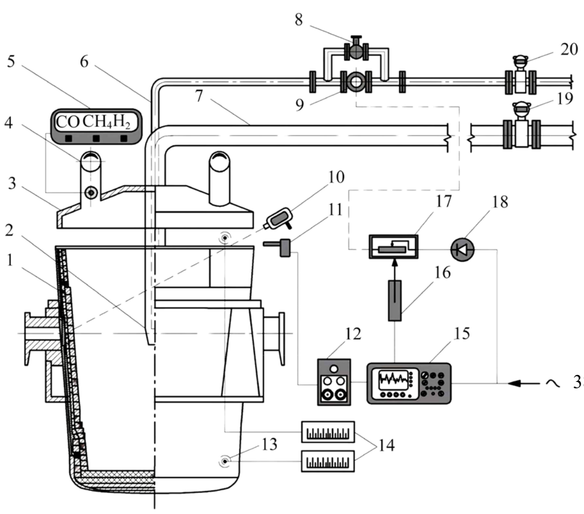


Fig. 3. Schematic of equipment for the pulsed resonant fuel combustion at the post of steel-casting ladle drying: 1 — ladle; 2 — burner; 3 — cover; 4 — gas pipeline to discharge combustion products; 5 — chromatographer; 6 — gas pipeline; 7 — air pipeline; 8 — bypass pipe; 9 — pulsation unit; 10 — radiation pyrometer; 11 — acoustic probe; 12 — preamp; 13 — thermocouple; 14 — potentiometers; 15 — spectrum analyzer; 16 — controlling element; 17 — rheostat; 18 — straightener; 19, 20 — flowmeters

The scheme of equipment for the pulsed resonant fuel combustion at a ladle warming post is shown in Fig. 4.

Our experiments involved ladles after a long idling time, that is, the warming of the ladles started from a cold state. A ladle was placed on a mobile trolley in a horizontal position and moved towards the fencing (refractory) wall with a protruding burner, the HNP-9 type. The axis of the burner is located at a distance of 1/3 of the diameter of the ladle from the bottom edge. The results of the experiments are given in Table 2 (H – regular ladle).

Table 1

Test results at the post of steel-casting ladle drying

Experiment No.	Ladle No.	Pulsation frequency, Hz	Lining temperature, °C	Casing temperature, °C	Total natural gas flow rate, m^3	Natural gas savings, %
–	H	–	~900	75	2,570	–
1	36	45÷55 18÷25	~900	77	2,370	7.8
2	31	18÷25	1,050÷1,060	78	2,500	2.7
3	2	18÷25	~1,100	75	2,295	10.7
4	5	18÷25	1,050÷1,120	79	2,230	13.2
5	12	18÷25	1,050÷1,120	80	2,215	13.8
6	25	18÷25	~900	87	2,020	21.4
7	36	18÷25	~900	74	1,900	26.1
8	30	18÷25	~900	76	2,200	14.4

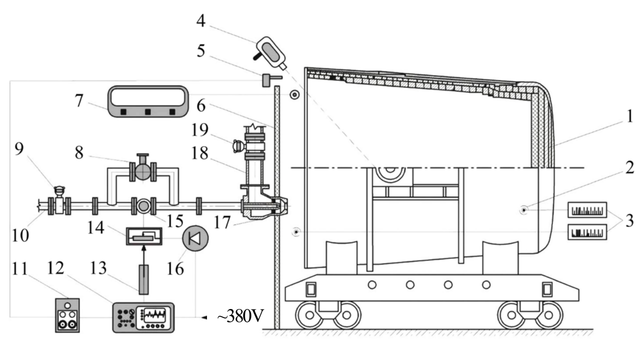


Fig. 4. The scheme of equipment for the pulsed resonant fuel combustion at the post of intensive warming of ladles for melting: 1 — ladle; 2 — thermocouple; 3 — potentiometers; 4 —radiation pyrometer; 5 — acoustic probe; 6 — fencing wall; 7 — chromatographer; 8 — bypass pipe; 9 — flow meter;10 — gas pipeline; 11 — preamp; 12 — spectrum analyzer; 13 — controlling element; 14 — rheostat; 15 — pulsation unit; 16 — straightener; 17 — burner; 18 — air pipeline; 19 — flow meter

The results of testing the system for the pulsed resonant fuel combustion at the post of steel-casting ladle warming allow us, in addition to the above features in the system operation at the drying post, to note the following:

– the high excitability of resonance frequencies in a ladle due to the short length and volume of the section of a gas pipeline between the pulsation unit and burner compared to the drying bench;

– a noticeable increase in the warm-up intensity compared to drying due to the lower end temperature of the lining (777–910 °C instead of 900–1,120 °C) and the lack of moisture evaporation;

– the expediency of using the pulsed resonant fuel combustion mode at the posts of intensive warming of ladles for melting as the pulsed resonant mode makes it possible, along with the increased gas consumption, to force the warm-up by the resonance pulsation of the flame;

– the savings of natural gas at the warming post amounted to 19.5÷37.8 %, which allows us to recommend the pulsed resonant fuel combustion mode at the warm-up benches for experimental implementation.

Table 2

Test results at the post of steel-casting ladle warming

Experiment No.	Ladle No.	Pulsation frequency, Hz	Lining temperature, °C	Casing temperature, °C	Total natural gas flow rate, m^3	Natural gas savings, %
–	H	18÷30	700	93	2,000	–
1	38	18÷30	879	89	1,550	22.5
2	9	18÷30	910	97	1,610	19.5
3	19	18÷30	750	82	1,335	33.3
4	8	18÷30	737	77	1,245	37.8
5	12	18÷30	777	84	1,425	28.8

6. Thermal balance analysis

An analysis of the thermal balances of the processes of steel-casting ladle drying and warming implied comparing the usable utilized heat and heat losses.

The usable unitized heat includes the consumption of heat for warming the working masonry Q_w, the reinforcement row Q_r, insulation Q_{in}, casing Q_{cas}, and for evaporating the moisture Q_{ev} at drying. The remaining consumption of heat relates to losses: the loss of heat with outgoing gases Q_{out}, from the chemical underburning of fuel Q_{ch}, the heat transmission to the environment through the ladle lining Q_{htll} and through the cover Q_{htc} as well as the loss of heat to warm the cover Q_c and the loss of heat by radiation into the gap between the top cut of the ladle and the cover Q_{rad} (Fig. 3).

At the warm-up bench, instead of the losses of heat associated with the ladle cover ($Q_{htc,}$ Q_c and Q_{rad}), the consumption part of the thermal balance includes the loss of heat associated with the fencing wall of the bench Q_{wb} (Fig. 4).

The input part of the thermal balance includes the heat of fuel combustion.

$$Q_{com} = B \cdot Q_{ng}, \text{ MJ,} \tag{1}$$

where B is the consumption of natural gas for drying or warming up a ladle, m^3; Q_{ng} is the heat of natural gas combustion, MJ/m^3.

The output part of the thermal balance was determined as follows:

1) the consumption of heat to warm the working masonry:

$$Q_w = M_w \cdot \left[\left(c_w\right)_0^{\bar{t}_w} \cdot \bar{t}_w - \left(c_w\right)_0^{t_{init}} \cdot t_{init} \right] \cdot 10^{-3}, \text{ MJ,} \tag{2}$$

where M_w is the weight of working masonry, kg; $\bar{t}_w$ is the average temperature of the working masonry at the end of drying or warming, °C; $\left(c_w\right)_0^{\bar{t}_w}$, $\left(c_w\right)_0^{t_{init}}$ are the mean heat capacities of the material for a working masonry, kJ/kg·K; t_{init} is the initial temperature of ladle lining, °C;

2) the consumption of heat to warm the reinforcement row:

$$Q_r = M_r \cdot \left[\left(c_r\right)_0^{\bar{t}_e^r} \cdot \bar{t}_e^r - \left(c_r\right)_0^{t_{init}} \cdot t_{init} \right] \cdot 10^{-3}, \text{ MJ,} \tag{3}$$

where M_r is the weight of the lining reinforcement row, kg; $\bar{t}_e^r$ is the average temperature of the reinforcement row at the end of drying or warming, °C; $\left(c_r\right)_0^{\bar{t}_e^r}$, $\left(c_r\right)_0^{t_{init}}$ are the mean heat capacities of the material for a reinforcement row, kJ/kg·K;

3) the consumption of heat to warm the insulation:

$$Q_{in} = M_{in} \cdot \left[\left(c_{in}\right)_0^{\bar{t}_e^{in}} \cdot \bar{t}_e^{in} - \left(c_{in}\right)_0^{t_{init}} \cdot t_{init} \right] \cdot 10^{-3}, \text{ MJ,} \tag{4}$$

where M_{in} is the mass of the thermal insulation, kg; $\bar{t}_e^{in}$ is the average temperature of the thermal insulation at the end of heating, °C; $\left(c_{in}\right)_0^{\bar{t}_e^{in}}$, $\left(c_{in}\right)_0^{t_{init}}$ are the average heat capacities of the thermal insulation material, kJ/kg·K;

4) the consumption of heat to warm the casing:

$$Q_{cas} = M_{cas} \cdot \left[\left(c_{cas}\right)_0^{\bar{t}_e^{cas}} \cdot \bar{t}_e^{cas} - \left(c_{cas}\right)_0^{t_{init}} \cdot t_{init} \right] \cdot 10^{-3}, \text{ MJ,} \tag{5}$$

where M_{cas} is the weight of the ladle casing, kg; $\bar{t}_e^{cas}$ is the average temperature of the casing at the end of the process, °C; $\left(c_{cas}\right)_0^{\bar{t}_e^{cas}}$, $\left(c_{cas}\right)_0^{t_{init}}$ are the mean heat capacities of the casing material, kJ/kg·K;

5) the consumption of heat to warm the cover:

$$Q_c = M_c \cdot \left[\left(c_c\right)_0^{\bar{t}_e^c} \cdot \bar{t}_e^c - \left(c_c\right)_0^{t_{init}} \cdot t_{init} \right] \cdot 10^{-3}, \text{ MJ,} \tag{6}$$

where M_c is the cover weight, kg; $\bar{t}_e^c$ is the average cover temperature at the end of the process, °C; $\left(c_c\right)_0^{\bar{t}_e^c}$, $\left(c_c\right)_0^{t_{init}}$ are the mean heat capacities of the cover material, kJ/kg·K;

6) the consumption of heat to evaporate the moisture of ladles (when warming the ladles, this cost item is absent):

$$Q_{ev} = W_{evm} \cdot \left[c_{whc}\left(100 - t_{init}\right) + r + \left(c_{wv}\right)_0^{\bar{t}_{out}} \cdot \bar{t}_{out} - \left(c_{wv}\right)_0^{100} \right] \cdot 10^{-3}, \text{ MJ,} \tag{7}$$

where c_{whc} is the water heat capacity, kJ/kg·K; r is the specific consumption of heat to evaporate moisture, kJ/kg; $\left(c_{wv}\right)_0^{\bar{t}_{out}}$, $\left(c_{wv}\right)_0^{100}$ are the average heat capacities of water vapor according to temperatures $\bar{t}_{out}$ and 100 °C, kJ/kg·K; $\bar{t}_{out}$ is the average temperature of outgoing gases during drying, °C; W_{evm} is the mass of evaporating moisture, determined from the following formula:

$$W_{evm} = \left(M_w + M_r\right) \cdot \frac{\omega_{init} - \omega_e}{100 - \omega_e} \cdot \frac{100}{100 - \omega_e}, \quad \text{kg,} \tag{8}$$

Here, ω_{init} and ω_e are, respectively, the initial and final relative humidity of the ladle lining, %;

7) the loss of heat with outgoing gases:

$$Q_{out} = 1{,}1 \cdot V_{cp} \cdot B \cdot \left[\sum_{i=1}^{n} \left(c_i\right)_0^{\bar{t}_{out}} v_i \cdot \bar{t}_{out} \right] \cdot 10^{-3}, \text{ MJ,} \tag{9}$$

where 1.1 is a factor that takes into consideration the air suction; V_{cp} is the specific output of combustion products, m^3/m^3;

$\left(c_i\right)_0^{\bar{t}_{out}}$ is the average heat capacity of the components of combustion products at temperature $\bar{t}_{out}$ kJ/m^3·K; v_i are the volumetric shares of the components of combustion products, shares of units;

8) the loss of heat from the chemical fuel combustion underburning:

$$Q_{ch}=\left(12{,}64\cdot v_{CO}+10{,}75\cdot v_{H_2}+35{,}7\cdot v_{CH_4}\right)\cdot V_{cp}\cdot B,\ \text{MJ},\qquad(10)$$

where v_{CO}, v_{H_2}, v_{CH_4} is the content (shares of units) of combustible components (the multipliers correspond to the combustion heat of combustion components);

9) the losses of heat due to the heat transmission through the lining of a ladle (through a working layer, reinforcement row, thermal insulation, and casing):

$$Q_{htll}=\frac{1}{\sum_{i=1}^{n}\frac{\delta_i}{\lambda_i}+\frac{1}{\alpha_{os}}}\cdot\left(\bar{t}_{sur}^{c}-t_{ama}\right)\cdot\bar{F}\cdot3600\cdot\tau\cdot10^{-6},\ \text{MJ},\qquad(11)$$

where δ_i is the thickness of the corresponding i-th layer of the lining, m; λ_i is the thermal conductivity factor of a material of the i-th layer of the ladle lining at an average temperature per cycle of drying or warming, W/m·K; α_{os} is the heat output ratio from the outer surface of the ladle casing, W/m^2·K; $\bar{t}_{sur}^{c}$ is the average, per cycle of drying or warming, the surface temperature of the ladle casing, °C; t_{ama} is the temperature of the ambient air, °C; $\bar{F}$ is the average value of the area of the surface of the ladle lining (between the inner and outer surfaces), m^2; τ is the cycle duration of ladle drying or warming, h;

10) the losses of heat due to the heat transfer through the cover:

$$Q_{htc}=\frac{1}{\frac{\delta_c}{\lambda_c}+\frac{1}{\alpha_{osc}}}\cdot\left(\bar{t}_c^{c}-t_{ama}\right)\cdot F_c\cdot3600\cdot\tau\cdot10^{-6},\ \text{MJ},\qquad(12)$$

where δ_c is the thickness of the cover, m; λ_c is the thermal conductivity factor of a cover's material at an average temperature per cycle, kJ/kg·K; α_{osc} is the heat output ratio from the outer surface of the cover to the surrounding air, W/m^2·K; $\bar{t}_c^{c}$ is the average temperature of the cover per cycle, °C; F_c is the surface area of the cover, m^2;

11) the losses of heat through the radiation into the gap between the top cut of the ladle and the cover:

$$Q_{rad}=5{,}67\cdot\left(\frac{T_l}{100}\right)^4\cdot S\cdot D\cdot3600\cdot\tau\cdot10^{-6},\ \text{MJ},\qquad(13)$$

where 5.67 is the radiation factor of an absolutely black body, W/m^2·K^4; T_l is the average temperature in the volume of a ladle during drying, K; S is the area of the gap between the ladle and cover, m^2; D is the diaphragm factor.

The heat losses associated with the fencing wall of the warming bench Q_{wb}, which include warming the wall, heat transfer through the wall, and radiation into the gap between the wall and the ladle cut, which are in a horizontal position at the trolley (Fig. 4). These losses are determined from the difference between the heat input Q_{com} (1) and the sum of heat consumption Q_w (2), Q_r (3), Q_{in} (4), Q_{cas} (5), Q_{out} (9), Q_{ch} (10) and Q_{htll} (11).

The calculation of the thermal balances of the processes of steel-casting ladle warming has been performed in accordance with the recommended procedure given in work [16].

The ratio between the usable utilized heat and the loss of heat is shown in Fig. 5, 6; hence, the following conclusions can be drawn:

– the usable utilization of heat during drying is on average 9.6 % higher under all experimental modes than that in the warming process, which is due to the additional consumption of heat to evaporate the moisture at drying;

– the usable utilization of heat under the pulsed resonant fuel combustion in all experiments is higher than that when drying and warming a regular ladle (while drying the ladle, it is higher by 5.3–11.4 %, and when warming – by 4.9–7.2 %);

– accordingly, the losses of heat under the pulsed resonant fuel combustion in a ladle are lower than those for a regular ladle, that is, at conventional burning.

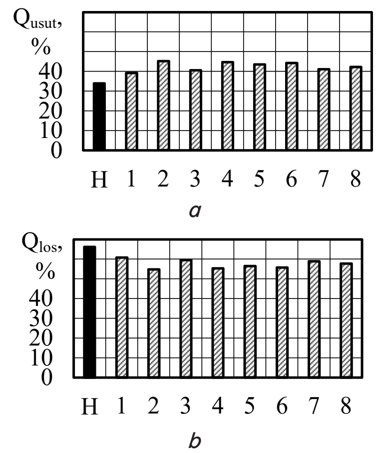


Fig. 5. The ratio between the usable utilization of heat and the losses of heat when drying steel-casting ladles (H – drying of a regular ladle, 1...8 – numbers of experimental modes): *a* – the ratio between the usable utilization of heat Q_{usut}; *b* – the ratio between the losses of heat Q_{los}

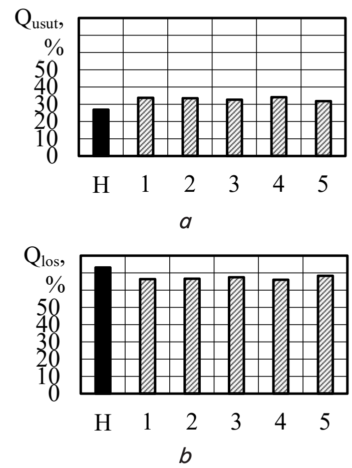


Fig. 6. The ratio between the usable utilization of heat and the losses of heat when warming steel-casting ladles (H – drying of a regular ladle, 1...5 – numbers of experimental modes): *a* – the ratio between the usable utilization of heat Q_{usut}; *b* – the ratio between the losses of heat Q_{los}

Comparing the cost items based on the average values of the usable utilization of heat for experimental modes, shown in Fig. 7, allows us to draw the following conclusions:

– the most essential cost items in terms of the usable utilization of heat in the drying of the ladles are the consumption of heat to warm the working masonry Q_w, the reinforcement row Q_r, and the evaporation of moisture Q_{ev};

– the most essential cost items in terms of the usable utilization of heat when warming the ladles are the consumption of heat to warm the working masonry Q_w and the reinforcement row Q_r;

– the usable utilization of heat for all cost items at the pulsed resonant fuel combustion in prototype ladles exceeds the same cost items at the standard fuel combustion in a regular ladle.

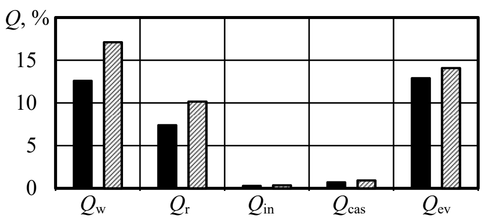


Fig. 7. Comparing the cost items of the usable utilization of heat when drying the ladles; Q_w, Q_r, Q_{in}, Q_{cas} are, respectively, the consumption of heat to warm the working masonry, reinforcement row, thermal insulation, and the ladle casing; Q_{ev} — the heat used to evaporate moisture at drying; ■ — standard regime; ▨ — averages for the experimental modes

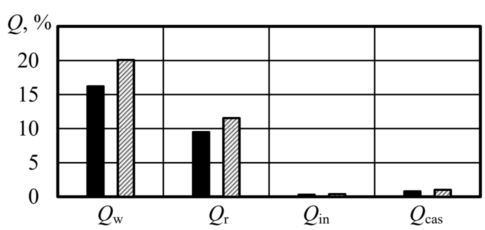


Fig. 8. Comparing the cost items of the usable utilization of heat when warming the ladles; Q_w, Q_r, Q_{in}, Q_{cas} are, respectively, the consumption of heat to warm the working masonry, reinforcement row, thermal insulation, and the ladle casing; ■ — standard regime; ▨ — averages for the experimental modes

The comparison of cost items based on the average values of heat losses for experimental modes is shown in Fig. 9, 10.

Our comparison of the cost items related to heat losses leads to the following conclusions:

– the most essential losses of heat in the processes of steel-casting ladle drying and warming are the losses of heat with outgoing gases Q_{out} (on average, when drying the ladles, these losses amounted to 43.1 %; when warming – 53.0 %);

– in all experiments, the losses of heat with outgoing gases at the pulsed resonant fuel combustion in a ladle are lower than those during standard combustion (when drying the ladles, they are lower by an average of 6.9 %, when warming – by 4.0 %);

– the pulsed resonant fuel combustion significantly reduces the losses of heat due to the chemical fuel underburning Q_{ch} (on average, when drying the ladles, these losses amounted to 4.1 % while losses in a regular ladle were 7.4 %; at warming – 3.5 % while losses in a regular ladle – 6.1 %);

– a certain increase in the heat losses associated with the drying bench cover (Q_c and Q_{rad} in Fig. 8) and the fencing wall of the warming bench (Q_{wb} in Fig. 8) is due to the higher temperature level in experimental ladles at the pulsed resonant fuel combustion compared to conventional combustion in regular ladles (Tables 1, 2)

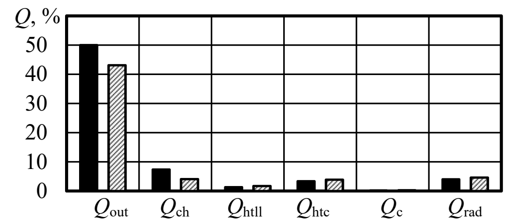


Fig. 9. Comparison of cost items related to the losses of heat when drying the ladles: Q_{out} — losses of heat with outgoing gases; Q_{ch} — losses of heat from the chemical fuel underburning; Q_{htll} — losses of heat due to the heat transfer through the ladle wall; Q_{htc} — losses of heat through the heat transfer through the cover of the ladle; Q_c — losses of heat to warm the cover; Q_{rad} — losses of heat through the radiation into the gap between the top cut of the ladle and the cover; ■ — regular regime; ▨ — averages for experimental modes

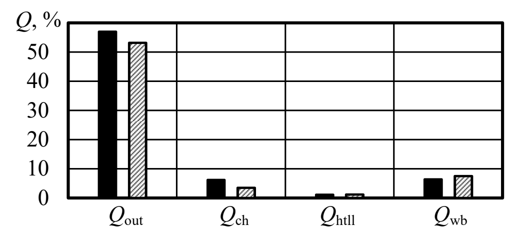


Fig. 10. Comparison of cost items related to the losses of heat when warming the ladles: Q_{out} — losses of heat with outgoing gases; Q_{ch} — losses of heat from the chemical fuel underburning; Q_{htll} — losses of heat due to the heat transfer through the ladle wall; Q_{wb} — losses of the heat related to the fencing wall of the warming bench; ■ — regular regime; ▨ — averages for experimental modes

In general, our analysis of thermal balances of the experimental modes allows us to draw the following conclusions about the effectiveness of the pulsed resonant combustion:

– the pulsed resonant combustion significantly increases the usable utilization of fuel, which leads to an increase in the efficiency of the drying and warming processes and the appropriate fuel savings;

– the increase in the proportion of the usable utilization of heat is due to the increase in the accumulation of heat by the working masonry, reinforcement row, thermal insulation, and the ladle casing;

– the pulsed resonant fuel combustion reduces the chemical underburning, which reduces fuel losses, increases the temperature within the working volume of the ladle, and intensifies the heat output;

– the pulsed resonant fuel combustion mode considerably reduces the losses of heat with outgoing gases, which generally indicates the intensification of heat exchange within the working volume of the ladle.

7. Discussion of results of studying the effectiveness of the pulsed resonant fuel combustion in the processes of steel-casting ladle drying and warming

A technique of the pulsed resonant fuel combustion in the processes of steel-casting ladle drying and warming has been developed. The pulsed resonant combustion preserves the basic principles of conventional drying and warming technology. At the same time, it creates the prerequisites for more efficient combustion of fuel in the ladle with a reduction in the underburning (Fig. 9, 10), more intensive heat exchange between combustion products and the ladle lining, and more even heat treatment of the inner surface of the ladle (Fig. 7, 8).

In comparison with the standard technique of fuel combustion, our experimental studies have shown the rather high performance of the developed system and a decrease in the consumption of natural gas: when drying the ladles, 2.7÷26.1 % (Table 1), when warming – 19.5÷37.8 % (Table 2).

The special features of the proposed method are the search for the resonance frequencies during pulsations. The result of testing the pulsed resonant fuel combustion has confirmed the possibility of finding the pulsation-resonance frequencies under industrial conditions, despite the negative impact of high temperatures, acoustic interference, and the equipment inertia. We have established the high enough operability of the pulsation unit, as well as the possibility to steadily maintain the necessary resonance frequencies of gas pulsations.

The results of tests at the post of steel-casting ladle warming indicate the expediency of using the pulsed resonant fuel combustion mode at the posts of intensive warming of ladles for melting. The pulsed resonant mode makes it possible to force the warming for melting by the resonance pulsation of the flame.

Our analysis of the thermal balances has confirmed that the pulsed resonant fuel combustion mode significantly increases the usable utilization of heat, which provides for an increase in the efficiency of the drying and warming processes and, accordingly, in the fuel savings compared to conventional combustion (Fig. 5, 6). The increase in the proportion of the usable utilization of heat occurs due to the increase in the accumulation of heat by the working masonry, reinforcement row, thermal insulation, and the ladle casing (Fig. 7, 8). The reduction in the chemical fuel underburning (Fig. 9, 10) contributes to the increase in the proportion of the usable utilization of heat. The pulsed resonant fuel combustion mode significantly reduces the losses of heat with outgoing gases, indicating the intensification of heat exchange within the working volume of the ladle (Fig. 9, 10).

The results of our research confirm that using the pulsed resonant fuel combustion is applicable in the processes of steel-casting ladle drying and warming.

The main limitation for the broad implementation of the pulsed resonant fuel combustion in the processes of steel-casting ladle drying and warming is the ability to adapt the technique. The technique must be adjusted in a specific production setting in compliance with acting technological instructions of drying and warming. At the same time, the existing technologies of the ladle drying and warming processes at different enterprises vary considerably depending on the type of lining and the equipment used.

The proposed technique could be advanced by designing an automated control system for the pulsed resonant fuel combustion, in compliance with the current drying and warming technology. An automated control system would make it easier to adapt the proposed technique to acting drying and warming technologies. The automated system could reduce the duration of search for the resonance frequencies and thus make it more energy-efficient.

8. Conclusions

1. A technique of the pulsed resonant fuel combustion in the processes of steel-casting ladle drying and warming has been developed, which makes it possible to adjust the pulsation to resonance frequencies and, by maintaining these frequencies, to ensure the most effective result of pulsation. The technique has been adapted to ensure that the consumption of the fuel burned and the time intervals are in accordance with technological instructions. The appropriate equipment for the processes has been designed: we have introduced a pulsator with a bypass pipe, a resonance frequency adjustment scheme to enable the necessary response to changes in the consumption of gas and fuel intervals in accordance with the technological instruction. The devised technique, while preserving the basic principles of the conventional drying and warming technology, creates the prerequisites for more efficient combustion of fuel in a ladle with the reduced underburning, for the intensification of heat exchange between combustion products and the ladle lining, and for more even heat treatment of the ladle.

2. The result of testing the pulsed resonant fuel combustion has confirmed the possibility of finding the pulsation-resonance frequencies under industrial conditions, despite the negative impact of high temperatures, acoustic interference, and the equipment inertia. We have established the feasibility of the pulsation unit, as well as the possibility to steadily maintain the necessary resonance frequencies of gas pulsations.

The results of tests at the post of steel-casting ladle warming indicate the expediency of using the pulsed resonant fuel combustion mode at the posts of intensive warming of the ladles for melting. The pulsed resonant mode makes it possible to force the warming for smelting by the resonance pulsation of the flame.

3. Our analysis of the thermal balances has confirmed that the pulsed resonant fuel combustion mode significantly increases the usable utilization of heat, which provides for an increase in the efficiency of the drying and warming processes and, accordingly, in the fuel savings compared to conventional combustion. The increase in the proportion of the usable utilization of heat occurs due to the increase in the accumulation of heat by the working masonry, reinforcement row, thermal insulation, and the ladle casing. The reduction in chemical fuel underburning contributes to the increase in the proportion of the usable utilization of heat. The pulsed resonant fuel combustion mode significantly reduces the losses of heat with outgoing gases, indicating the intensification of heat exchange within the working volume of the ladle.

Reducing the consumption of natural gas amounts to: when drying the ladles, 2.7÷26.1 %, at warming – 19.5÷37.8 %.

References

1. Santos, M. F., Moreira, M. H., Campos, M. G. G., Pelissari, P. I. B. G. B., Angélico, R. A., Sako, E. Y. et. al. (2018). Enhanced numerical tool to evaluate steel ladle thermal losses. Ceramics International, 44 (11), 12831–12840. doi: https://doi.org/10.1016/j.ceramint.2018.04.092
2. Kushnir, R. M., Popovych, V. S., Yanishevsky, V. V. (2012). Thermal and Thermoelastic State of Thin-Walled Thermosensitive Structures Subject to Complex Heat Exchange. Journal of Thermal Stresses, 35 (1-3), 91–102. doi: https://doi.org/10.1080/01495739.2012.654747
3. Popovych, V. S., Zavodovs'ka, N. O. (2014). Heat-Sensitive Cylinder Under the Conditions of Convective Heat Exchange with Media of Variable Temperature. Materials Science, 50 (1), 22–30. doi: https://doi.org/10.1007/s11003-014-9687-6
4. Luo, X., Wang, S., Jager, B. de, Willems, F. (2015). Cylinder Pressure-based Combustion Control with Multi-pulse Fuel Injection. IFAC-PapersOnLine, 48 (15), 181–186. doi: https://doi.org/10.1016/j.ifacol.2015.10.026
5. Jilavu, D., Rizea, V., Gaba, A. (2011). Performant installations for drying and heating the steel ladles. The Scientific bulletin of Valahia University, 6, 52–62.
6. Gaba, A., Jilavu, D., Rizea, V. (2013). Valentin Natural gas consumption reduction for the drying - Preheating stands of the ladles through burnt gas heat recovery. Metalurgia International, 18, 160–164.
7. Shanqing, X., Daohong, W. (2015). Design Features of Air and Gas Double Preheating Regenerative Burner Reheating Furnace. Energy Procedia, 66, 189–192. doi: https://doi.org/10.1016/j.egypro.2015.02.015
8. García, A. M., Colorado, A. F., Obando, J. E., Arrieta, C. E., Amell, A. A. (2019). Effect of the burner position on an austenitizing process in a walking-beam type reheating furnace. Applied Thermal Engineering, 153, 633–645. doi: https://doi.org/10.1016/j.applthermaleng.2019.02.116
9. Xu, P., Yu, B., Qiu, S., Poh, H. J., Mujumdar, A. S. (2010). Turbulent impinging jet heat transfer enhancement due to intermittent pulsation. International Journal of Thermal Sciences, 49 (7), 1247–1252. doi: https://doi.org/10.1016/j.ijthermalsci.2010.01.020
10. Pandey, K. M., Debnath, P. (2016). Review on Recent Advances in Pulse Detonation Engines. Journal of Combustion, 2016, 1–16. doi: https://doi.org/10.1155/2016/4193034
11. Jin, L., Fan, W., Wang, K., Gao, Z. (2013). Review on the Recent Development of Multi-mode Combined Detonation Engine. International Journal of Turbo & Jet-Engines, 30 (3). doi: https://doi.org/10.1515/tjj-2013-0002
12. Peng, C., Fan, W., Zheng, L., Wang, Z., Yuan, C. (2013). Experimental investigation on valveless air-breathing dual-tube pulse detonation engines. Applied Thermal Engineering, 51 (1-2), 1116–1123. doi: https://doi.org/10.1016/j.applthermaleng.2012.10.026
13. Yan, Y., Fan, W., Wang, K., Zhu, X., Mu, Y. (2011). Experimental investigations on pulse detonation rocket engine with various injectors and nozzles. Acta Astronautica, 69 (1-2), 39–47. doi: https://doi.org/10.1016/j.actaastro.2011.03.002
14. Hichov, Yu. O., Stupak, M. Yu., Zhovtonoha, M. M., Vasilkiv, T. A., Popova, A. S., Pertsevyi, V. O. (2014). Pat. No. 110873 UA. Sposib sushinnia abo rozihrivannia futerivky metalurhiynoi yemnosti. No. a201407415; declareted: 02.07.2014; published: 25.02.2016, Bul. No. 4.
15. Gichev, Yu. A., Stupak, M. Yu., Pertsevoy, V. A., Matsukevich, M. Yu. (2016). Development of Method of Pulsatile - Resonance Fuel Combustion for Drying and Heating of Steel-Teeming Ladles. Tekhnichna teplofizyka ta promyslova teploenerhetyka, 8, 43–55.
16. Gubinskiy, V. I., Timoshpol's'kiy, V. I., Ol'shans'kiy, V. M. et. al.; Timoshpol's'kiy, V. I., Gubinskiy, V. I. (Eds.) (2007). Metallurgicheskie pechi. Teoriya i raschety. Vol. 2. Minsk: Belorus. Nauka, 832.