Досліджено вплив теплофізичних параметрів факела допалювання монооксиду вуглецю з урахуванням аеродинамічних процесів від теплотехнічних параметрів плавки. На підставі сучасних методів отримані відомості про характер макрофізичних процесів, що протікають в реакційній зоні і в робочому просторі агрегату. Виконано порівняльний аналіз форми і температурних полів факела при різних інтенсивностях продування ванни сталеплавильного агрегату киснем

Ключові слова: теплофізичні параметри, теплотехнічні параметри, факел, допалювання монооксиду вуглецю, температурне поле

Исследовано влияние теплофизических параметров факела дожигания монооксида углерода с учетом аэродинамических процессов от теплотехнических параметров плавки. На основании современных методов получены сведения о характере протекающих в рабочем пространстве агрегата и в реакционной зоне макрофизических процессов. Выполнен сравнительный анализ формы и температурных полей факела при различных интенсивностях продувки ванны сталеплавильного агрегата кислородом

Ключевые слова: теплофизические параметры, теплотехнические параметры, факел, дожигание монооксида углерода, температурное поле

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INVESTIGATION OF THE CARBON MONOXIDE POST-COMBUSTION FLAME IN THE WORKING SPACE OF A STEELMAKING UNIT

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1. Introduction

Development of ferrous metallurgy under contemporary conditions is characterized by a significant consumption of natural gas in the process of steelmaking. Relevant tasks [1, 2] in this regard are the development of theoretical and practical aspects of the new energy- and resource-saving techniques for steel smelting in steelmaking units with oxygen blowing (O_2) and post-combustion of carbon monoxide (CO).

In order to meet these challenges, promising is the application of modes of steel smelting with an increased degree of CO post-combustion in the flue gases by jets of O_2 with the subsequent transfer of heat from the CO post-combustion flames to the melt and a steelmaking bath.

The rational mode of CO post-combustion by jets of oxygen in the flow of high temperature gases discharged from the zone of blowing [3] should ensure more efficient use of the heat released from the CO post-combustion in the system of gas flows in order to heat the bath, reduce natural gas consumption and to improve other technical-economic indicators without compromising resistance of the unit's lining.

2. Literature review and problem statement

In paper [4], authors studied effect of oxygen jet flow on the process of CO post-combustion when changing the inclination angles of a blowing device from 8° to 12°. Other ranges of change in the inclination angles and their influence on temperature fields of the CO post-combustion flame were not, however, examined.

Article [5] investigated influence of the blowing device's nozzle inclination angle, equal to 16°, on the process of CO post-combustion and agitation of the melt in the bath of a steelmaking unit. It, however, did not address other possible variations of inclination angles and their effect on the temperature field of a CO post-combustion flame.

The blowing process of the bath of a steelmaking unit using a cold model simulation was studied in paper [6]. The work, however, was limited to modeling the intensity of blowing up to 450 m^3/h.

Authors of article [7] examined conditions of overheating reaction zones relative to the peripheral part of the bath and estimated temperature gradients. In this case, the research is limited only to surface measurements of the bath's temperature fields, without detailed examination of macrophysical processes in the reaction zone and of the effect of change in the intensity of blowing on the temperature fields of a CO post-combustion flame.

In paper [8], authors theoretically studied physical-chemical processes in the reaction zone when blowing the melt with oxygen. Results of the work, however, were not tested under industrial conditions.

Authors of article [9] performed theoretical modeling of the effect of changing the intensity of blowing in the bath of 75 tons of arc furnace. Results of the study, however, were not tested at the industrial unit; formation of the temperature fields of a CO post-combustion flame was not studied.

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Parameters and shape of reaction zones in steelmaking units when designing and applying experimental multi-nozzle lance and their influence on the process of CO post-combustion were investigated in paper [10]. In this case, the authors did not take into consideration the influence of aerodynamic processes in the bath and changes in the temperature fields of a CO post-combustion flame.

The process of blowing the bath of a steelmaking unit using a cold model simulation was studied in [11]. The authors, however, did not specify the effect of changing blowing intensity on the temperature fields in the unit.

Intensive splashing and the existence of a post-combustion flame of carbon monoxide in the region of the lance in a general form was recorded by a photographing method [12] excluding the impact of change in the intensity of blowing.

It is worth noting that all the above studies consider behavior of a post-combustion flame of carbon monoxide and the effect on it resulting from the carbon monoxide flow discharged from the reaction zone, including the bubbles of CO formed when oxygen interacts with the melt. They do not take into consideration the influence of aerodynamic processes in the bath of an industrial steelmaking unit, formed under the influence of thrust produced by the fume collection vanes. Their influence on the temperature fields of a CO post-combustion flame was not examined either.

3. The aim and objectives of the study

The aim of present study is to examine a CO post-combustion flame in the working space of a two-bath steelmaking unit. This will make it possible to proceed to the optimization of thermal mode of steelmaking process, which would reduce energy consumption per unit.

To achieve the set aim, the following tasks have been solved:

– based on existing approaches and methods, to obtain data on the nature of macro-physical processes that occur in the workspace of the unit and in the reaction zone, taking into consideration the effect of aerodynamic processes in the bath of a steelmaking unit;

– to establish dependences of thermophysical parameters of a post-combustion flame of carbon monoxide, taking into consideration the effect of aerodynamic processes on the thermotechnical parameters of steel melting;

– to perform comparative analysis of the shape and temperature fields of the flame considering the influence of aerodynamic processes under different intensities of blowing the bath of a steelmaking unit with oxygen for various types of blowing devices.

4. Methods applied for studying working space of the unit and the reaction zone

The methods of theoretical research are the formalization and synthesis.

The methods of empirical studies are the laboratory and field experiment (industrial tests).

The most common methods for examining a reaction zone of the interaction between oxygen jets and the melt in a steelmaking unit are the methods of photo- and video recording and filming, which were widely used in paper [12].

We propose to employ these methods to study the reaction zone and a post-combustion flame of carbon monoxide. Additionally, we used the thermal imaging camera NEC H2640 (NEC Avio Infrared Technologies Co. Ltd., Japan) and the infrared pyrometer Rayngr (Raytek, USA) with additional blocks.

5. Results of examining the working space of a steelmaking unit during interaction between oxygen jets and the melt

While conducting balance melting during blowing the bath of a two-bath steelmaking unit (TSU) (Fig. 1) at the PAO ZMK (Ukraine), we obtained information on the character of macro-physical processes that occur in the reaction zone. The experiments were carried out using oxygen lance with an oxygen flow rate of 1,800 m^3/h and above.

Fig. 1. TSU heating schematic: 1 — oxygen lance (3 per each bath), 2 — gas burner (3 per each bath), 3 — scrap metal, 4 — exhaust gas flow, 5 — melt after pouring cast iron (scrap+liquid cast iron)

The furnace operates in the following way: one bath (hot) is used for melting and finishing with intense blowing of the metal with oxygen while the second bath (cold) is used at the same time for filling and warming the hard charge. Gases under the influence of thrust created by the fume collection vanes, are directed from the “hot” part of the furnace to the “cold”. In the cold part of the furnace, CO burns to CO_2 with warming the solid charge by the released heat. The heat lacking for the heating process is replenished by supplying natural gas through the burners installed in the roof of the furnace.

Some fragments of imaging managed to record that the discharge of CO proceeded in several separate regions corresponding to the jets of oxygen that enter the bath from each nozzle of the lance. A diameter of the area of the released carbon monoxide from one such region is 0.25–0.31 m.

There are metal splashes observed within the range of a near-lance flame on the circle with a radius of up to 0.7 m, flying out at a velocity of 5–15 m/s to a height of 0.4–0.6 m. Departure of large splashes (0.05–0.35 m in length, with a diameter of 0.03–0.04 m) occurs at a speed of 4–5 m/s, and for the smaller ones (with a diameter of 0.01–0.02 m) this velocity is of up to 15 m/s. The intensity of splashing and the overall diameter of a near-lance flame decreases with a decrease in the content of carbon in the melt.

At the same time, we registered, when oxygen is fed through the lance placed over the surface of the bath, the interaction modes between the blowing and the melt with an increase in the pressure from jet to the bath, which has a slag cover of insignificant thickness (0.2–0.3 m). The formation of a near-lance flame is observed during operation mode of blowing when the lance head is located at the slag-metal boundary and above, within a circle of radius up to 0.5–0.8 m (Fig. 2). The flame is formed as a result of after-burning of the carbon monoxide flow released from the reaction zone in the flow of air streams. The oxidizer flow moves inside TSU from one bath to another under the influence of thrust produced by the fume collection vanes.

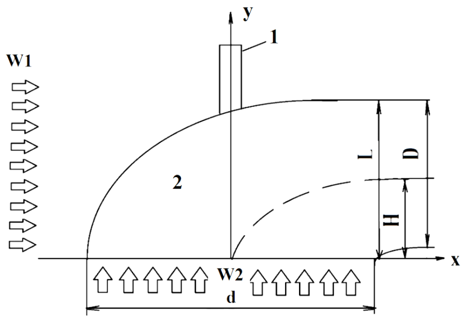


Fig. 2. Schematic of a near-lance flame formed when blowing the bath ([C]=3 %) with an oxygen flow rate through the lance of 2,000 m^3/h: 1 – lance; 2 – flame; W1 – velocity of the entraining flue gas flow; W2 – carbon monoxide flow velocity

A shape of the near-lance flame is typical for jets, blown into entraining flow (Fig. 3).

When captured by a photo camera, it is possible to see that the flame is displaced to the right from the lance body (in the direction of the discharged gas motion). At the same time, the CO that is released from the melt is sucked by the flame, followed by its pulsating ignition at a distance of 0.4–0.5 m from the lance.

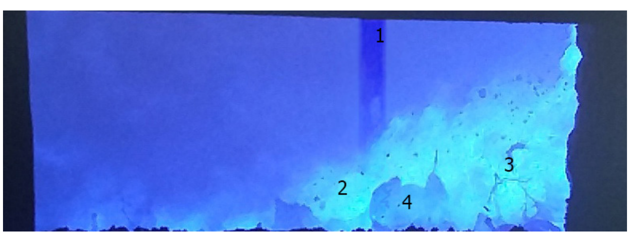


Fig. 3. Image of the near-lance flame formed when blowing the bath ([C]=3 %) with an oxygen flow rate through the lance of 2000 m^3/h: 1 – lance; 2 – flame; 3 – metal splashes; 4 – CO bubble at tearing of the oxide film

The formation of flame along the length of the bath, carried away by the flow of flue gases at a different content of carbon in the melt is shown in Fig. 4.

Based on the photo-recording (Fig. 4) and the measurement of temperatures in the visible part of the carried-away flame on TSU throughout the entire melting, we constructed a dependence of change in the length and temperature of the carrying flame at a different content of carbon in the melt (Fig. 5). Fig. 5 shows that in the range of carbon content in the melt of 3.5–4.0 %, the flame is 1.25–1.43 m. At a decrease in the content of [C] from 3.5 to 1.4–1.5 %, we observe a sharp decrease in the length of the flame from 1.1–1.2 m to 0.4–0.45 m. Subsequently, in the range of [C]=0.6–1.4 %, we observe relative constancy of the flame within 0.3–0.4 m. At a decrease in [*C*] from 0.5 to 0.1 %, the flame monotonically attenuates. At a content of [C]=0.1 % and below, the flame is missing.

Temperature of the visible part of the drifted flame (Fig. 5) monotonically decreases depending on the reduction of carbon content in the melt. At the same time, there are some deviations from the observed dependence in the range [C]=2.5–4.0 %, because of the intensive dust formation of both mechanical and evaporation origin during bath boiling. This may affect the measurement of temperature of the visible length of the flame.

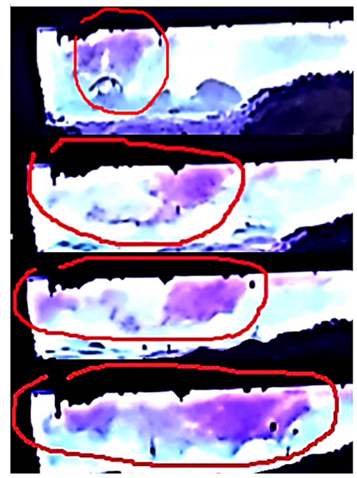


Fig. 4. Formation of the flame lengthwise the bath, drifted by the flow of flue gases at a different content of carbon in the melt

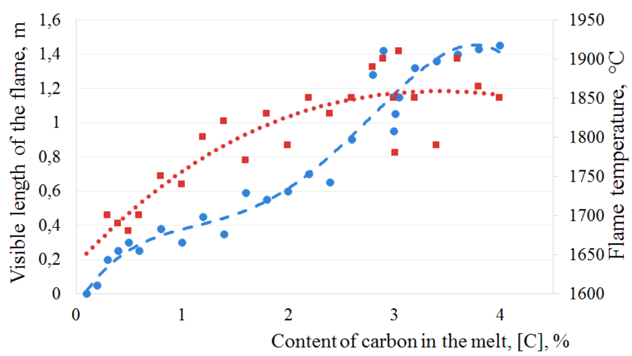


Fig. 5. Change in the length and temperature of the drifted flame on TSU at a different content of carbon in the melt (at intensity of oxygen blowing 2,200 m^3/h):
● – flame length (experiment);
■ – flame temperature (experiment);
– – – – polynomial (flame length, experiment);
●●● – polynomial (flame temperature, experiment)

Based on the results of processing actual data on the results of experiments in TSU, we obtained polynomial dependences for determining the length and temperature of the drifted flame depending on the carbon content in the melt:

– Length of the drifted flame on the carbon content in the melt, m:

$$l_f = -0{,}047\cdot[C]^4 + 0{,}372\cdot[C]^3 - 0{,}89\cdot[C]^2 + 1{,}019\cdot[C] - 0{,}075. \quad (1)$$

In this case, correlation coefficient *R* reached 0.95, the relative error when testing the regression equation against actual data amounted to 1.5–2 %.

– Temperature of the drifted flame on the content of carbon in the melt, °C:

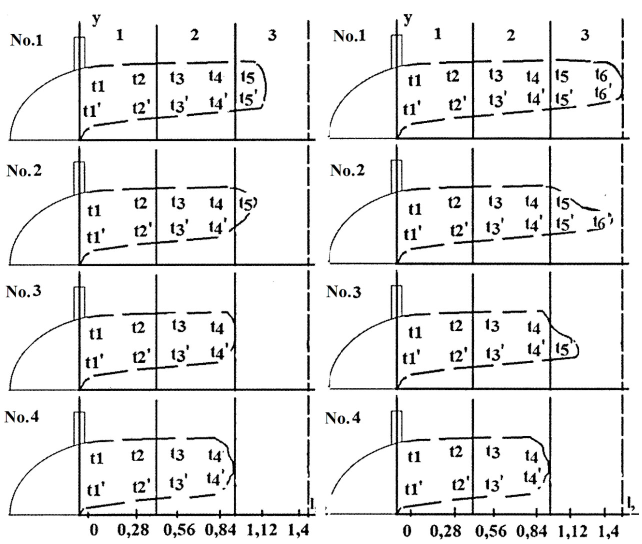
$$t_f=1,453\cdot[C]^3-28,881\cdot[C]^2+146,62\cdot[C]+1637, \qquad (2)$$

where [C] is the carbon content in the melt, %.

In this case, correlation coefficient R amounted to 0.87, the relative error when testing the regression equation against actual data reached 1.7–2.5 %.

In order to perform a detailed analysis of temperature fields of the visible part of the flame, we split the flame lengthwise into 3 conditional sections (zones). Each zone was divided into 2 vertical parts (top and bottom) and 2 horizontal parts (beginning and end of the zone). According to a special test program, during balance melting, we conducted 8 experimental measurements of the visible part of temperature fields of the drifted flame: 4 experimental measurements on basic lances (a) with the same inclination angle of nozzles relative to the melt (30°) and 4 experimental measurements on the tested lances (b) with a combined inclination angle of the nozzles relative to the melt (20/50°). During tests, the intensity of blowing the bath with oxygen varied from 1,800 to 2,400 m³/h at a content of carbon in the melt of 3 %. The measurements were carried out using the infrared pyrometer Raynger 3i and thermal imager NEC H2640.

Results of experiments are shown in Fig. 6–10 and are summarized in Table 1, 2.



a *b*

Fig. 6. Schematic representation of contours of the visible part of temperature fields of the drifted flame on the basic (a) and experimental (b) lances based on the results of measurements in TSU at different intensities of blowing the bath with oxygen: 1, 2, 3 — zones of the flame, t_1–t_6 — points of temperature measurements of the top part of the flame, °C; t_1'–t_6' — points of temperature measurements of the bottom part of the flame, °C; l_f. — flame length, m

The blowing was conducted through basic six-nozzle lances (inclination angle of the nozzles to the vertical is 30, diameter of nozzles – 15 mm) and experimental (at inclination angles of the nozzles up to 50° to the vertical and with varied nozzle diameters from 10 to 20 mm).

Fig. 6 shows that when using lances of both basic design (experiment No. 1–4) and experimental lances (experiment No. 1–4), the flame length and its temperature increased from 0.65–0.70 to 1.05–1.15 m (basic lances) and from 0.70–0.85 to 1.30–1.40 m (experimental lances). The experiments were performed with an increase in the intensity of blowing the bath with oxygen from 1,800 to 2,400 m³/h (per one lance). In this case, both types of lances in experiments No. 1–3 exhibited a good organization of the flame; the flame is strong; during experiment No. 4 the organization of the flame deteriorated markedly, the flame became wider and shorter with an increase in the intensity of pulsations to 3–4 seconds.

It follows from Table 1, 2 and Fig. 7–10 that the magnitude of temperature fields of the drifted flame on experimental lances, in comparison with the basic ones, increases by 16–104 °C (42 °C on average): in zone No. 1 – by 28–85 °C, in zone No. 2 – by 16–38 °C, in zone No. 3 – by 27–104 °C.

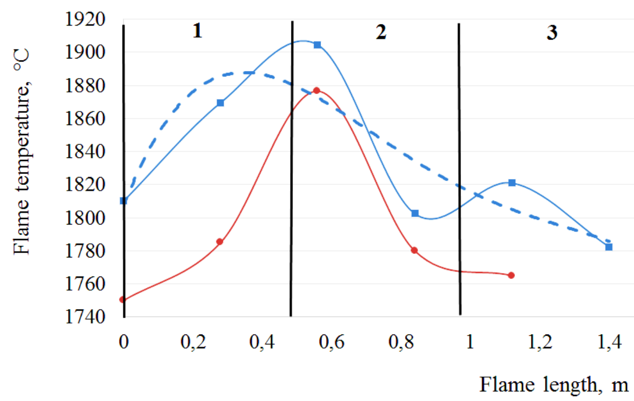


Fig. 7. Distribution of temperature fields of the drifted flame when using experimental and basic lances with a carbon content of 3 %; dotted line marks estimated dependence for experimental lance with the intensity of blowing the melt with oxygen at 2,400 m³/h (experiment No. 1): — experimental lance; — basic lance; — polynomial (experimental lance)

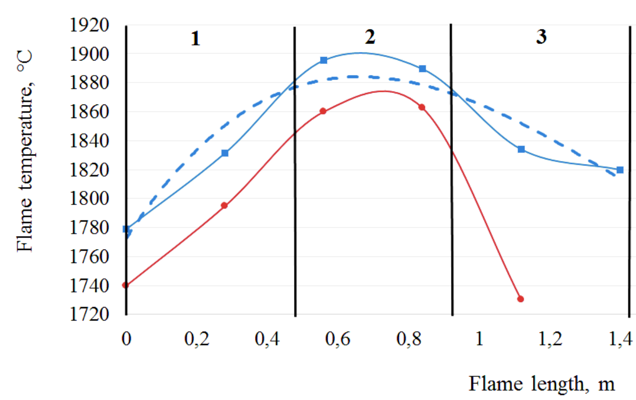


Fig. 8. Distribution of temperature fields of the drifted flame when using experimental and basic lances with a carbon content of 3 %; dotted line marks estimated dependence for experimental lance with the intensity of blowing the melt with oxygen at 2,200 m³/h (experiment No. 2): — experimental lance; — basic lance; — polynomial (experimental lance)

Table 1

Results of measurements of temperature fields of the drifted flame (basic lances) at a carbon content of 3 %

No. of experiment	Oxygen flow rate, m³/h	Temperature value by the flame's conditional zones						Length of the flame's visible part, m	Pulsating intensity, s	Note
		1		2		3				
Section length, m		0	0.28	0.56	0.84	1.12	1.4			
Denotation	bottom part	t_1	t_2	t_3	t_4	t_5	t_6			
	top part	t_1'	t_2'	t_3'	t_4'	t_5'	t_6'			
1	2,400	1,700	1,750	1,863	1,790	1,730	–	1.05–1.15	1	Organization of flame is good, flame is strong
		1,800	1,820	1,890	1,770	1,800	–			
average		1,750	1,785	1,877	1,780	1,765	–			
2	2,200	1,705	1,790	1,830	1,850	1,730	–	0.9–1.1	to 2	Organization of flame is good, flame is strong
		1,775	1,800	1,890	1,875	–	–			
average		1,740	1,795	1,860	1,863	1,730	–			
3	2000	1,730	1,785	1,780	1,730	–	–	0.8–0.85	2–3	Organization of flame is good, flame is strong
		1,700	1,705	1,782	1,755	–	–			
average		1,715	1,745	1,781	1,743	–	–			
4	1,800	1,700	1,790	1,815	1,770	–	–	0.65–0.7	3–4	Organization of flame deteriorated, flame grew wider and shorter
		1,750	1,793	1,845	1,805	–	–			
average		1,725	1,792	1,830	1,788	–	–			

Table 2

Results of measurements of temperature fields of the drifted flame (experimental lances) at a carbon content of 3 %

No. of experiment	Oxygen flow rate, m³/h	Temperature value by the flame's conditional zones						Length of the flame's visible part, m	Pulsating intensity, s	Note
		1		2		3				
Section length, m		0	0.28	0.56	0.84	1.12	1.4			
Denotation	bottom part	t_1	t_2	t_3	t_4	t_5	t_6			
	top part	t_1'	t_2'	t_3'	t_4'	t_5'	t_6'			
1	2,400	1,790	1,854	1,898	1,808	1,799	1,761	1.3–1.4	1	Organization of flame is good, flame is strong
		1,830	1,885	1,911	1,797	1,843	1,804			
average		1,810	1,870	1,905	1,803	1,821	1,783			
2	2,200	1,748	1,820	1,871	1,870	1,820	–	1.2–1.25	to 2	Organization of flame is good, flame is strong
		1,810	1,843	1,920	1,909	1,848	1,820			
average		1,779	1,832	1,896	1,890	1,834	1,820			
3	2,000	1,782	1,820	1,783	1,778	–	–	0.95–1.05	2–3	Organization of flame is good, flame is strong
		1,720	1,743	1,811	1,784	1,750	–			
average		1,751	1,782	1,797	1,781	1,750	–			
4	1,800	1,715	1,830	1,852	1,807	–	–	0.7–0.85	3–4	Organization of flame deteriorated, flame grew wider and shorter
		1,790	1,833	1,882	1,838	–	–			
average		1,753	1,832	1,867	1,823	–	–			

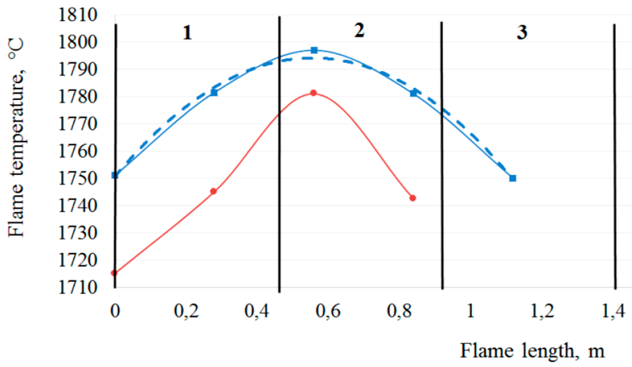


Fig. 9. Distribution of temperature fields of the drifted flame when using experimental and basic lances with a carbon content of 3 %; dotted line marks estimated dependence for experimental lance with the intensity of blowing the melt with oxygen at 2,000 m^3/h (experiment No. 3): — experimental lance; — basic lance; — — — polynomial (experimental lance)

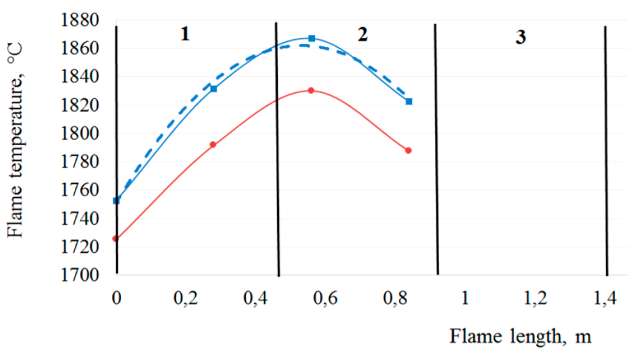


Fig. 10. Distribution of temperature fields of the drifted flame when using experimental and basic lances with a carbon content of 3 %; dotted line marks estimated dependence for experimental lance with the intensity of blowing the melt with oxygen at 1,800 m^3/h (experiment No. 4): — experimental lance; — basic lance; — — — polynomial (experimental lance)

An analysis of Fig. 7–10 and Table 1, 2 reveals that the size and temperature of the flame directly depend on the intensity of blowing. In this case, the most rational are the parameters and results of experiment No. 2.

6. Discussion of results of examining the post-combustion flame of carbon monoxide in the working space

By comparing the results of temperature fields of the drifted flame obtained in experiment No. 2 on experimental lances with the values received when using the lances of basic design under similar parameters of the supplied energy carriers (the intensity of blowing is 2,200 m^3/h), it can be concluded that the application of lances of the new design (at an increase in the inclination angle of the nozzles to 50° and by varying nozzle diameters from 10 to 20 mm) makes it possible to:

– improve organization of the drifted flame, including;

– increase length of the flame by 0.15–0.3 m (from 0.9–1.1 to 1.2–1.25 m);

– increase temperature of the flame by 49–97 °C (from 1,730–1,779 to 1,798–1,895 °C);

– improve uniformity of the flame structure;

– increase the surface of heat exchange between the flame and the bath;

– improve heating capability of the bath in a steelmaking unit.

This is explained by the increased intensity of CO release from the bath due to an increase in the intensity of agitation of the bath with an oxygen jet. As a result, a more intense post-combustion of CO occurs, the luminosity increases, as well as the temperature and area of the flame's radiating surface.

Based on the obtained dependences for TSU, by assigning the magnitude of intensity of blowing the bath with oxygen, it is possible to determine temperature of the drifted flame at each point of the flame using the following equations (Table 3):

Table 3

Dependence of temperature of the drifted flame on the intensity of blowing the bath with oxygen and a flame length

Blowing intensity, m^3/h	Equation	R
1,800	t_f=–393.8·l_f^2+418.4·l_f+1,750 l_f^2	0.95
2,000	t_f=–140.7·l_f^2+156.7·l_f+1,750	0.95
2,200	t_f=89.2·l_f^3–371.9·l_f^2+375.3·l_f+1,772	0.89
2,400	t_f=–220·l_f^4+874·l_f^3 –1,197·l_f^2+552·l_f+1,806	0.75

It was observed during photo recording that the use of the experimental lances (Fig. 11), when compared with the standard lances (Fig. 12), results in a more intensive release of carbon monoxide bubbles from the melt.

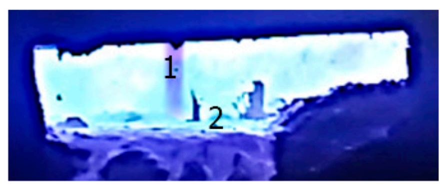


Fig. 11. Basic lance (nozzle inclination angle is 30°): 1 – lance; 2 – CO bubble (when blowing the bath ([C]=2.0 % with an oxygen flow rate through the lance of 2,000 m^3/h)

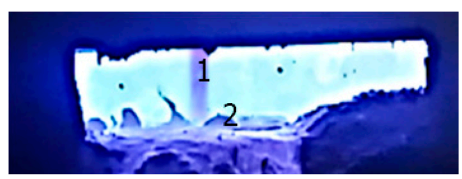


Fig. 12. Experimental lance (varied nozzle inclination angles): 1 – lance; 2 – CO bubble (when blowing the bath ([C]=2.5 % with an oxygen flow rate through the lance of 2,000 m^3/h)

Thus, the research conducted revealed the dependence of thermophysical parameters of the CO post-combustion flame considering the influence of aerodynamic processes on the thermal-technological parameters of smelting and pointed to the superiority of experimental lances with a combined location of nozzles over the standard lances.

The reported results are applicable in the industrial steelmaking units with the intensity of blowing the bath with oxygen in a range of 1,800–2,400 m^3/h (per one blowing device).

The shortcoming and limitation of the completed study: the results are valid for the intensity of blowing the bath with oxygen in a range of 1,800–2,400 m^3/h. It should be noted that the next stage of the planned research implies conducting study at elevated values of the intensity of blowing.

The results received allow us to come close to the development of a rational design of the blowing device to optimize a thermal mode of steelmaking process in order to reduce energy consumption.

7. Conclusions

1. Based on the results of balance melting in TSU, by using the methods of photo- and video recording, we obtained data on the character of macro-physical processes that occur in the reaction zone. In this case, there is a formation of the flame lengthwise the bath, drifted by the flue gas flow.

2. Based on the photo-registration of the near-lance flame and temperature measurements in the visible part of the drifted flame in TSU, we performed analysis and established temperature dependence of the flame on its length and the intensity of blowing the bath with oxygen.

3. We conducted a comparative analysis of the shape and temperature fields of the drifted flame when using basic and experimental blowing devices at different intensities of blowing the bath of a steelmaking unit with oxygen. At the same time, increasing inclination angle of the nozzles to 50° and varying the nozzle diameters from 10 to 20 mm allowed us to determine superiority of the experimental lances with a combined arrangement of nozzles in comparison with standard lances with a uniform inclination angle of the nozzles. The results obtained bring us closer to the development of a rational design of the blowing device and optimization of the thermal mode of steelmaking process that will make it possible to reduce energy consumption in steel production.

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