The possibility of increasing the efficiency of temperature distribution control in reheating furnaces

***Aleksandr Yeromin*[1]*, Oksana Yeromina*[2]*, Ladislav Lukáč*[3]*, Ján Kizek*[3] *and Róbert Dzurňák*[3]**

The concepts of creating the uniform temperature distribution in the reheating facilities equipped with high-effective regenerators have been considered in the present work. Uniformity of the temperature in the working space of reheating furnaces favours the removal of the local high-temperature three-dimensional zones in the furnace. This causes increasing the quality of metal heating, decreasing waste of metal, harmful gas-like ejections (including nitrogen oxides) with flue gases and improving conditions of the lining exploitation of the heating facilities.

High-temperature preheating of the combustion air predetermines the low consumption of the fuel in furnaces and the deep utilisation of the heat of furnaces gases. It is proposed to bring off the maintenance of the uniform temperature distribution in reheating furnaces at the expense of the new distributed three-dimensional practice of burning fuel.

Organisation of the new practice of fuel combustion is connected with special conditions of mixing fuel and air, recirculation and reverse of the furnace gases. Three dimensional (volumetric) fuel combustion is ensured by the modern design of burners equipment at the expense of the structural parameters of a burner and working space of the furnace, the arrangement of the fuel combustion facilities, duct openings of flue gases and gas dynamic characteristics of the furnace gases. Solutions for ensuring volumetrically distributed fuel burning for the main types of reheating facilities: several types of reheating pits, various types of batch and continuous reheating furnaces.

Keywords: *heating furnaces, temperature, combustion*

Introduction

The torch way of burning remains as the most widespread practice in furnaces using the gaseous fuel in the present time. This practice is notable for the simplicity of regulation of heat power and heat escaping in the furnace.

Technological processes of raw processing include many processes of transfer, accumulation and transformation of mass, energy and momentum (Terpák, Dorčák and Madula, 2007).

In consequence of the concentrated heat supply and removal of the fuel smoke at the torch burning of the preconditions arise to the appearance of the non-uniform temperature distribution and heating of metal. In zones at high temperatures formation of the "thermal" NOx is intensified. These phenomena are redoubled in the presence of the high-temperature heating-up of the burning air.

Investigations on operational parameters of afterburning chambers included in metallurgical thermal equipment have been presented in the source (Gil, Rozpondek and Bialik, 2014). The effects of temperature and modernisation within the firing system on concentrations of nitrogen oxides and carbon oxide have been analysed.

Uniformity and standard character of heating in furnaces are reached by recirculation and reverse of furnace gases, pulsed heating, separate, by the periods of heating, feed of the fuel, rocking of the burner, changing the direction of the torch, multistage combustion of the fuel and other ways (Gubinskiy, 2005; Shults, 1995; Gubinskiy and Lu Chzhun, 1995). In the source (Gubinskiy and Lu Chzhun, 1995) and the works by A.V. Kavaderov and Y.P. Ivantsov, the locality of the external heat exchange is described. According to this principle, the heating of the charge is determined with radiation and convection from gas volumes located in immediate proximity to the surface. In accordance with this principle, attainment of uniformity in heating of the charge in the furnace is brought off by the rational control of gases movement ensuring heat transfer to the local sections of metal and lining.

In high-temperature heating furnaces, as well as in low-temperature chamber heat furnaces (LTCF), the optimization of the schedule of gas movement in the furnace of the burners, the way of removal of the flue gases, external and internal recirculation of the flue gases, employment of impulse burners (Revun and Zinchenko, 2006) and other practices bringing combustion nearer to volumetric one. "Questions of using the volumetric

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[1] *Aleksandr Yeromin*, NMetAU, Faculty of Computer Systems, Power Industry and Automation, The department of Ecology, Heat-Transfer and labour protection, av. Gagarina, 4, Dnepropetrovsk, 49600, Ukraine, aoeremin@gmail.com

[2] *Oksana Yeromina*, NMetAU, Faculty of Economy and Management, Department of Accounting and Audit, av. Gagarina, 4, Dnepropetrovsk, 49600, Ukraine, oleremina@gmail.com

[3] *Ladislav Lukáč, Ján Kizek, Róbert Dzurňák*, TU of Košice, Faculty of Materials, Metallurgy and Recycling, Institute of Metallurgy, Letná 9, 042 00, Slovakia, ladislav.lukac@tuke.sk , jan.kizek@tuke.sk , robert.dzurnak@tuke.sk

combustion of the fuel in LTCF are still demanding their design solution and technological grounding” (Revun and Zinchenko, 2006).

Using the volumetric fuel combustion leads to changes of condition for the local heat transfer to metal and lining in different points. The absence of concentrated heat forces, which are the most brightly expressed for the torch practice of fuel combustion, leads to the situation when the whole of the surface of the metal to be heated is under the equivalent condition of heating. There is no stagnant zones or metal being in zones of stagnation. The volumetric burning of the fuel can be arranged by regulated intermixing of the burning reagents. Heat transfers and combustion processes are described by the authors (Ferstl and Masaryk, 2011; Rimár and Fedák, 2014; Varga et al., 2013)

In contribution (Durdán and Kostúr, 2015; Durdán and Kostúr, 2006), a proposal of the system for indirect measurement temperatures in the underground coal gasification (UCG) process is presented. A two-dimensional solution results from the Fourier partial differential equation of the heat conduction was used for the calculation of the temperature distribution in the real coal seam. An algorithm of queue burning movement for modelling the boundary conditions in gasification channel was created.

The objective of the work (Lazić et al., 2011) was to investigate the essential features of radiation and convection heat transfer in the chamber furnace heated with roof flat-flame burners and conventional side-fired torch burner. The effect of change in the furnace chamber height on the heat transfer rate in the furnace enclosure, particularly on the heat flux onto the heated material, was determined numerically and experimentally.

Experimental evolution of heat flux distribution in a reheating aluminium furnace with a pair of regenerative burners was conducted in the study (Zhang and Deng, 2017). Reheating furnace with regenerative system has been widely applied in the non-ferrous metal industry due to its great advantages, such as high energy efficiency, low pollutant emission and high production yield.

Combustion of the fuel with air at the regulated intermixing

The methods for changing the torch length by way of regulating the quality of intermixing the fuel with oxidiser are known. They are: the pulsed way of burning the fuel; periodical change of the torch direction and the dynamic characteristics of the torch and other practices trained on the change of conditions for external heat exchange. The proposed practices only bring the regime of fuel combustion closed to volumetric one, as the torch in these practices is present at certain stretches of time or in the definite point of the furnace working space.

The practice of multi-stage fuel burning is the nearest to the volumetric burning. Only a part of the air necessary for the complete combustion of the fuel is conveyed to the burner, and the rest is carried along the trajectory of movement of the furnace gases. With the more step introduction of air and gradually complete combustion of the fuel, the longer flame is achieved under conditions that are close to the volumetric combustion. Such burning is practised on a large scale in the boiler equipment. In industrial furnaces, the burning of fuel by stages was connected with the necessity of organising the low-oxidising and oxidising free heating of steel before metal forming. It is also noted in the literature (Shults, 2005) that the burning of fuel by stages allows shortening ejections of the nitrogen oxides by 20-80% and creating a low-oxidising atmosphere in the working space of a furnace.

- *Method for calculating emissions of nitrogen oxides*

Basic studies of nitrogen oxides were performed by Zeldovich J.B. in 1947 (Zeldovich, J.B., Sadovnikov, P.P and Frank-Kameneckiy, D.A, 1947). According to J.B. Zeldovich content (amount) of NOx in the combustion products is determined: the temperature of the flame and the resulting combustion products; the content of the oxidising agent in the gases and other factors.

In the Shults L. A. (2005) work, the following relationships were used to determine the concentrations of nitrogen oxides in fuel combustion products:

$$[NO] = 0.24\ 10^{10} K_g\ K(O_2)\ K(\varepsilon)\ K_v\ exp\left[\frac{35\ 000}{T_{k_1}^{0.25}\ T_{k_2}^{0.5}\ T_n^{0.25}}\right] \qquad (1)$$

where the following variables are used:

K_g - coefficient reflecting the type of burner. $K_g=0.5\text{-}3.5$. For turbulent burners $K_g=1$

$K(\varepsilon)$ - coefficient depending on the optical density of the combustion products

$K(\varepsilon)=0.3\text{-}1.0$;

K_v - concentration coefficient. $K_v = \frac{V_\alpha}{V_{\alpha=1}}$, V_α - specific (measured) amount of exiting flue gases from calculations of fuel combustion stoichiometry, $V_{\alpha=1}$ - standard flue gas outlet;

$K(O_2)$ – a coefficient dependent on the oxygen content of the combustion products. With excess air greater than one $K(O_2) = (0.7 + O_2)^{0.5}$;

T_{k_1} - standard calorimetric temperature (K);
T_{k_2} - calorimetric flame temperature (K);
T_n – the temperature of the flue gases leaving the furnace (K).

- *Low oxidation atmosphere in furnaces*

Combustion of hydrocarbon fuels (which contain carbon and hydrogen compounds, for example, natural gas) provide the following components of CO-carbon (carbon monoxide) and H_2 (gaseous hydrogen) which are formed in two- and multi-stage combustion.

The amount of such reducing gases (CO and H_2) and their ratio to total combustion oxidising gas (CO_2 and H_2O) depends on the coefficient of the amount of air used to burn the hydrocarbon fuel.

With sequential fuel combustion in the first stage, the 45-60% of the air required by air stoichiometry is supplied. The remainder of the air, with a slight excess (up to 5-10%), is fed to the second or further stages of combustion.

This achieves a triple effect of reducing the emissions of nitrogen oxides:

- The specific concentration of oxidising gases(CO_2 and H_2O); decreases
- The specific concentration of reducing gases (CO and H_2) increases ;
- The temperature in the combustion zone decreases.

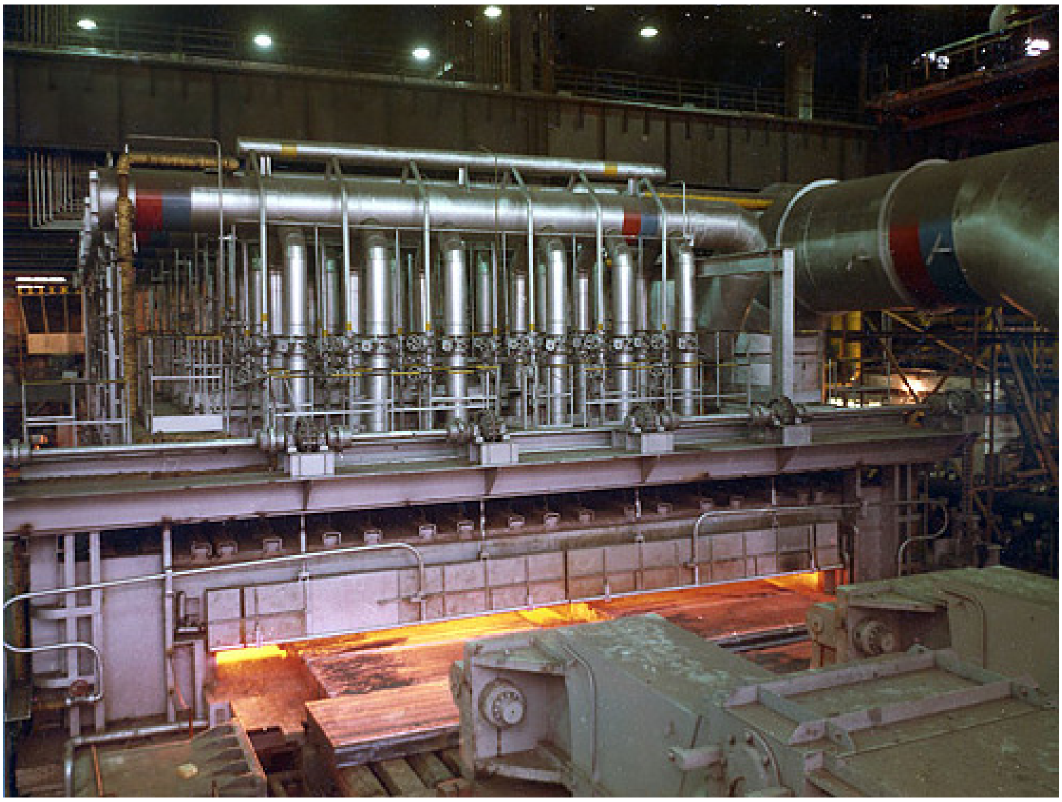

Fig. 1. View of the pusher furnace.

The work (Shults, 2005) shows that "stretched" in time burning in the working space of the heat engineering equipment is achieved by dispersion of the lead-in air by the length of torch, as well as by deregulating the work of burners, layers of burners or burners of different zones of burning open to each other as to gas dynamic and connected mutually, in accordance with coefficient of air consumption. The realisation of the fuel burning by stages in practice is entailed with some difficulties. A bulky system of pipelines, additional blocking and regulating accessories and complication of the system of automatic equipment, the unsolved question about the organisation of multistage schedule of burning at the variable heat power of burners, which is connected with carrying out the heat process, put limitations on using the given practice in heating furnaces.

A typical example of the use of temperature distribution control in reheating furnace is the pusher furnace, which is shown in Fig. 1.

Regulated (specified) intermixture of the burning reagents and distributed fuel burning in heating furnaces with high-temperature preheating of the combustion air

The organisation of volumetric fuel burning by means of the specified regulated intermixture of the burning reagents, when fuel in the working space of the furnace is burning on all the length of the trajectory of the furnace gases movement without creating local high-temperature zones, could become alternative to the stage combustion.

To the recent time, slowed intermixture of the fuel with air was not widespread in industrial furnaces. Traditional burners do not assure the complete intermixture of the fuel with air. The unsatisfied intermixture of the burning reagents leads to creating so-called physical under burning and over expenditure process in heating furnaces equipped with recuperates or operated without heat utilises. The situation is different in the furnaces with regenerators. If the complete combustion of the fuel is organised before leaving the flue gases from the packing of regenerators, the released chemical heat with a high coefficient of regeneration will return back to the furnace with heated air. The only condition is the complete combustion before leaving the packing of regenerators. When the combustible components of the fuel are burnt in the regenerator, the nozzle does not exceed 2-3% at 10% underburning of the fuel in the furnace. This is ensured by a high degree of recovery (regeneration) of the heat of flue gases (up to 80%) in modern ball regenerators and regenerative burners.

The presence in the volume zone of the burning of the fuel-air mixture with temperature exceeding the temperature of fuel ignition at the expense of high-temperature air heating in the modern regenerators makes possible burning at any quantity of oxygen.

The heat escape can be distributed along all the trajectories of moving the furnace gases at the expense of regulated intermixing fuel and air. In the view of the distributed burning, the low oxidising atmosphere is created in the furnace, the local high-temperature zones disappear, the uniformity of metal heating is improved and the quantity of harmful ejections during the burning.

Organization of distributed volume fuel combustion in heating furnace equipped with high-efficient regenerators (or in other words "volume-regenerative practice of fuel combustion") is ensured at the expense of dividing the flows of fuel and air in burners facility and assuring the dynamic characteristics of the gas-air streams, which guarantee the specific quality of mixing the reagents of burning. Due to the choice of number, geometric characteristics and mutual arrangement of gas nozzles, flue gases openings in regenerators and other structural parameters of the furnace and its elements, the conditions are created for regulated mixing of fuel and air.

Gas-dynamic characteristics of furnace gases

1. The speed of the motion and dimensionless speed of the motion.

Stability of the flame and combustion process in the furnace depend on the velocity of reactants. If the velocity of reactants exceeds the flame speed, the flame will begin to move in the direction of the reactant flow. This would extinguish the flame and result in uncombusted fuel. This condition is known as a liftoff. If the reactants have a velocity much lower than the flame speed, the flame moves opposite the direction of the reactant flow. This condition is known as a flashback (Semikin, Averin and Radchenko, 1965).

2. Consumption pulse of jets and flows.

In the paper (Semikin, Averin and Radchenko, 1965), it was shown by I.D. Semikin "that the decisive influence in the determination of the length of turbulent flame at fuel burning has the ratio of the mass flows of the air and gas".

By analogy with the notion of the thermal heat capacity of the flow (W_t/K), the notion of consumption pulse had to be introduced (or the notion of consumption quality of the medium motion (H)).

$$I_{med} = \rho_{0med} \frac{V_{0med}^2}{f_{med}} \left(1 + \frac{t_{med}}{273}\right) \tag{2}$$

where

$V_{0\,med}$ – volumetric consumption of the medium (fuel, air, flue gases) under n.c. (normal conditions), m^3/s;

f_{med} – the area of section for passage of the medium (section of the gas nozzle for fuel, or section of the canal for flue gases and so on), m^2;

t_{med} – the temperature of the medium, °C;

$\rho_{0\,med}$ – density of the medium under the n.c., kg/m^3.

It is possible to judge which reagent in the fuel-air flow is the key by the ratio of the motion quantity of one reagent to the general pulse of fuel *(lower index f)* and air *(lower index a)*.

$$\Delta I = \frac{I_f}{I_f + I_a} = \frac{\frac{\rho_{of}}{f_f}\left(1+\frac{t_f}{273}\right)}{\frac{\rho_{of}}{f_f}\left(1+\frac{t_f}{273}\right)+\rho_{oa}\frac{L_n^2}{f_a}\left(1+\frac{t_a}{273}\right)} \tag{3}$$

The difference of pulses of burning reagent by the value, which does not exceed 10-15%, assures the minimal interaction of jets and the slowed regulated mixing of the fuel and high-temperature air.

3. *The kinetic energy of jets to be consumed.*

The kinetic energy of burning reagent related to the second consumption of reagents shows to what extent the energy potential of these gases can be transformed into rectilinear or recirculating motion of the combustion gases*(lower index s)* with *Vs* and kinetic energy to be consumed (Yeromin, 2012)

$$E = \frac{\rho_0\, \overline{w}_0^2\, V_0}{2}\left(1+\frac{t}{273}\right)^2 \tag{4}$$

where

ρ_0 – density under n.c., m/s;

V_0 – volumetric consumption of the heat-transport medium under n.c., m^3/s.

Using the notions of the consumed kinetic energy of furnace gases allows expressing the energy balance of medium circulation as equality of presented power of circulation and power of furnace gases consumed for their motion along the specified trajectory in the form of expression.

$$\frac{\rho_f\, \overline{w}_0^2}{\rho_f\, \overline{w}_s^2\, v_s} + \frac{\rho_f\, \overline{w}_a^2\, L_n}{\rho_s\, \overline{w}_s^2\, v_s} - 1 = \sum_{i=1}^{i} \lambda_{eqi}\, \frac{L_{av\,i}}{d_{eqv\,i}}\, K_{rec}^3 \tag{5}$$

where

λ_{eqv} – coefficient of the energy losses at the circulating motion of gases in the *i*-th section;

L_{av} – the average length of the motion trajectory of the furnace gases in the *i*-th section, m;

d_{eqv} – equivalent diameter of the middle section of the flue gases flow in the *i*-th section in the furnace, m;

K_{rec} – the multiplicity of the flue gases recirculation;

i – the number of the section of the trajectory of the furnace gases motion;

v_s – the specific output of combustion gases during burning, m^3/m^3.

4. *The energy of furnace gases circulation*

The kinetic energy of furnace gases, which is spent for circulation in one second (energy of circulation *N*, *W$_t$*) is equal to the kinetic energy of the flow of flue gases introduced to the furnace, minus the kinetic energy of the flow of flue gases leaving the furnace through the flue gases ducts (Yeromin and Gubinskiy, 2011).

$$\mathbf{N} = \frac{\rho_f\, \overline{w}_f^2\, v_f\left(\frac{T_f}{273}\right)^2 + \rho_a\, \overline{w}_a^2\, v_a\left(\frac{T_a}{273}\right)^2 - \rho_s\, \overline{w}_s^2\, v_s\left(\frac{T_s}{273}\right)^2}{2} = \frac{\rho_f\, w_f^3\, F_f\left(\frac{T_f}{273}\right)^2 + \rho_a\, w_a^3\, F_a\left(\frac{T_a}{273}\right)^2 - \rho_s\, w_s^2\, F_s\left(\frac{T_s}{273}\right)^2}{2} \tag{6}$$

where

F_f, F_a, F_s are the passage section of the gas nozzle, air ducts and flue gases ducts, m^2.

5. *and 6. The specific energy of circulating in dimensional and dimensionless representation.*

The quantity of kinetic energy in $1m^3$ of furnace gases is called the specific energy of circulated N_{sp} (Yeromin and Gubinskiy, 2011) expressed in the form:

$$N_{sp} = \lambda_{eqv}\, \frac{L_{av}}{d_{eqv}}\, K_{rec}^3\, \frac{\rho_s\, \overline{w}_s^2}{2}\, \frac{T_s}{273} \tag{7}$$

$$N_{sp} = \frac{\rho_f\, \overline{w}_f^2\, V_f\left(\frac{T_f}{273}\right)^2 + \rho_a\, \overline{w}_a^2\, V_a\left(\frac{T_a}{273}\right)^2 - \rho_s\, \overline{w}_s^2\, V_s\left(\frac{T_s}{273}\right)^2}{2\, V_s\left(\frac{T_s}{273}\right)} \tag{8}$$

Eq. 7 and Eq. 8 allow determining the gas-dynamic characteristics of furnace gases ensuring the specified multiplicity of recirculation and the length of trajectories of these gases motions in the working space of the furnace.

It is easy to judge about the range of the furnace gases flow in the furnace by the specific energy of circulation in dimensionless form.

7. The multiplicity of recirculating the furnace gases.

According to the opinion of the professor V.I. Gubinskiy (Gubinskiy and Lu Chzhun, 1995), “in the practice of designing furnaces, one needs taking into account and using the active part of conditions of gases circulation and the fuel burning. As opportunities for gases motion control with the purpose of equalisation of the temperature in the furnace working space can serve the internal and external recirculations as well as the reverse of the furnace gases. The final evaluation and the choice of schedules for gas circulation and burning fuel can be done by way of calculating the conjugate temperature distributions of openings, metals and refractories of the furnace”.

The multiplicity of recirculation K_{rec} to be found from the equation of energy balance including pressure losses on all the sections of the trajectories of furnace gases motion from a burner to the flue gases ducts. This equation for the energy of circulation has the next dimensional form:

$$K_{rec} \sqrt[3]{\frac{\rho_f\, \overline{w}_f^2\, V_f \left(\frac{T_f}{273}\right)^2 + \rho_a\, \overline{w}_a^2\, V_a \left(\frac{T_a}{273}\right)^2 - \rho_s\, \overline{w}_s^2\, V_s \left(\frac{T_s}{273}\right)^2}{\lambda_{eqv} \left(\frac{T_s}{273}\right)^2 \sum_{i=1}^{i} \left(\frac{L_{av\,i}}{d_{eqv\,i}}\, \rho_{s\,i}\, \overline{w}_{s\,i}^2\, V_s\right)}} = \tag{9}$$

$$= \sqrt[3]{\frac{2\, N_{sp}}{\lambda_{eqv} \frac{T_s}{273} \sum_{i=1}^{4} \left(\frac{L_{av\,i}}{d_{eqv\,i}}\, \rho_{s\,i}\, \overline{w}_{s\,i}^2\right)}}$$

The increase of the heating efficiency in reheating furnaces

Flame combustion of fuel

Flame combustion of fuel (Fig. 2) is characterised by:

1. concentrated heat input,
2. non-uniform temperature distribution and low quality of metal heating,
3. intensive NOx formation,
4. formation of the scale,
5. durability and melting of the lining, especially under the high temperatures.

Uniformity of temperature distribution in furnaces can be achieved with the help of controlled air-fuel mixing (impulse method, variable consumption of reagents, change of direction and dynamic flame characteristics, gradual fuel combustion, slow mixing of reagents).

Fig. 2. Flame combustion of fuel.

Distributed fuel combustion in the volume

The organisation of volume fuel combustion requires adjustment of the furnace and burner design construction parameters such as:

1. gas nozzles and ducts for combustion air supply,
2. flue gases openings (number, layout, geometric parameters),

3. mixing angle of reagents streams,
4. mutual layout of: burners, flue gases openings, metal in furnace and others.

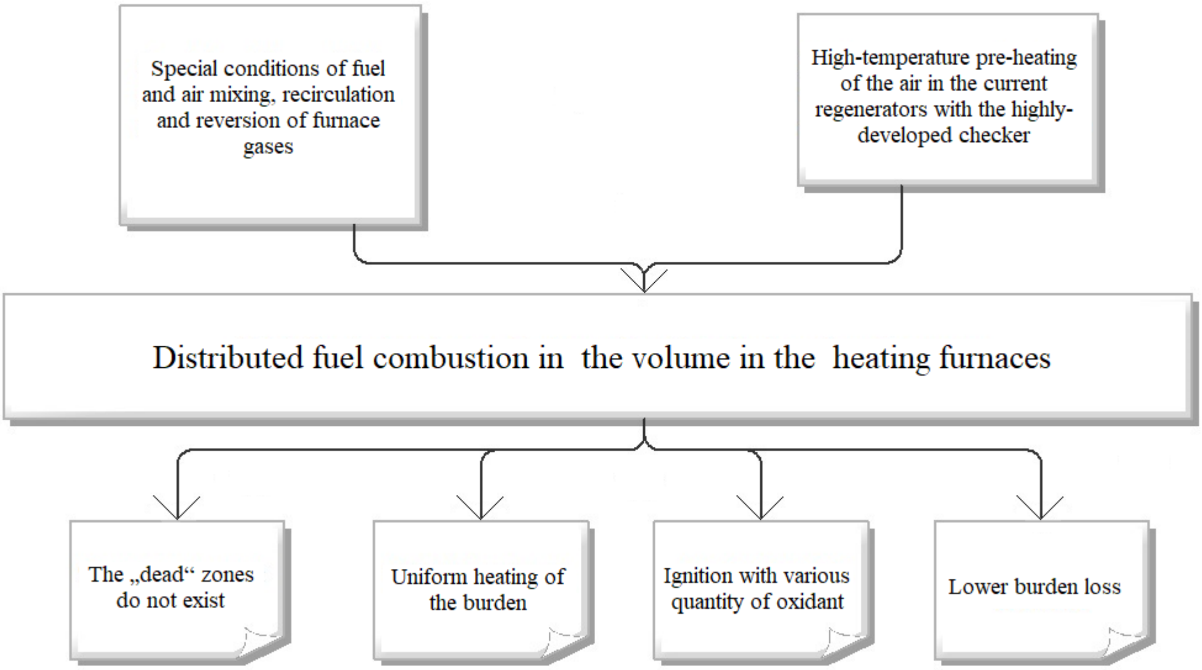

Fig. 3. Distributed fuel combustion in the volume.

Utilisation of the regenerative heating shaft

The practical benefits of distributed volume fuel combustion and efficient temperature distribution control are shown for the application of a regenerative heating shaft. The indicators of the work of the reheating furnace (Fig. 4) before the reconstruction and after reconstruction are presented in Tab. 1.

Fig. 4. View of the ingot reheating furnace.

Tab. 1. Indicators of the work of the heating furnace to the reconstruction and after reconstruction.

Indicator	Dimension	Heating method	
		Recuperative	Regenerative
Type of fuel	-	mix gas	mix gas
Calorific value (Higher heating value)	MJ/m^3	8,2	8,2
Maximum fuel consumption	m^3/h	2100	1500
Maximum air consumption	m^3/h	10000	5000
Maximum heat output	MW	4,87	3,48
Mass of charge	t	120	120
Lining volume in recuperator or regenerator	m^3	31,75	0,75
Temperature of ingots	°C	900 - 950	900 - 950
The temperature of preheating air	°C	do 600	do 1100
Coefficient of fuel utilization	%	50	75
Specific fuel consumption for batch heating	kg/t	18	12
Average specific fuel consumption (cold run)	kg/t	25,3 – 28,4	30,3
The amount of scale per 1t of metal per year	kg	10,9 – 12,8	8,4 – 9,35

Conclusions

It is possible to organise distributed volumetric fuel combustion in the regenerative furnaces by means of ensuring gas-dynamic characteristics of the furnace gases, their reverse and recirculation, and by structural parameters of the furnace elements. Uniform temperature distribution in the working space of a furnace, formed as a result of distributed volumetric fuel combustion in reheating furnaces equipped with high-effective regenerators, predetermines: uniformity heating of ingots considering the height and the length of the working space (Yeromin, Gubinskiy and Sibir, 2007), decreasing the quantity of harmful ejections and creating the low oxidizing atmosphere in the working chamber of the furnace.

At present, increasing the energy efficiency of thermal aggregates is one of the pillars of the energy policy not only of the EU *(European Union, 2018; Europarl.europa.eu, 2018)* but also of global interest. Addressing these issues contributes to meeting these declared environmental policy goals and reducing the impact of global warming.

The European Commission has also subscribed to the conclusions of the Paris Conference on Climate Change held in December 2015 (COP2l), which confirmed that the way to "clean energy" is irreversible (Klepáč, 2016).

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