Low-temperature swirl method of burning combustible waste

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Abstract. Burning combustible industrial waste increases the efficiency of using raw materials while at the same time solving the issues of protecting the environment from pollution by eliminating waste dumps. The paper deals with the low-temperature swirl method of waste incineration of microbiological production – hydrolytic lignin. A combustion device has been developed that allows using hydrolytic lignin as a fuel for the production of electrical energy and heat without illumination of the torch and with high efficiency and reduced emissions of gaseous pollutants into the atmosphere. On the basis of the developed model of the boiler TP-35U, a quantitative estimate of the level of nitrogen oxides was made when introducing the low-temperature swirl method. The results of the calculations show the advantages of low-temperature swirl combustion of hydrolytic lignin.

1 Introduction

An increase in the consumption of wood raw materials entails the formation of a significant amount of bark, chips, sawdust unsuitable for processing, and necessitates their disposal or storage. In full, this applies to hydrolytic lignin - waste processing plant materials at hydrolysis and biochemical plants [1]. Despite the wide potential applications, hydrolyzed lignin in enterprises is used in obviously insufficient quantities, and is burdensome waste.

The most appropriate and economically feasible at the present time is the direct combustion of hydrolytic lignin in boiler furnaces for the production of electrical energy and heat [2, 3]. The greatest problems with burning hydrolytic lignin occur in the combustion chamber of the boiler. Due to the low calorific value (~1600 kcal/kg) and high humidity (Table 1), additional torch lighting with gas or fuel oil is required to burn lignin. The presence of illumination leads to the melting of the mineral part and intensive slagging of the heating surfaces, which makes impossible reliable operation of the boiler plant.

The low-temperature swirl combustion method eliminates the listed drawbacks, and also provides reduced emissions of toxic gaseous pollutants into the atmosphere.

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Table 1. Calculated characteristics of hydrolytic lignin.

Name	Designation	Dimension	Amount
Moisture	W_i^r	%	64.83
Ash	A^r	%	1.17
Sulfur	S^r	%	21.3
Carbon	C^r	%	2.13
Hydrogen	H^r	%	0.27
Nitrogen	N^r	%	0.11
Oxygen	O^r	%	10.19
Net calorific value	Q_i^r	kcal/kg	1590
		MJ/kg	6.7
Yield of volatiles on dry ashless condition	V^{daf}	%	65
Granulometric composition of dust			
Total residue on a 100 μm sieve	R_{90}	%	90–98
Total residue on a 200 μm sieve	R_{200}	%	65–85
Total residue on a 1000 μm sieve	R_{1000}	%	15–45

2 Principles and organization of low-temperature swirl furnace process

The concept of the low-temperature swirl combustion (LTS) method was proposed in the late 1960s by Professor V.V. Pomerantsev. Orange as an alternative to direct-flow torch (Fig. 1, a). The LTS method is based on the principle of organizing the multiple circulation of relatively large fuel particles with their periodic return to the zones with the initial oxygen concentration [4–7] (Fig. 1, b).

a)   b)
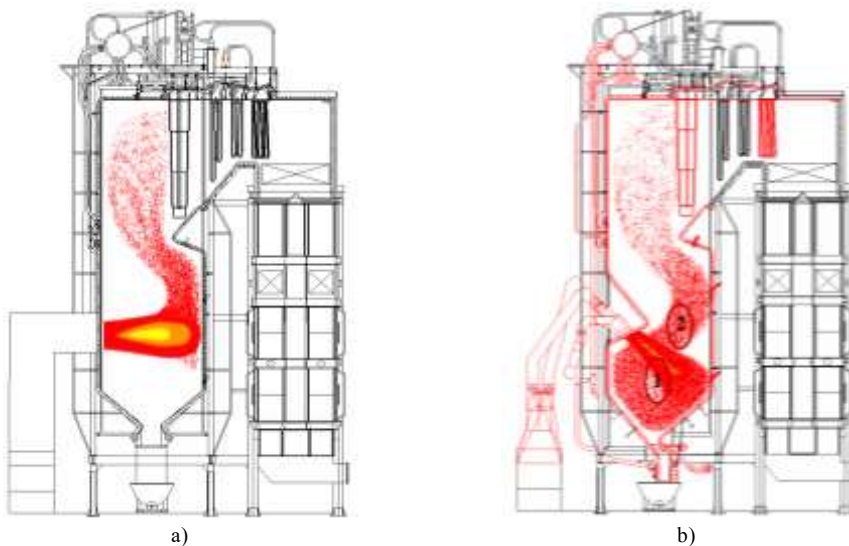
Fig. 1. Boiler with steam capacity of 220 t/h: a) – with traditional technology of pulverized coal combustion; b) – with low-temperature swirl technology: (1 – lower swirl zone, 2 – flow-through zone).

The introduction of the LTS method is equally possible both in the case of new construction and in the reconstruction of existing equipment at power facilities. In the case of new construction, the use of the LTS-method allows reducing the cost of building a boiler shop due to the reduction in the height of the building compared to traditional

combustion technology [8, 9]. In the case of replacement of boiler equipment that has developed its life, the use of the LTS method allows to install new boilers in existing building cells (Fig. 2), which drastically reduces the cost of building a new building [10, 11].

Fig. 2. The layout of the boiler with low-temperature swirl furnace in the boiler room.

In addition, the low-temperature swirl method is a technological method of protecting the environment from harmful emissions of nitrogen oxides and sulfur oxides [12–16], implemented at the stage of fuel combustion by the design of the combustion device and operating characteristics of its operation.

3 Object and research methods

The object of the study is the boiler TP-35U (produced by the Belgorod boiler plant) of one of the enterprises of the microbiological industry and its reconstruction with the LTS-method of combustion. The subject of research is the combustion of hydrolytic lignin in the LTS-furnace, the generation and conversion of gaseous flue gas pollutants.

The reconstruction of the cat TP-35U with the transfer to low-temperature swirl combustion of hydrolytic lignin involves changing the geometry of the combustion chamber (while maintaining the external dimensions), and its installation in gas-tight design. In the lower part of the front and rear firebox, slopes of a "cold" funnel is forming. In the middle part of the firebox of the front wall panel form a front aerodynamic protrusion, on the lower generator of which two direct-flow burners are installed. Secondary air is supplied to the lower part of the burners. To create a swirl zone in the mouth of the furnace funnel mounted bottom air nozzle. On the rear screen are the nozzles of the tertiary blast. To reduce costs, the fuel supply system is performed in the millfree version. Equipment in front of the boiler includes fuel bunkers and feeders for metering and supplying fuel to the burners of the boiler. A general view of a boiler installation with an LTS-boiler TP-35U for the millfree combustion of hydrolytic lignin is shown in Fig. 3

Calculations of the burning of hydrolytic lignin in the LTS-furnace of the boiler TP-35U and determining the amount of gaseous pollutants formed are made using the developed mathematical model of the combustion process and a computer program.
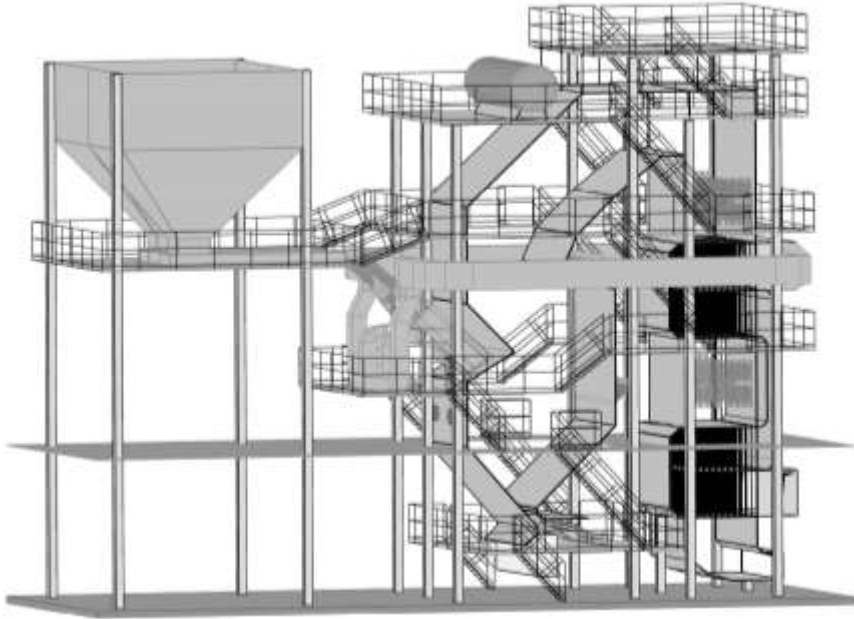
Fig. 3. Boiler installation with LTS-boiler TP-35U for the millless combustion of hydrolyzed lignin.

4 Model of the combustion process in a low-temperature swirl furnace and calculation method

The model of the hydrolysis lignin combustion process includes the complex aerodynamics of the LTS furnace, the movement of reacting particles of polyfractional solid fuel, the generation and decomposition of toxic nitrogen oxides on the surface of coke particles under the conditions of their multiple circulation [17−19].

The vectors of gas-air flow rates (Fig. 4) were located using the Ansys Fluent software package at the nodal points of the elementary cells into which the combustion chamber was divided.
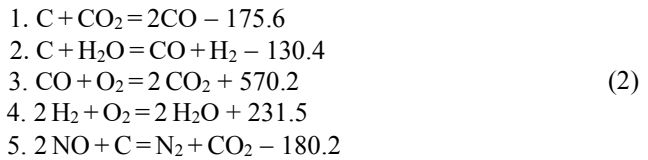
Calculations of particle trajectories in a known velocity field were carried out by numerically solving the Meshchersky equation, written in the projection on the axis of a Cartesian coordinate system, taking into account the influence of two main forces: gravity and aerodynamic drag:

$$\begin{cases} m\dfrac{dV_x}{d\tau} = \dfrac{cf\rho_g}{2}\left(W_x - V_x\right)\sqrt{(W_x - V_x)^2 + (W_y - V_y)^2 + (W_z - V_z)^2} \\[2mm] m\dfrac{dV_y}{d\tau} = \dfrac{cf\rho_g}{2}\left(W_y - V_y\right)\sqrt{(W_x - V_x)^2 + (W_y - V_y)^2 + (W_z - V_z)^2} \\[2mm] m\dfrac{dV_z}{d\tau} = \dfrac{cf\rho_g}{2}\left(W_z - V_z\right)\sqrt{(W_x - V_x)^2 + (W_y - V_y)^2 + (W_z - V_z)^2} - mg \end{cases} \qquad (1)$$

The combustion model of hydrolytic lignin in the LTS furnace uses the theory of "reduced film" proposed by V.V. Pomerantsev and S.M. Shestakov et al. [20]. Combustion of large coke particles of highly moist fuel is described by a set of chemical reactions (thermal effect in kJ/mol) typical for the "double burning" boundary layer scheme (the case of "wet" gasification):

a) b)
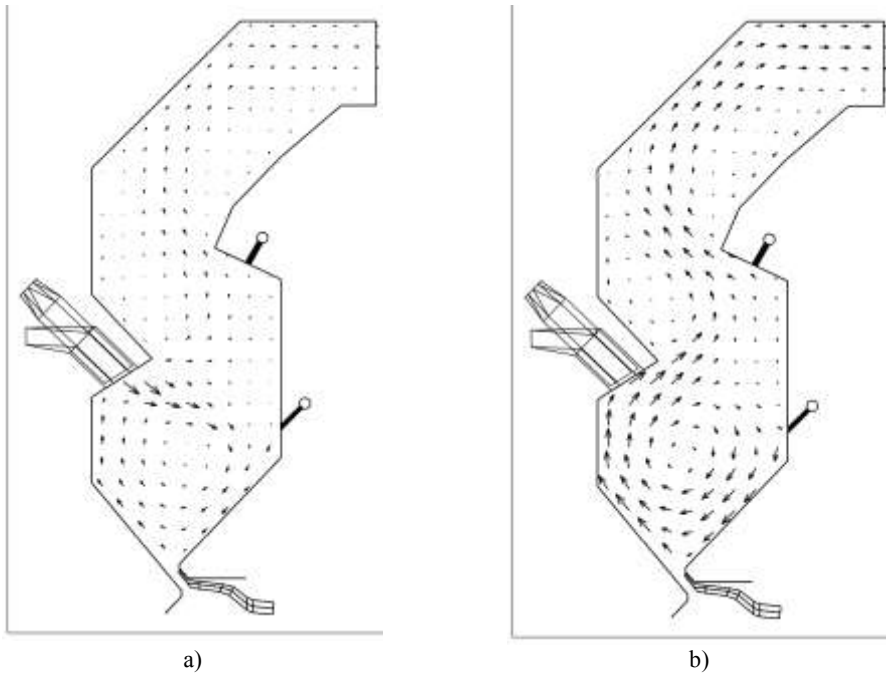
Fig. 4. Velocity of gas-air flows in the LTS-furnace of the boiler TP-35U: a − in the plane of the axis of the burner; b − in the plane between the burners.

$$
\begin{aligned}
&1.\ C + CO_2 = 2CO - 175.6\\
&2.\ C + H_2O = CO + H_2 - 130.4\\
&3.\ CO + O_2 = 2\,CO_2 + 570.2 \qquad\qquad (2)\\
&4.\ 2\,H_2 + O_2 = 2\,H_2O + 231.5\\
&5.\ 2\,NO + C = N_2 + CO_2 - 180.2
\end{aligned}
$$

The combustion process is described by a system of nonlinear differential equations of diffusion and kinetics:

$$
\begin{cases}
dG_j = -(D/RT)\cdot(d^2 p_j / dx^2)dx\\
G_j = (\alpha_D / RT)\cdot(p_j - p_{j0}) \qquad ,\\
dG_i / d\tau = C_i \cdot k_i
\end{cases} \qquad (3)
$$

taking into account the oxidation and reduction reactions occurring on the surface of the particle and the reactions occurring within its boundary layer (Fig. 5).

To solve the problem, we use the concepts of a dimensionless coordinate ($\xi = x/\Delta$); criterion of Semenov ($Se = (k_4 \cdot \Delta / D)^{0.5}$); diffusion-chemical criterion ($N_i = k_i / \alpha_D$); the Arrhenius dependences for reaction rate constants ($k_i = k_{0i} \cdot \exp(-E_i/(RT))$); "poles" with coordinates $k^* = 100$ m/s, $T^* = 2600$ K [21, 22].

The loss of mass and particle size is calculated by the expressions:

$$
\begin{cases}
dm/d\tau = dm_{W^r}/d\tau + dm_{volat}/d\tau + dm_c/d\tau,\ \text{kg/s}\\
dm_c/d\tau = -G_c \cdot M_c \cdot \pi \cdot \delta^2,\ \text{kg/(m}^2\cdot\text{s)} \qquad ,\\
d\delta/d\tau = -(2M_c/\rho_c)\cdot G_c,\ \text{m/s}
\end{cases} \qquad (3)
$$
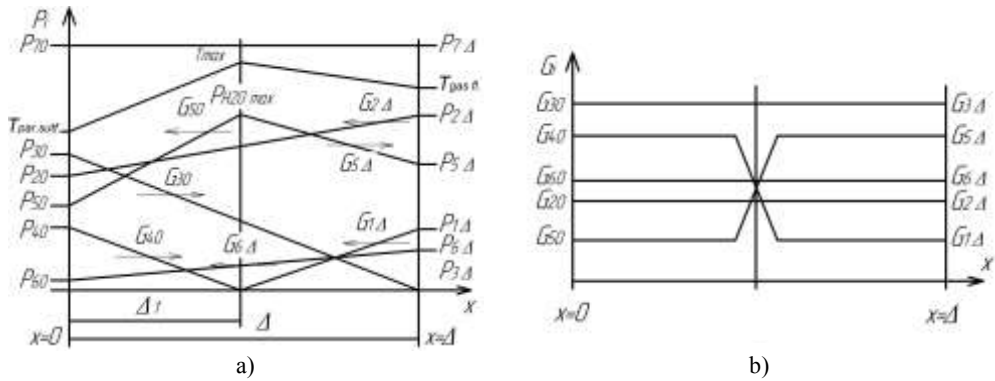
Fig. 5. Distribution of partial pressures (a) and flows (b) of the components in the given film of coarse ash particle: $1 - O_2$; $2 - CO_2$; $3 - CO$; $4 - H_2$; $5 - H_2O$; $6 - NO$; $7 - N_2$; the "0" indexes – particle surface; "□" – flow.

where $M_c = 12$ kg/kmol is the molar mass of carbon; $m = \pi/6 \cdot \delta^3_{eq} \cdot \rho_c$ is the mass of the spherical particle, kg; $f = \pi \cdot \delta^2_{eq} -$ is the area of the outer surface, m^2.

When calculating the combustion of coke carbon, the "shrinking particle" model was used provided that its density remains unchanged with the introduction of a coefficient K^r taking into account the relative content of coke in the working mass of the fuel:

$$K^r = 1 - (W^r + A^r + V^r)/100. \qquad (4)$$

Fields of concentrations of the main reactive gas components (O_2, CO_2, H_2O) were taken as typical for LTS furnaces, Fig. 6.
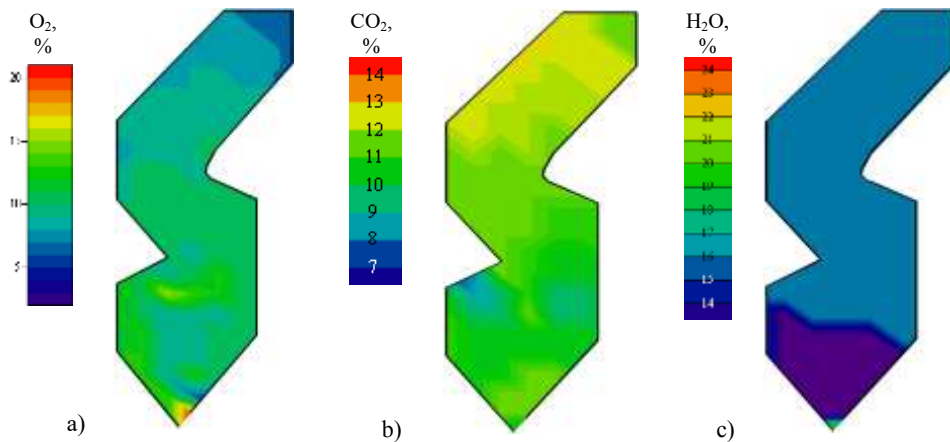
Fig. 6. TP-35U, %: a – oxygen; b – carbon dioxide; c – water vapor.

The particle size distribution of the initial fuel was described by the Rosin-Rammler-Bennet dependance [20, 21]:

$$R_{0i} = \exp(-b \cdot \delta^n_{0i}), \qquad (5)$$

where b and n are experimental coefficients.

The distribution of NO concentrations along the section of the furnace in a known gas flow velocity field was determined by numerical solution (the "anti-flow" scheme) of the differential mass transfer equation, in the presence of a source term (NO generation zone) for each of the unit cells [22]:

$$\frac{\partial}{\partial \tau}(\rho \cdot C_{NO}) + \nabla \cdot (\rho \vec{w} C_{NO}) = \rho D_{NO} \nabla^2 C_{NO} + J_{NO} \ , \tag{6}$$

where C_{NO} – mass concentration of nitrogen oxides; w – gas flow rate; J_{NO} – the intensity of generation of nitrogen oxides (power source NO [21]):

$$J_{NO} = \begin{cases} dN_{2i}/d\tau_i = k_{01} e^{-E_1/RT_i} \cdot (1/T_i) \cdot [N_i]^2 \\ dNO_{x_i}/d\tau_i = k_{02} e^{-E_2/RT_i} (1/T_i) \cdot [O_2]_i^{1,8} [N]_i \end{cases} , \tag{7}$$

D_{NO} – the average effective diffusion coefficient of NO in a mixture of flue gases, determined by the Wilk dependence, and the mutual diffusion coefficients of substances under real conditions according to Winkelman:

$$D_{1,2} = D_{0,1,2} (T/T_0)^{1.75} \cdot (P/P_0), \tag{8}$$

where D_{012} − coefficient of mutual diffusion of substances at $P_0 = 101.3$ kPa, $T_0 = 273$ K.

The amount of nitrogen oxides decomposed on the surface of burning carbon particles is calculated from the balance of reaction No. 5 of system (2).

5 Calculation results, their analysis and discussion

Calculations of the combustion process of hydrolytic lignin in the low-temperature swirl furnace of the TP-35U boiler were carried out for fuel (Table 1) with particle size characteristics $R_{90} = 90\%$, $R_{200} = 65\%$. The burnout curves of hydrolytic lignin particles in the LTS-furnace of the TP-35U boiler are shown in Fig. 7. Fine lignin particles ($\delta = 0.1...1.0$ mm) completely burn out within 1...2 seconds, managing to make the bottom swirl zone from 1 to 2 turns. The burning time of large particles increases to 20...30 seconds, and the time of complete combustion of 1 kg of fuel is ∼ 40 seconds.
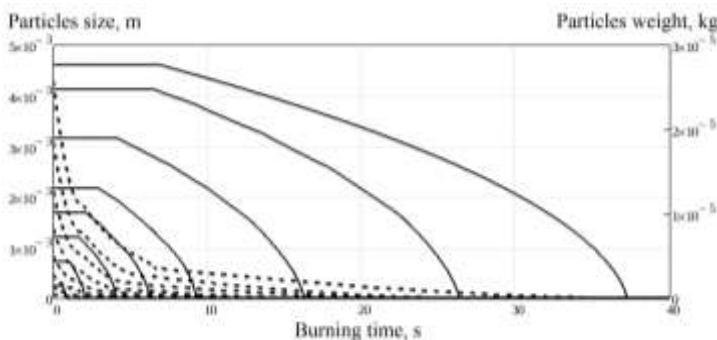
Fig. 7. Burnout of lignin particles in LTS furnace of TP-35U boiler: ——— – particle size, m;
- - - - – mass of particles, kg.

The trajectories of the reacting particles of hydrolytic lignin are shown in Figure 8. The particles of lignin, dried during the multiple circulation process, are evenly distributed across the width of the furnace and sufficiently fill the volume of the lower swirl zone, where the maximum concentrations of nitrogen oxides formed during the release and combustion of volatile substances are located. After the combustion of volatile, almost the entire mass of fuel continues to circulate in the lower swirl zone, where reaction No. 5 of the system (2) decomposes nitrogen oxides on the surface of burning particles [23]. As a result, molecular nitrogen and carbon monoxide are formed, which, in turn, burns down in

the gas stream by reaction No. 4. In addition, a significant amount of large particles are retained on the frontal slope of the combustion funnel under the action of gravity burning carbon coke.

Fig. 8. Trajectories of the hydrolytic lignin burning particles motion in the LTS furnace of TP-35U boiler.

Fig. 9. Concentrations of nitrogen oxides in the LTS furnace of TP-35U boiler, mg/m³ (at normal conditions and $\alpha = 1,4$).

In the middle (above the burners) and top (at the exit window level) parts of the furnace, the generation of nitrogen oxides practically does not occur, and their concentration to the output is at a level of 150 mg/nm³ (near the screens) to 300 mg/nm³ (along the axis of the furnace) torch), Fig. 9.

According to the requirements of the Ministry of Energy, emissions of nitrogen oxides when burning hydrolyzed lignin should not exceed 470 mg/nm³. Thus, the implementation of the LTS-method when burning lignin makes it possible to reduce emissions of NO_x by a factor of 1.5 to 2 relative to the established standards. This allows considering LTS-burning as a low-cost technological method of protecting the environment from harmful emissions during operation of power boilers.

6 Final provisions and conclusions

The results of the work confirm the high technical, economic and environmental performance of a low-temperature swirl boiler designed to burn hydrolyzed lignin. As applied to the boiler with a steam generating capacity of D = 35 t/h (9.72 kg/s), it is shown that its conversion to lignin combustion by the LTS method allows, with minimal capital expenditures for reconstruction, to increase the efficiency factor of operation of the boiler

to 89 %, reduce emissions of nitrogen oxides by 1.5...2 times and reach a level lower than that established by regulatory documents. In addition, the development of lignin dumps contributes to the release of territories and the improvement of the state of the environment as a whole.

References

1. M.I. Chudakov, *Promyshlennoye ispolzovaniye lignina* (Lesnaya promyshlennost, Moscow, 1983)

2. A.L. Popov, *Sozdaniye i issledovaniye topochnogo ustroystva i sistemy podgotovki topliva dlya bezmelnichnogo szhiganiya gidroliznogo lignina* (LPI, Leningrad, 1987)

3. I.B. Kubyshkin, *Razrabotka i osvoyeniye unifitsirovannogo topochnogo ustroystva dlya utilizatsii drevesnykh otkhodov i gidroliznogo lignina* (SPbSTU, Sankt-Peterburg, 1994)

4. Yu.A. Rundygin, K.A. Grigoriev, V.E. Skuditsky, S.M. Shestakov, *Low-temperature swirl technology of burning: experience of implementation, perspective of use. Victor Vladimirovich Pomerantsev. To the 100 anniversary since birth* (Publishing house Politekhn, St. Petersburg, 2006)

5. K.A. Grigoriev, V.E. Skuditsky, Yu.A. Rundygin, A.A. Trinchenko, Swirling-type furnace, Patent of 2253801 (2005)

6. K.A. Grigoriev, V.E. Skuditsky, Yu.A. Rundygin, A.A. Trinchenko, Swirling-type furnace, Eurasian patent of 008691 (2007)

7. K.A. Grigoriev, V.E. Skuditsky, Yu.A. Rundygin, A.A. Trinchenko, Swirling-type furnace. Patent of 83761 (2008)

8. K.A. Grigoriev, Yu.A. Rundygin, V.E. Skuditsky, A.A. Trinchenko, *Use of technology of low-temperature swirl burning at modernization of boiler installations* (Publishing house Politekhn, St. Petersburg, 2003)

9. A.A. Trinchenko, *Low-temperature swirl technology of coal combustion during the transition of domestic energy to the solid fuels use, Materials of the day of the young scientist at the Polytechnic University* (Publishing house of Polytechnic. University, SPb, 2007)

10. K.A. Grigoriev, Yu.A. Rundygin, V.E. Skuditsky, A.A. Trinchenko, *Sat. Doc. IV Int. Scientific-technical. Conf. "Achievements and prospects for the development of Siberia's energy industry"* (Publishing house of SIBVTI, Krasnoyarsk 2005)

11. K.A. Grigoriev, Yu.A. Rundygin, V.E. Skuditsky, A.A. Trinchenko, *Proceedings of the 4th Seminar of the Higher Schools of Siberia and the Far East on Thermal Physics and Heat Power Engineering* (DVGTU Publishing house, Vladivostok, 2006)

12. A.A. Trinchenko, A.P. Paramonov, M.R Kadyrov, Procedia Eng. **206**, 546−551 (2017) doi : 10.1016/j.proeng.2017.10.514

13. A.A. Trinchenko A.P. Paramonov, M.R Kadyrov, Procedia Eng. **206**, 558−563 (2017) doi: 10.1016/j.proeng.2017.10.516

14. A.A. Trinchenko, A.P. Paramonov, IOP Conf. Ser.: Earth Environ. Sci. **90** (2017)

15. A. Trinchenko, SHS Web of Conferences **44**, 00076 (2018) doi.org/10.1051/shsconf/20184400076

16. A. Trinchenko, MATEC Web of Conferences **193**, 03054 (2018) doi.org/10.1051/matecconf/201819303054

17. A.A. Trinchenko, A.P. Paramonov, J. Sci. and tech. sheets SPbSTU **4**, 231 (2015)

18. A.A. Trinchenko, S.M. Shestakov, J. Sci. and tech. sheets SPbSTU **2**, 54 (2008)

19. A.A. Trinchenko, *Low-temperature swirl technology of combustion of coals during transition of domestic power to use of solid fuels* (Publishing house Politekhn, St. Petersburg, 2007)

20. V.V. Pomerantsev, K.M. Arefiev, D.B. Akhmedov, Yu.A. Rundygin, S.M. Shestakov, *Fundamentals of the practical theory of combustion* (Energoatomizdat, Leningrad, 1986)

21. V.I. Babiy, V.F. Kuvayev, *Combustion of coal dust and coal-dust flame calculation* (Energoatomizdat, Moscow, 1986)

22. M. Patankar, *Numerical methods for solving problems of heat transfer and fluid dynamics* (Energoatomizdat, Moscow, 1984)

23. A.A. Trinchenko, V.V. Sergeev, M.R. Kadyrov, E.G. Porshneva, A.P. Paramonov, V.G. Urvantsev, J. Sci. and tech. sheets SPbSTU **24(02)** (2018) DOI: 10.18721/JEST.240203