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Numerical simulation of the processes of burning lignite in a vortex furnace with swirling countercurrent flows

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Abstract
This work presents the results of a numerical study of the working processes of burning lignite in a vortex furnace with swirling countercurrent flows. The results of computer simulation of the processes of burning lignite with a moisture content of 30%, an ash content of 20% and 35% and a higher calorific value of Qpв = 13.9 MJ/kg and 9.7 MJ/kg, respectively are given. The fields of temperature distribution, gas velocity and particle trajectory in the volume and at the outlet of the furnace are determined. The values of the swirling flow velocity near the exit from the furnace reach 150-170 m/s. Mechanical underburning is 3.7% and 9.4% depending on the ash content. The results of a numerical study have showed that the diameter of lignite particles affects their combustion process: coke particles with an initial diameter from 25 microns to 250 microns burn out by 96%. The furnace provides a complete combustion of pulverized coal particles - 99.8% and of volatiles - 100% at volumetric heat stress in the 2500 kW/m^3 furnace. The afterburning of fuel particles containing carbon is ensured by their circulation

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1. Introduction

Increasing the efficiency of energy saving in heat supply is possible using the low-grade solid-fuels, wood and coal waste (Basu, 2010; Redko, 2021; Rundygin et al., 2000). In the countries of the European Union aimed at using secondary energy resources, coal continues to play an important role. Brown coal is mined in Germany - 176.1 million tons, Poland - 131.1 million tons, Czech Republic - 46.0 million tons. Brown coal production in Ukraine is 41.8 million tons (2016).

In the United States, brown coal production amounted to 660.6 million tons (2016).

Poland ranks 6th in the world for the extraction of brown coal. Lignite reserves are estimated at 14 billion tons. Brown coal is used in the power industry in Poland. More than 80% of thermal power plants use coal for power generation. At the same time, Poland is reducing the share of coal in the structure of electricity production from 72% in 2020 to 56% in 2030. Replacement of natural gas in heating boilers is possible by using lignite as fuel. Ukraine has significant reserves of lignite, amounting to about 2 billion tons.

Lignite reserves are concentrated in the Donetsk, Lviv-Volyn and Dnipropetrovsk coal basins. Coal mining is conducted by OJSC "Alexandria - Coal" in an open quarry. The issue of development of the Novodmytrivka lignite deposit in the Barvinkivskyi district of the Kharkiv region with the reserves of over 390 million tons is being considered.

Brown coals of the Dnepropetrovsk basin are characterized by high humidity and high sulfur content as well as low calorie content. The use of brown coal in thermal power plants and boiler houses requires thermal processing. The low cost of brown coal mining is offset by high transportation costs. Therefore, the use of brown coal is effective as a local fuel at a short distance from the place of their extraction.

Thermal characteristics of lignite are as follows: ash content (about 30%), humidity (up to 30%), volatile yield (45-55%), combustion heat of about 10-26 MJ/kg. Combustion of lignite at HEGS and small heating boilers with ball furnaces is inefficient and therefore not used. For low and medium power boilers, furnaces with a reverse chain grate and mechanical spreaders are being developed, which provide the combustion of lignite with a humidity of 33-43% and an ash content of 30-35%. There is experience in burning lignite with humidity up to 60% at an ash content of 4-10%. It is difficult to ensure efficient combustion of lignite with high humidity and ash content (W^p = 33-37%, A^p = 35-45%). It is difficult to reconcile the modes of removing moisture and ash from the furnace with a reverse chain grate. On the one hand, the grate speed should be low (to remove moisture), on the other hand it should be high (to remove ash). In this case, the mode of coal combustion is influenced by the fractional composition of the fuel. At the content of small fractions of 45-50% the layer is condensed and the combustion mode is broken. The burning of lignite with high humidity and ash content (W^p+A^p > 60-70%) is characterized by insufficiently stable ignition, the requirement of increasing the temperature in the combustion zone. Moreover, if the yield of volatile V_g < 25%, the use of finer coals is required. The requirements for the organization of the combustion process and fuel preparation are increasing. Fine grinding of the fuel ensures the release of volatiles and a high rate of coke burnout - (1-2s). However, the grate furnaces of boilers need their modernization for burning low-calorific solid fuels with high humidity and ash content, polydisperse components (Shestakov, 2014). The fluidized bed furnaces need to improve the particle separation that are carried out, and their return to the furnaces to finish the combustion (Safarik, 2019). Vortex furnaces are effective, but they are characterized with significant combustible losses which require their modernization as well (Anikin, 2012).

2. State of the art and literature review

According to the "Energy Strategy of Ukraine 2035", coal remains one of the main sources of energy supply in Ukraine and continues to be a guarantor of state security. Therefore, it is important to involve local energy sources in the country's fuel and energy balance. This is especially true for heat generation in the system of housing and communal services (boilers of municipal heating systems). The use of local fuels reduces the consumption of imported natural gas.

In Ukraine, there are 235 municipal and industrial thermal power plants, more than 66 thousand industrial and 26 thousand municipal boiler houses in operation (Chernyavsky, 2012). The enterprises operate steam and hot water boilers. These are low-power boilers NIISTU-5 and 'Universal', DKVR steam boilers, hot water boilers with chamber furnaces of KVG, TVG, PTVM, KVGM types with a thermal power of 2 to 200 MW. Industrial HPPs are equipped with steam boilers with chamber furnaces of E, BKZ, TP, GM types with a steam output of 35 to 220 t/h. To burn brown coal, it is necessary either to modernize boiler units, which is cheaper, or to replace them with new boilers.

Modern furnace technologies for burning brown coal have been tested and there is practical experience in their application. In low-power boilers, mechanized layered furnaces are used. The furnaces are characterized by high mechanical underburning. Wellons VS rotary grate fireboxes are more efficient. The experience of burning brown coal in layered furnaces is given in (Nechaev, 1968).

Medium-power boilers use technologies for fuel combustion in a fluidized bed (Baskakov, 1995) and technologies in which fuel is burned in a fluidized bed and vortex afterburning in the above-layer space (Pitsukha, 2019).

Vortex low-temperature furnaces are used at the boilers of medium productivity. The burners are inclined downwards by 45°. Jets of primary and secondary air form vortices of horizontal rotation.

To burn brown coals, furnaces with liquid slag removal are recommended. Furnaces with liquid slag removal are single-chamber and two-chamber ones. In two-chamber furnaces, the fuel combustion chamber with liquid slag and the cooling chamber are separated by a slag separation grate made of a tube bundle (Munts, 2005). However, the installation of a separation tube bundle increases the aerodynamic drag. The combustion chamber consists of two vortex vertical octahedral pre-furnaces.

The experience of burning brown coal in vortex furnaces of power boilers is given in (Rundygin, 2000; Shestakov, 2014; Pomerantsev, 1986; Ryabov, 2021; Grigoriev, 2009; Puzyrev, 2003; Likhacheva, 2004), in circular vortex furnaces (Salomatov, 2012; Serant, 1988).

Currently, technologies are being developed that combine low-temperature combustion of solid fuels and vortex combustion (Puzyrev, 2003).

In (Likhacheva, 2004), the results of combustion of local fuels and brown coal in a vortex furnace with a horizontal axis of rotation and V-shaped direct-flow burners are presented. Reconstruction of the ECHM-60 boiler ensured the operation of the boilers without fuel oil lighting. Burning unground coal eliminates the need for a pulverizing system. At the same time, the fractional composition of brown coal after crushing and thermal grinding consisted of particles with a size of 1 mm to 5 mm.

Vortex prismatic furnaces with different orientation of the axis of rotation (horizontal, vertical) are given in (Shchurenko, 2004). The results of testing KV-1.86 VD hot water boilers with a thermal power of 1.86 MW, equipped with an inclined grate with double-sided ignition and a vortex afterburner, are presented.

Furnaces with a vertical axis of rotation are structurally simpler ones (RF Patent No. 2126932, 22127399). KE-6.5-14-270 DV boilers are equipped with these furnaces, where screen wear is eliminated and a low-temperature fuel combustion process is provided. This technology has been implemented at 30 boilers with a capacity of up to 2.5 t/h.

The paper presents the results of the reconstruction of gas-oil boilers of small and medium power by replacing the chain grate with a low-temperature fluidized bed.

Secondary air is supplied through the front and rear nozzles, forming a vertical vortex, which ensures the afterburning of gases and fine fuel particles. The maximum losses with mechanical underburning do not exceed 2.5%. As can be seen, the use of vortex furnaces is promising.

3. Theoretical formulation

In the work under study while doing the mathematical description of the physicochemical processes in the furnace, the following basic assumptions are made: the flow of the carrier gas medium is three-dimensional, chemically reacting, quasistationary, incompressible, turbulent, multicomponent; the rate of gas-phase chemical reactions is infinitely high; the gas mixture is in a state of thermodynamic equilibrium; buoyancy, bulk viscosity and viscous heating are negligible; lignite particles are spherical, polydisperse; the volume occupied by the particles is neglected; the burning of lignite particles includes the processes of release and ignition of volatiles and the burning of coke residue; heat exchange by radiation is taken into account; isotropic turbulence is isotropic; particles do not affect turbulence parameters; turbulent dispersion of particles is taken into account. A dust- lignite mixture is modeled as a two-phase mixture with an Euler description of the gas phase (continuous medium) and a Lagrangian description of the movement of lignite particles (trajectory model). The phase interaction is taken into account on the basis of the "particle-source in the cell" model (Hong, 2016), according to which the presence of a particle in the flow manifests itself through additional sources in the equations of conservation of the continuous phase. The instantaneous thermochemical state of the flow is believed to be uniquely determined by the conservative scalar quantity – the dimensionless Schwab – Zeldovich function f, which has the meaning of the mass fraction of reduced fuel. The interaction of chemical processes and turbulence is described statistically using the probability density function. Under the above assumptions, the behavior of the gas phase is described by a system of partial differential equations consisting of Reynolds averaged Navier-Stokes equations, two equations of the differential turbulence model k-ε type (Krou, 1982), conservation equations for the dimensionless Schwab – Zeldovich functions f_n and for the pulsations of these functions $g_n = f_n'^2$ and the integro-differential radiation transfer equation (Loitsyanskii, 1978; Badzioch, 1970).

Discretization of the initial partial differential equations is carried out by means of the control volume method using a first-order accuracy scheme for approximating convective terms. The solution of the resulting systems of linear algebraic equations is solved by the Gauss-Seidel method using the SIMPLE algorithm. The integro-differential equation was solved by the method of spherical harmonics. The system of ordinary differential equations is integrated by the Runge-Kutta method. To calculate the conditions of chemical equilibrium, an algorithm based on minimizing the Gibbs free energy is used. (Badzioch, 1970)

The following boundary conditions of the continuous phase are set at the boundaries of the computational domain: at the incoming sections – the value of independent variables; on the walls – adhesion conditions; in the initial region – "soft" boundary conditions. Empirical wall functions are used to describe the turbulent boundary layer (Launder, 1972). When modelling the discrete phase, the initial conditions are set for each calculated particle: the particle position (xj coordinates), its velocity (ups components), diameter, temperature as well as the mass flow rate of particles following along the trajectory. It is taken into account that when they collide with the walls, the particles elastically repel them. A more detailed description of the mathematical model is given in (Redko, 2020). The creation of the furnace with oncoming swirling flows is based on the researches.
The system of differential privileges looks like this:

$$\rho \frac{\partial u_j}{\partial x_j} = S_n \tag{1}$$

$$\rho \frac{\partial u_j u_i}{\partial x_j} - \frac{\partial p}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} = S_{fi}, j = 1,2,3 \tag{2}$$

$$\rho \frac{\partial u_j h}{\partial x_j} - \frac{\partial}{\partial x_j}\left(\frac{\mu}{Pr} + \frac{\mu_m}{Pr_m}\right)\frac{\partial h}{\partial x_j} = S_q, j = 1,2,3 \tag{3}$$

$$\rho \frac{\partial u_j k}{\partial x_j} - \frac{\partial}{\partial x_j}\left(\mu + \frac{\mu_m}{\sigma_k}\right)\frac{\partial k}{\partial x_j} - \rho\,(G - \varepsilon) = 0, j = 1,2,3 \tag{4}$$

$$\rho \frac{\partial u_j \varepsilon}{\partial x_j} - \frac{\partial}{\partial x_i}\left(\mu + \frac{\mu_m}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j} - \rho(G_{\varepsilon 1} G - G_{\varepsilon 2}\varepsilon) =$$

$$= \frac{\varepsilon}{k} = 0, j = 1,2,3 \tag{5}$$

$$\rho \frac{\partial(\vec{u} f_n)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_m}{\sigma_m}\cdot\frac{\partial f_n}{\partial x_j}\right) + S_n, j = 1,2,3;\ n = 1,2,3 \tag{6}$$

$$\rho \frac{\partial \vec{u} g_n}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_m}{\sigma_m}\cdot\frac{\partial g_n}{\partial x_j}\right) + C_g \mu_m \left(\frac{\partial f_n}{\partial x_i}\right)^2 - C_d \rho \frac{\varepsilon}{k} g_n, j =$$

$$=1,2,3; n = 1,2,3 \tag{7}$$

$$\frac{1}{\beta_0}\cdot\frac{dI\,(\vec{r},\vec{s})}{ds} + I(\vec{r},\vec{s}) =$$

$$= (1-\omega_0) I_b(\vec{r}) + \frac{\omega_0}{4\pi}\int_{\Omega'=4\pi} I\,(\vec{r},\vec{s})\, d\Omega' \tag{8}$$

$$\tau_{ij} = (\mu + \mu_m)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{9}$$

Turbulent viscosity is determined by the Kolmogorov – Prandtl formula.

$$\mu_m = C_\mu \rho \frac{k^2}{\varepsilon} \tag{10}$$

$$k = \frac{1}{2} u_i^` u_i^` \tag{11}$$

$$\varepsilon = \frac{1}{2}\nu\left(\frac{\partial u_j^`}{\partial x_i} + \frac{\partial u_i^`}{\partial x_j}\right)^2 \tag{12}$$

$$h = \sum_i Y_i \left(\Delta h_{fi}^0 + \int_{T^0}^{T} c_{pi}(T) dT\right) \tag{13}$$

The generation of kinematic energy of turbulence due to shear stresses is determined by the formula:

$$G = \mu_m \frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{14}$$

4. Results and discussion

Calculations are made for five cases in which the scheme of fuel and air supply, the design (profile) of the furnace (with and without a central pipe), and the ash removal scheme (lower and upper) are changed.

The geometric model of the furnace is shown in Fig. 1. Fuel and primary air supply pipes, secondary air supply pipes and combustion product removal pipes are shown as well.

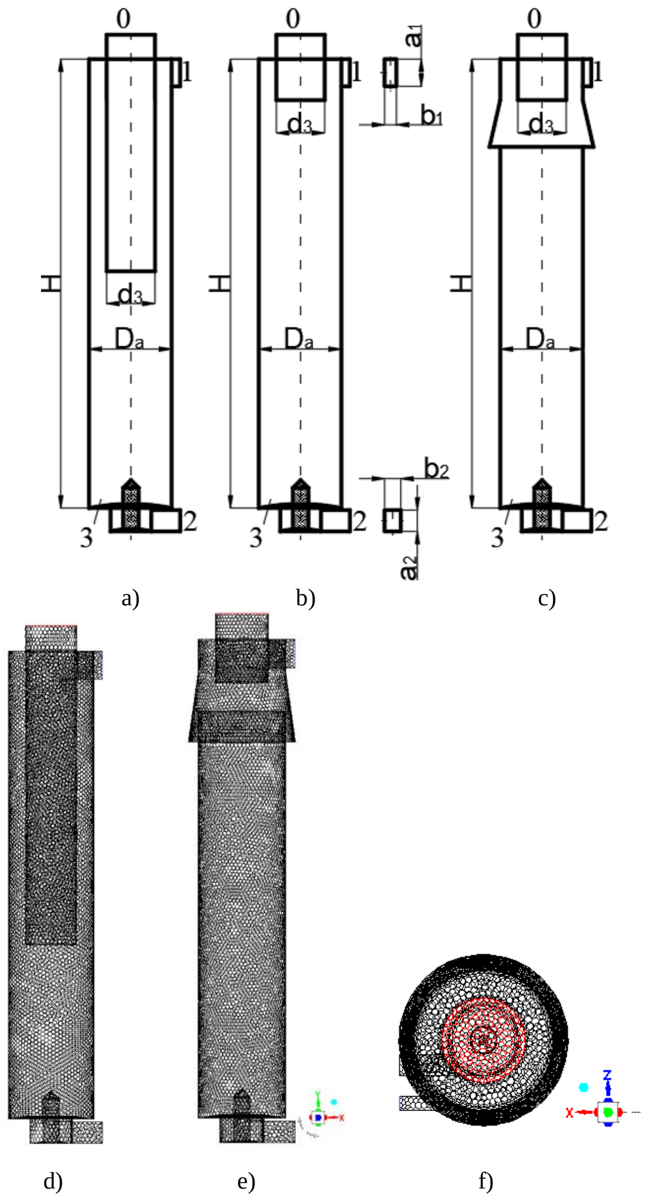

Fig. 1. General view of a vortex furnace with a different profile: a) a furnace with a central tube; b) a furnace without a central pipe; c) a furnace with an upper cone and design grids (d, e, f) of design variants of the vortex furnace a, b, c

Also, the swirlers of the lower air-fuel flow and the upper secondary air flow are shown. The dimensions of the furnace, air supply pipes and combustion product exhaust pipes are given.

According to the geometrical parameters of the furnace, using a preprocessor, a computer model of the furnace has been built - the computational grid of the furnace (Fig.1). Fig. 1 (d, e, f) shows the design grid of the furnace. The solution is found in the computational domain corresponding to the furnace part of the furnace. The computational area is covered with a non-uniform polygonal grid, including 64265 control cells and 87896 control cells.

The computer model is adapted:

– chemical parameters of the combustion process are determined;
– convergence criteria are determined;
– the consumption of primary air and fuel at the inlet to the furnace and static pressure are given;
– secondary air consumption and static pressure are set;
– air composition and excess air coefficient, stoichiometric coefficient are set;
– the pressure at the outlet of the furnace is set

The dispersed composition of lignite is represented by a histogram of the distribution of mass fractions of lignite particles by their size and grain characteristics. Dust is characterized by the following residues on the sieves: R90 = 17%, R200 = 2.5% and is finely ground dust. Kinetic characteristics for calculating the combustion process of lignite are accepted according to.

The main results of the calculations are given in table 1.

The following options have been investigated:

Case 1 - the process of burning lignite when feeding the air-fuel mixture into the furnace from above, the composition of lignite: $A^P = 20\%$; $W^P = 30\%$; $V^P = 25\%$, removal of slag from the bottom of the furnace;

Case 2 - the process of burning lignite when feeding the air-fuel mixture into the furnace from below, the composition of the coal: $A^P = 20\%$; $W^P = 30\%$; $V^P = 25\%$, feeding into the furnace from below, removing slag from the bottom of the furnace;

Case 3 - the process of burning lignite when the fuel-air mixture is supplied to the furnace from below, the primary air consumption is increased to 84% ($\alpha_1 = 1.67$), the composition of the coal, removal of slag from the bottom of the furnace;

$A^P = 20\%$; $W^P = 30\%$; $V^P = 25\%$;

Case 4 - the process of burning lignite when the fuel-air mixture is supplied from below, the composition of coal: $A^P = 20\%$; $W^P = 30\%$; $V^P = 25\%$, removal of slag from the top of the furnace;

Case 5 - the process of burning lignite when supplying the air-fuel mixture from below, the composition of coal: $A^P = 35\%$; $W^P = 30\%$; $V^P = 30\%$, removal of slag from the top of the furnace.

Analysis of the calculation results given in Table 1

The aerodynamic structure of the furnace sphere is determined by the gas velocity (Fig.1). The absolute speed of the fuel - air mixture is 100-110 m/s at the furnace inlet. A higher gas velocity (up to 150-170 m/s) along the furnace section is observed near the furnace walls. An extended zone with a low gas velocity (up to 20-30 m/s) is formed on the furnace axis. At the outlet of the furnace, the gas velocity is about 200 m/s. As can be seen the aerodynamic structure is also determined by the trajectory of the movement of fuel particles. The mass of dispersed material (part of the fuel) rotates on average along the height of the furnace and moves to the outlet pipe.

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Table 1. Analysis of the calculation results

Parameter, Unit	Furnace variant number				
	1	2	3	4	5
D, mm	600	600	600	600	600
H, mm	3645	3645	3645	3645	3645
m_f, kg/s	0.184	0.184	0.184	0.184	0.2575
W, MW	2.55	2.55	2.55	2.55	2.5
m_{a1}, kg/s	1.26	1.26	1.325	1.325	1.325
t_{a1}, °C	377	377	377	377	377
m_{a2}, kg/s	0.315	0.315	0.25	0.25	0.25
t_{a2}, °C	377	377	377	377	377
$m_{a\Sigma}$, kg/s	1.575	1.575	1.575	1.575	1.575
q_{a1}, %	80	80	84	84	84
q_{a2}, %	20	20	16	16	16
α_1	1.58	1.58	1.67	1.67	1.66
α_Σ	2.0	2.0	2.0	2.0	1.97
$d_{p.min}$, μm	25	25	25	25	25
$d_{p.max}$, μm	250	250	250	250	250
$\bar{d}$, μm	57	57	57	57	57
$t_{g.out}$ °C	1888	1908	1919	1870	1966
$g_{O2.out.ave}$, %	3.4	3.2	3.2	3.8	1.1
The degree of volatile burnout, %	100	100	100	100	100
The degree of coke burnout from the removed particles, %	-	100	100	100	-
The degree of coke burnout of from the captured particles, %	93.9	100	92.5	83.8	34.4
The degree of coke burnout from soaring particles (accumulate inside the TZZP), %	-	100	100	100	100
Mechanical underburn of particles trapped, % (of combustible mass)	3.04	0	3.7	8.1	9.4
Mechanical underburn of soaring particles (accumulate inside the TZZP), % (of combustible mass)	-	0	0	0	0
Particle capture, %	100	0.4	0.8	99.4	99.6
Particle removal, %	0	19.6	19.2	0.4	0
Soaring (accumulation inside TZZP) of particles, %	0	80	80	0.2	0.4

*where: $\alpha_1 = m_{a1}/m_f * V_0$; $\alpha_\Sigma = m_{a\Sigma}/m_f * V_0$;

The concentration of the part varies along the height of the furnace, while increasing in the upper part due to the supply of a counter flow of secondary air. This limits the height of the furnace and allows you to reduce its volume.

The aerodynamic structure of the movement of particles in the furnace determines the regime of a swirling fluidized bed (SFB) (Sreenivasan, 2002)

In this case, the difference between the studied swirling and the SFB is the presence of an oncoming rotating flow, which provides a limitation of the height of the SFB, which is important when creating a CFB. This scheme is a modification of circulating fluidized bed schemes.

Comparing thermal schemes with the upper and lower fuel supply, it can be seen that the degree of coke burnout is 93.9% (option 1) and 92.5% (option 4), and the underburn of coke particles that are captured is 3.04% (option 1) and 8.1% (option 4). At the same time, particle ablation of 19.2% (option 4) and soaring of 80% of the mass of particles in the furnace volume are observed. When comparing with option 5, the values of the characteristics are the following: particle ablation – 0.4%, particle soaring – 0.2%, coke burnout rate - 83.8%, respectively. When particles are recycled in the furnace, the coke will burn out completely. The scheme difference (option 5) is the presence of a cold zone and the ability to realize solid slag removal during the high-temperature process of burning solid fuel.

The temperature distribution in the furnace volume is determined by the combustion process of solid particles and depends on the moisture and ash content of the fuel. Volatile fuels burn quickly in the lower zone of the furnace. The rate of ash formation is high and requires its removal, and the rate of moisture release is lower, which limits the combustion process. These processes determine the temperature distribution of the medium in the furnace volume. Fig. 1 shows that an isothermal temperature distribution is observed along the height of the furnace volume. In this case, the volumetric heat release is 2500 kW/m^3.

The trajectory of a part of the fuel affects the temperature distribution in the furnace volume. The high gas velocity at the periphery (near the walls) of the furnace creates conditions for the removal of particles to the wall and combustion occurs in the wall zone. Particles with a diameter of 25 mm move upward the furnace. The degree of burnout is 100%. Larger particles with a diameter of 250 mm are in the furnace for more than 2s, then they burn and are removed from the furnace. To completely burn them out, they can be returned in the circulation mode.

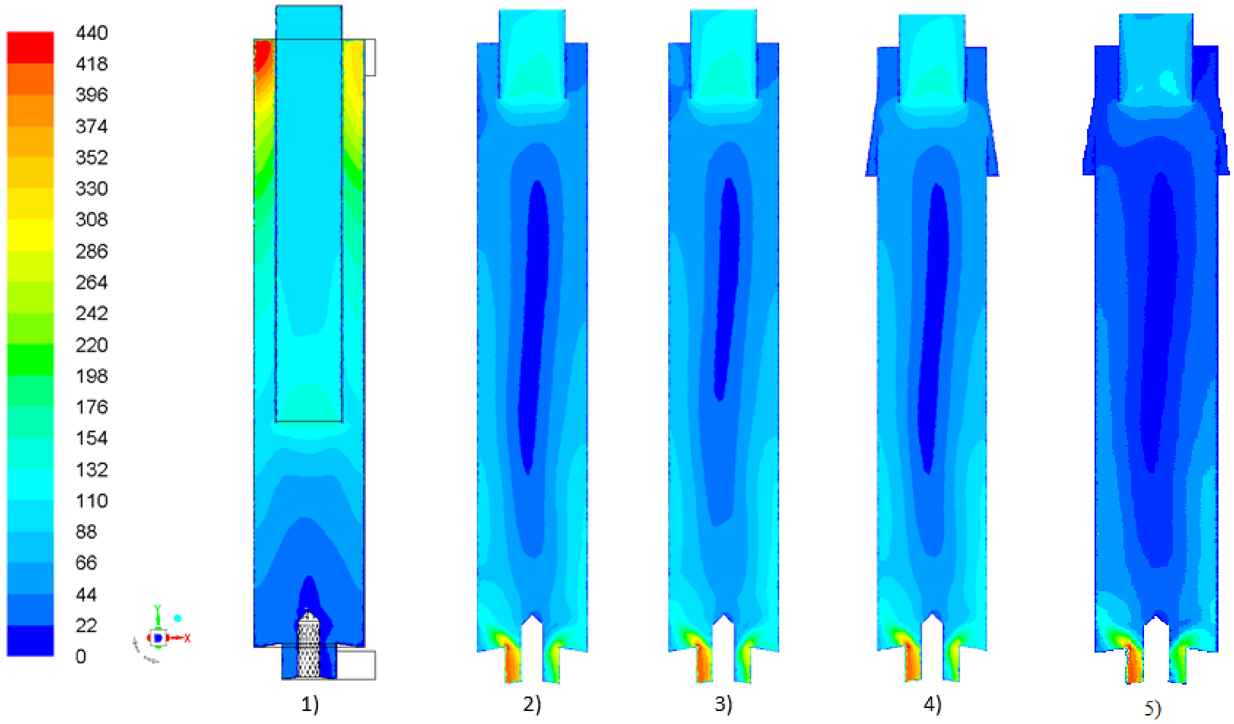

Fig. 2. Distribution of the absolute gas velocity (m/s) in the longitudinal section of the furnace

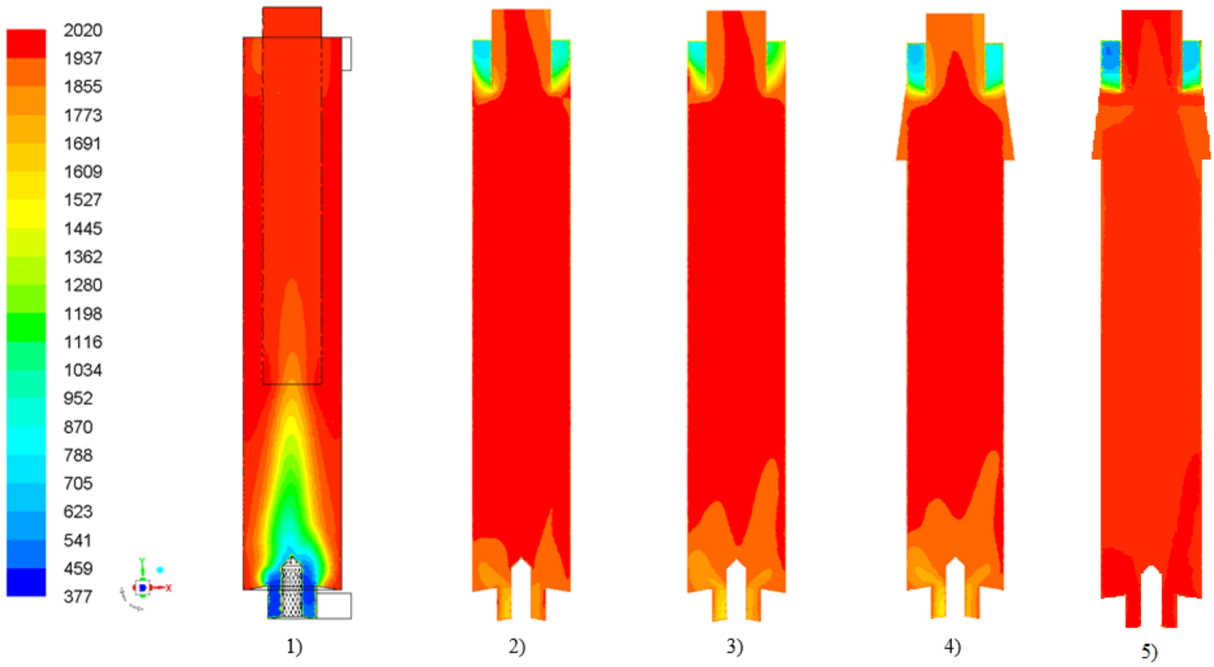

Fig. 3. Distribution of gas temperature (°C) in the longitudinal section of the furnace

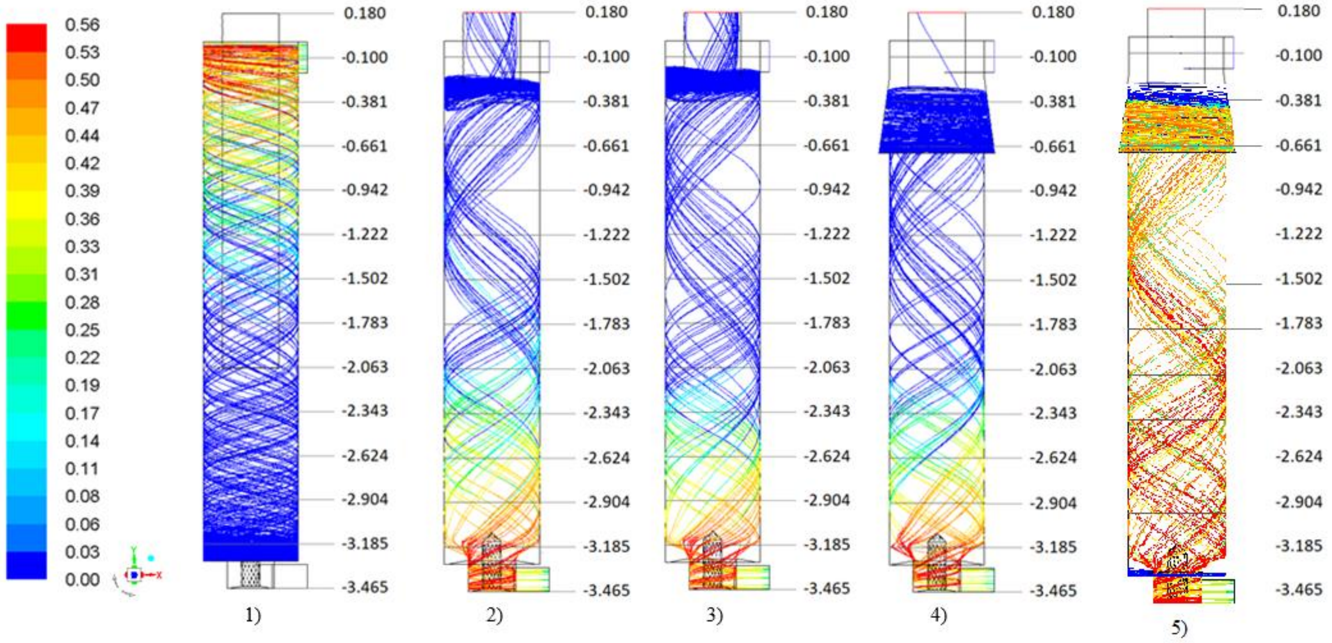

Fig. 4. Trajectories of lignite particles with an initial diameter of 25 μm, painted according to the mass fraction of coke in their composition; on the right - the height scale

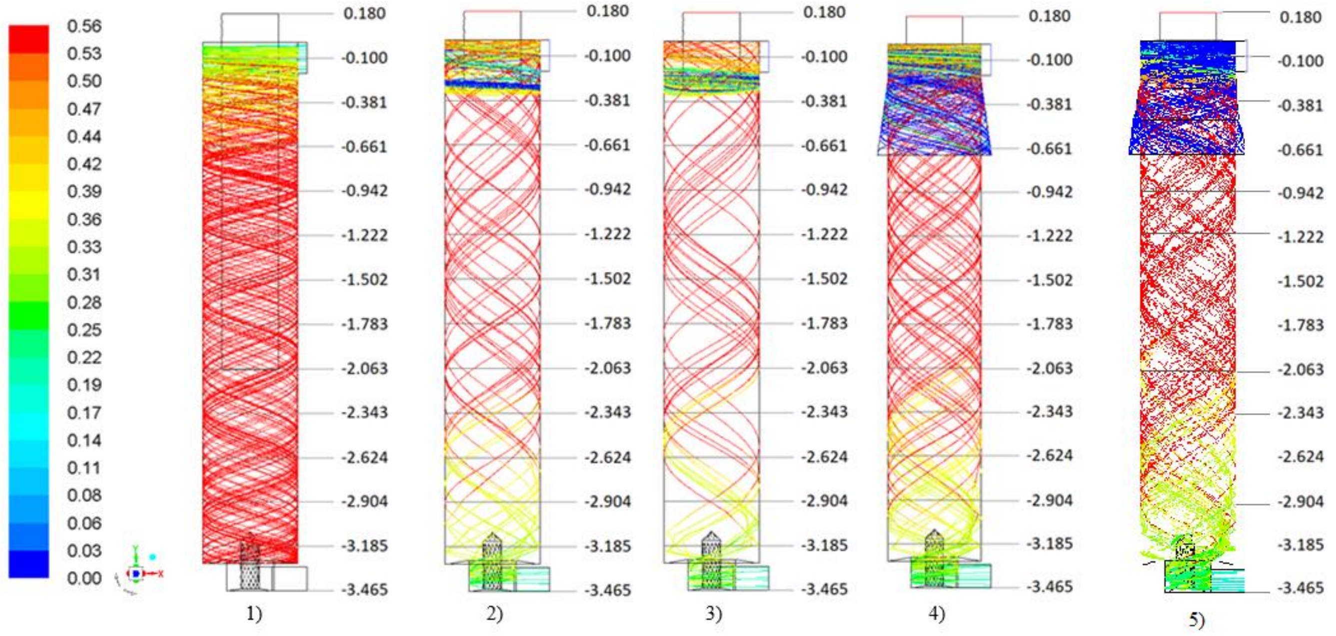

Fig. 5. Trajectories of lignite particles with an initial diameter of 250 μm, painted according to the mass fraction of coke in their composition

The main problem that arises in the process of burning coal at a lower fuel supply is the prolonged soaring of ash particles in the upper zone of the furnace, the increase in their concentration, the difficulty of removal and disruption of the combustion process. In option 5, this problem is solved by constructively changing the technological scheme and arranging an annular gap and a confuser in the upper part of the furnace 1 through which ash and unburned particles are removed and then returned to the afterburning furnace (Fig. 6). Unburned fuel particles are also collected in separator 2 and returned to the furnace by the feeder 3, which ensures the circulation of particles (Basu P. 2010, Blaszczyk A. 2017). The use of a vortex furnace with counter swirling flows in the scheme of a circulating fluidized bed makes it possible to reduce the dimensions of the furnace and the circulation ratio of solid fuel particles and thereby reduce the load on the separator.

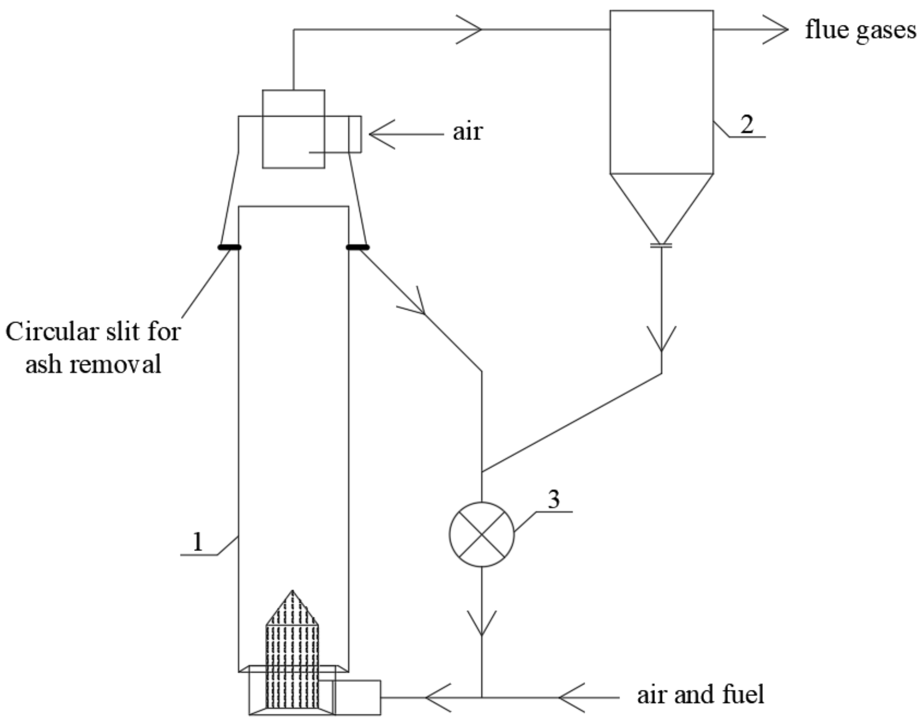

Fig. 6. Scheme of burning coal in a circulating SFB

5. Summary and conclusion

As a result of numerical study of the dried lignite powder particle combustion, the influence of the design factors of the furnace (diameter, height), the expenditure of primary and secondary air and their ratio, the fuel supply method (from the bottom of the furnace, from above one) is determined. The advantages of a top fuel supply have been found. The processes of lignite combustion in cooled and thermally insulated (lined) furnaces have been studied. It has been found that the combustion of lignite particles occurs at low temperatures (1300 - 1450°C). At the same time, conditions are provided for reducing the level of NOx emission. The results of a numerical study have proved that the diameter of lignite particles affects the process of their combustion: coke particles with an initial diameter of 25 μm to 250 μm burn out by 96%. When burning lignite of high ash content (up to 35%) according to the scheme, ash is captured and coke burns out completely, and coal particles are captured at furnace outlet (99.6%). Increasing a particle diameter up to 1000 μm, we decrease the degree of coke expulsion, but at the same time we decrease their removal. The thermal voltage of the furnace volume is 2500 kW/m3. In general, the results of the modeling indicate the efficiency of using the technology of low-calorie powdery solid fuel combustion in circumferential vortex furnace with counter swirl flow.

Nomenclature

D, mm is furnace diameter
H, mm is furnace height
m_f, kg/s is fuel consumption
W, MW is heating capacity
m_{a1}, kg/s is primary air flow
t_{a1}, °C is primary air temperature
m_{a2}, kg/s is secondary air flow
t_{a2}, °C is secondary air temperature
$m_{a\Sigma}$, kg/s is total mass air flow
q_{a1}, % is primary air concentration
q_{a2}, % is secondary air concentration
α_1 is excess air ratio
α_Σ is total excess air ratio
$d_{p.min}$, μm is minimum particle diameter
$d_{p.max}$, μm is maximum particle diameter
$\overline{d}$, μm is average particle diameter
$t_{g\ out}$, °C is gas temperature at the outlet of the furnace;
$g_{O2.out.ave}$, % is oxygen content at the outlet of the furnace.
Greek symbols
σ_s is volume scattering coefficient, [m^{-1}]
λ is coefficient of thermal conductivity, [$W \cdot K^{-1}$]
μ is coefficient of dynamic viscosity, [Pa·s]
ρ is density, [kgm^{-3}]

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旋流逆流涡流炉燃烧褐煤过程的数值模拟

關鍵詞
燃烧过程
数值模拟
褐煤
涡流炉
涡流逆流

摘要
这项工作介绍了在涡流逆流流动的涡流炉中燃烧褐煤的工作过程的数值研究结果。燃烧含水量为 30%、灰分含量为 20% 和 35% 以及较高热值 Qрв = 13.9 MJ/kg 和 9.7 MJ/kg 的褐煤过程的计算机模拟结果分别为给定的。确定了体积和炉子出口处的温度分布、气体速度和颗粒轨迹。靠近炉膛出口处的旋流速度值达到150-170m/s。机械欠燃为 3.7% 和 9.4%，具体取决于灰分含量。数值研究的结果表明，褐煤颗粒的直径会影响其燃烧过程：初始直径为 25 微米至 250 微米的焦炭颗粒燃烧 96%。该熔炉在 2500 kW/m^3 熔炉中的体积热应力下可完全燃烧 99.8% 的煤粉颗粒和 100% 的挥发物。含碳燃料颗粒的后燃通过它们的循环来确保