Numerical investigation of hydrodynamic processes in combustion chamber with an intensified fluidized bed

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Annotation. A gas suspension fluidized bed is reviewed, as an intensified fluidized bed, where the principles of classical spouted and fluidized beds are used together. A physical model of the process is presented. The working chamber consists of horizontally arranged sections, with spouted bed of gas suspension in the lower section and fluidized bed here in the upper section. Moreover, the lower section has a geometric shape in the form of a truncated regular pyramid. The basic formulas of mathematical modeling and the results of a numerical investigation of the hydrodynamics of a combustion chamber with an intensified fluidized bed are presented. The resulting mathematical model solved by the fourth-order Runge-Kutta method in the Matlab software environment. The graphs of changes in the velocity of gases and solid particles, pressure loss of a gas suspension depending on the height of the working chamber and the angle between the vertical axis and the side faces of the lower part of the section are obtained. Also obtained graphs characterizing the rise time of solid particles in height and their residence time in sections of the working chamber.

1. Introduction
The energy sector of Uzbekistan mainly uses high-ash grade B coal from Angren field. The heat of combustion of coal is 8000 - 9000 KJ / kg with an ash content of 45 - 50%. The mineral impurities accompanying the composition of coal are divided into: primary - components of 0.5% dry weight; secondary - accumulated in the underlying bed; tertiary - mineral impurities of surrounding rocks occurring during development of the bed. During flaring, associated minerals, for example, pyrites (FeS₂) wield major influence on wear rate, energy consumption of grinding units, the erosion and slagging of heating surfaces occurs. The use of fluidized bed (FB) technology to somewhat can increase the efficiency of high ash coal combustion. Efficient burning of solid fuel in fluidized bed furnaces is proposed based on an analysis of the influence of its parameters on the quality of pseudo fluidization and mixing of dispersed material [1]. The generalized experience of the practical development of low-temperature fluidized bed technology as applied to the combustion and gasification of oil shale, milled peat and various wood and high-ash floatation wastes is presented. Attention is paid to the inherent problems of this technology in the formation of agglomerates from fuel particles and its components and in the slagging of unscreened surfaces of the combustion chamber. The regularities of burning high-ash coals in various modifications of FB are also considered [2; 3; 4; 5; 6; 7].

Circulating fluidized bed (CFB) technology is a promising area and one of the widespread for the combustion of high-ash solid fuels. A lot of work has been devoted to the development and research of
this technology. In the works \[8; 9; 10\] presents the dependences of dimensionless liquefaction rates and their correspondence with experimental data of various authors and the relationship with critical pseudo fluidization rates and particle velocity. Here we describe transients using the provisions of the theory of automatic control and show the coincidence of the calculated parameters with the experimental data. Also studied the frequency of circulation in the furnaces with CFB.

A team of authors developed a method for calculating the circulation circuit in CFB technology system; new dependencies between the parameters of air and material flow rate, the resistance of the working chamber, cyclone, and the minimum liquefaction rate, as well as the boundary regimes of the onset of pressure and bed level, were obtained. Based on CFB hydrodynamics calculating method, the axial profile of particle concentration is determined along the height of the working chamber, taking into account the lifting and lowering movement of the particles. The concentration profile gives the relationship between the mass of the bed in the working chamber, gas and particle velocities \[11; 12; 13\] This methodology, including the specifics, can be applied in FB investigation in terms of feeding material into the working chamber.

The use of FB and CFB technologies for burning high-ash brown coal with associated minerals reduces their efficiency in terms of increasing the rate of wear of aggregates and heat transfer surfaces. In addition, mineral constituents exert downward pressure on hydrodynamic of processes. The presence of inert bodies is not always justified. In this regard, for the combustion of low-grade brown coal, a developed multi-sectional combustion chamber with an intensified fluidized bed (IFB) is proposed \[14; 15; 16\]. IFB technology operating principle based on the principles of classical spouted and fluidized beds. The process of burning solid fuel particles can be divided into the following stages: heating, drying, gasification, burning out of coke residue and cooling of ash. Hydrodynamic process intensification and control can improve the efficiency of all of the above processes.

The aim of this work is to carry out a theoretical study and obtain the results on hydrodynamics of IFB, used for further improvement of developed combustion chamber design. The object of the study is a multi-sectional working chamber, which serves for carrying out thermal and physical processes over mono- and polydisperse materials (heating, drying, gasification, burning, cooling, gas suspension separation and separation of solid particles by density and particle size distribution)

2. Physical model of the process

Physical model of processes and apparatuses improves the quality of research. In work \[17\], the possibilities of studying flows and heat transfer in various power plants using their own specialized programs are shown. We present the results of a study of processes in combustion chambers on experimental boiler models. These results can be used in the respective designs of combustion units.

![Figure 1. Physical model of the intensified fluidized bed process.](image-url)

This work (Figure 1) presents a physical model of the processes of hydrodynamics of IFB. The working chamber consists of successive sections. Each section conveniently divided into two parts: the upper one is a hollow box 1; the lower one is the truncated regular tetrahedral hollow pyramid 2. The
crushed polydisperse coal 3 enters the first section of the working chamber and mixes intensively with air. Inflate air 4 into the working chamber through the lower part 2 of the section. A spouted bed creates in the lower part 2 of each section, and a fluidized bed in the upper part 1. According to the principles of the fluidized bed, solid particles are transferred to the next section 5 through an open space located on the upper part on the connection lines between the sections. The number of sections can be large. Similar process also creates in subsequent sections. Relatively heavy particles removes by a special device located in the lower part of the first section of the working chamber, in the air inlet area. Particles of ash formed from the combustion of coal flows into the last section - into the ash collector 6. The exhaust air 7 removes from the working chamber. The parameter θ indicated in Figure 1 characterizes the angle between the vertical axis and the side faces of the truncated pyramid.

3. Mathematical model of the process

Physical and mathematical models are presented that describe processes close to real that occur in furnaces with the CFB. Study results regarding the effect of fineness grinding the particles of the initial fuel on the furnace processes is of scientific interest [18]. However, the use of existing mathematical models that describe work processes in furnaces with FB and CFB is not always suitable for other studies and researchers for all known reasons.

Based on IFB principles [14; 15; 19], we can write the equation of motion of a heterogeneous medium in the central longitudinal part of the furnace chamber section:

$$C_v \rho M (\vartheta V) = \rho M C_v g + \frac{3}{4} \xi \frac{\rho L}{d} \left| \vartheta - W \right| \left( \vartheta - W \right) - \nabla(C_v P)$$

(1)

where $\overline{W}$ and $\overline{\vartheta}$ are the solid phase and gas velocity, m/s; $\rho M$ and $\rho L$ - the density of coal and gas, kg/m$^3$; $C_v$ - volumetric concentration of the material in gas, m$^3$/m$^3$; $d$ is coal particle diameter, m; $\xi$ - is drag coefficient of coal particle; $P$ - gas pressure, kPa.

To solve this equation, the following assumptions are made: 1) the movement of coal and gas particles in the flow core is one-dimensional; 2) the drying and crushing of coal particles in the core of the upward flow are negligible; 3) the dependence of the resistance coefficient $\xi$ on the Reynolds number has the following form:

$$\xi = k_1 \left( 0.462 k_2 + 30 / \text{Re} \right),$$

(2)

where Re - is the Reynolds criterion; $k_1$ - coefficient inclusive material particles tightness; $k_2$ - coefficient inclusive geometric shape of particles $f$.

In view of the above, equation (1) takes the following form:

$$W_z \frac{dW_z}{dz} = g + \frac{3}{4} \frac{\rho L}{\rho M} f(\text{Re}) \left( \vartheta_z - W_z \right)^2 - \frac{1}{\rho M} \frac{dP}{dz}$$

(3)

where $z$ is vertical coordinate; $\vartheta_z$ and $W_z$ - projection of velocities $\vartheta$ and $W$ on the $z$-axis, m/s.

Gas radial velocity increases with increasing angle of deviation of radius from the vertical axis $z$, the angle. Then, the dependence $\vartheta_R = \vartheta_R(\theta)$ is approximated by quadratic law and takes the form

$$\vartheta_R(\theta) = B \theta^2$$

(4)

The proportionality coefficient $B$ is determined from the condition of material balance:

$$L = \int_0^\theta \vartheta_R(\theta)dS$$

(5)

The cross-sectional area of the cylinder S of radius R determined by the formula:
\[ S = 2 \pi R^2 (1 - \cos \theta) \]  
\[ \text{(6)} \]

We write the differential dependence:
\[ dS = 2 \pi R^2 \sin \theta \, d\theta \]  
\[ \text{(7)} \]

The radius \( R \) concluded between \( \theta \) and \( \theta + d\theta \) we can consider as a constant value. Substituting equation (4), equation (7) into equation (5) and integrating the resulting equation, we can find the value of the proportionality coefficient \( B \):
\[ B = \frac{L}{2 \pi R^2 [- \theta_0^2 \cos \theta_0 + 2 \theta_0 \sin \theta_0 + 2 \cos \theta_0 - 2]} \]  
\[ \text{(8)} \]

Then, the gas velocity component is determined by the following:
\[ \vartheta_k(\theta) = \frac{L \theta^2}{2 \pi R^2 [- \theta_0^2 \cos \theta_0 + 2 \theta_0 \sin \theta_0 + 2 \cos \theta_0 - 2]} \]  
\[ \text{(9)} \]

The spouted gas suspension has the form of a cylinder with a radius \( r_0 \) and a height \( h \) (accepted unambiguously as the height of the apparatus). The average gas velocity in the spouted flow we can calculate using the following equation:
\[ \vartheta_z = \frac{\int \vartheta_k(\theta) \, dS}{S(\theta')} \]  
\[ \text{(10)} \]

Substituting equation (6), equation (7), equation (9) into equation (10), we find the axial component of the gas flow velocity \( \vartheta_z \):
\[ \vartheta_k(\theta) = \frac{L (- \theta_0^2 \cos \theta_0 + 2 \theta_0 \sin \theta_0 + 2 \cos \theta_0 - 2)}{2 \pi R^2 (1 - \cos \theta_0)(- \theta_0^2 \cos \theta_0 + 2 \theta_0 \sin \theta_0 + 2 \cos \theta_0 - 2)} \]  
\[ \text{(11)} \]

The height of the combustion chamber is conventionally divided into \( n \) sections and in \( i \)-section (\( i = 1, n \)). In a fluidized bed, pressure loss we can write as follows:
\[ \frac{dP}{dz} = \frac{\Delta P}{\Delta h_i} = - \rho_m \, C_v \, g \]  
\[ \text{(12)} \]

where \( \Delta P \) - pressure drop in the flow core in \( i \)-section; \( \Delta h_i \) - height of \( i \)-section of the apparatus;

Then equation (3) takes the following form:
\[ \frac{dW_{z_i}}{dz} = (1 + C_v) \, g \, (W_{z_i})^{-1} + \frac{3}{4} \rho_m \, f_i \, (\text{Re}) \left( \vartheta_z - W_{z_i} \right)^2 \, (W_{z_i})^{-1} \]  
\[ \text{(13)} \]

The initial condition for equation (13) as follows:
The resulting mathematical model is solved by the fourth-order Runge-Kutta method. To implement this task, an algorithm has been compiled in the Matlab language. For the problem under review, the following notations are accepted: \( h_1 = z_0 \) — initial height of the combustion chamber; \( h_k = z_n \) — height of the working chamber; \( y_0 = W_{z0} \) — initial velocity of particle; \( m \) - number of parallel planes along the height of the working chamber.

To solve the problem on a computer, we will present equation (13) in the following form:

\[
\frac{dW_{z_k}}{dz} = f(z, W_{z_k})
\]  

(15)

where,

\[
f = (1 + C_V) \frac{g (W_{z_k})^{-1}}{4 \rho_m} \frac{\rho_f}{d} \left( \frac{\text{Re}}{W_{z_k}} \right) \frac{\partial_z}{(W_{z_k})^{-1}}
\]  

(16)

Corresponding dependences from mathematical model are introduced into the calculation program. Numerical calculations are made according to the following initial data: \( \rho_m = 800 \div 900 \) - coal density, kg / m³; \( \rho_g = 0.8 \div 0.9 \) - gas density, kg / m³; \( C_V = 0.04 \div 0.05 \) - volume concentration of the material in gas; \( d = 0.001 \div 0.008 \) - coal particles diameter, m; \( \gamma = 22.1 \times 10^6 \) - kinematic viscosity of gas, m² / s; \( \theta = (25^\circ \div 40^\circ) \) - the angle between the vertical axis and the side faces of the truncated pyramid; \( G_m = 100 \div 1000 \) - consumption of coal supplied to the working chamber, kg / h; \( r_0 = 0.10 \div 0.12 \) core radius the spouted bed, m; \( h = 1.0 \div 1.2 \) height of apparatus, m; \( h_1 = 0.1 \) - height of apparatus initial section, m; \( h_k = 1.2 \) - height of final section of the apparatus, m; \( W_{z0} = 3 \div 40 \) - initial velocity of the coal particle, m / s; \( m = 10 \div 50 \) - the number of conventional horizontal planes along the vertical axis of the working chamber.

4. Results and discussions

This work presents only some of the results of a numerical experiment, which from the authors’ point of view are more important. The air velocity at the entrance to the working chamber \( V_Z \) has a

Figure 2. Changes in air velocities \( V_Z \) and coal solid particles \( W_Z \) along the height \( h \) of the working chamber section for various values of the angle \( \theta \) and at \( W_{z0} = 12 \) m / s.

Curves obtained with:

- \( r_0 = 0.11; h_1 = 0.2; h_k = 1.2; W_{z0} = 12; L = 4000/3600; \rho_m = 900; \rho_g = 0.8; \)
- \( d = 0.001; G_m = 500/3600. \)
calculated maximum value and moving upward, into the expanding zone of the truncated pyramid, begins markedly decrease (Figure 2).

The spouted gas suspension bed gradually passes into a stable fluidized bed in the upper part 1 (Figure 1) of the working chamber, which is owing to IFB operating principles [4; 5: 6]. In this study, of special interest is the angle $\theta$ influence on the hydrodynamics of the process, since the set values of the parameter $\theta$ significantly affect the hydrodynamic situation in the sections of working chamber, for example, the height of spouting, hydraulic resistance of the bed, and gases and solid particles velocities.

The curves in Figure 2 obtained for various values of $\theta$. In this case, the extreme values of the angle $\theta$ are determined based on maintaining the stability of the spouted bed, passing into a fluidized bed. In Figure 2 we see, that with an increase $\theta$ from 25 to 40 degrees, the nature of the graphic lines does not change, only velocity value decreases due to an increase in the free space around the trunk of the spouted bed. Large values of gases and solid particles velocity appear when the angle $\theta$ has a smaller value.

Figure 3. Changes in air velocities $V_Z$ and coal solid particles $W_Z$ along the height $h$ of the working chamber section for various values of the angle $\theta$ and at $W_{Z0} = 4$ m / s.

Curves obtained with: $r_0 = 0.11; h_1 = 0.2; h_k = 1.2; W_{Z0} = 4; L = 4000/3600; \rho_m = 900; \rho_g = 0.8; d = 0.008; G_m = 500/3600.$

Figure 3 shows similar curves as in Figure 2, only with a three-fold decrease in the initial velocity of solid particles $W_{Z0} = 4$ m / s and a diameter of solid particles equal to $d = 0.008$ m. As can be seen from Figure 3, gas velocities are the same as in Figure 2, and velocity ratio $V_Z / W_Z$ are different. This is because the gas (air) flow rate in both cases has the same value equal to $G_m = 500/3600$, which gives identical gas flow rates. An eight-fold increase in particle diameter leads to a corresponding increase in particle weight and velocity decrease.

Figure 4 shows the curves obtained at different values of $W_{Z0}$ and at $\theta = 25^\circ$. The figure shows, the velocity of solid particles has a monotonously decreasing rectilinear character. This phenomenon predicts the presence of two factors affecting the process: the initial section explained by the expansion of the working chamber volume, as the gas suspension moves up; a further decrease explained by hydraulic resistance increase, as the gas suspension layer thickens. Here, the change in the value of the $V_Z / W_Z$ ratio has the same character as in the previous graphs.

When studying the hydrodynamics of a suspended layer, it is important to know its hydraulic resistance. Depending on this parameter, we determine the stability range of the hydrodynamic regime, in this particular case, the fluidized bed. Changes in air pressure $P$ along the height $h$ of the working chamber section at different values of $W_{Z0}$ are shown in Figure 5. As the layer thickness increases, the
pressure loss of the gas suspension layer increases, and large values of pressure loss are observed for relatively small values of $W_0$. This is due to the fact that with a decrease in the velocities of gas and solid particles, the density of the gas suspension and hydraulic resistance increases accordingly.

It was interesting to determine the time when the solid particles reached the upper level of the working chamber, since, depending on this, the rational value of the height of the wall located between the sections of the working chamber is determined. The sought value $\tau_1$ depends on several parameters i.e., on the diameter of solid particles, on the flow rate and velocity of the gas phase. Figure 6 shows the graphical dependences of time change for reaching the upper level of the working chamber with solid particles $\tau_1$ with a diameter $d = 0.005$ m, depending on their initial velocity. As it shown in the figure, a decrease in the initial velocity of solid particles leads to an increase in the time to reach the upper level of the working chamber.

Determination of solid particles residence time in working chamber will allow more efficiently carry out the planned thermal processes. However, due to heat exposure, the diameter and mass of the solid particles can change during the process. Usually, conditions are created so that the residence time of solid particles coincides with the time of thermal exposure. Figure 7 shows a characteristic curve.
describing the residence time of solid particles depending on their axial velocity $W_z$. In the figure, we can see that an increase in $W_z$ velocity led to a rapid decrease in $\tau_2$ value. It means that particles solids are approaching the exit of studied section into the subsequent section of the working chamber. In the same place, Figure 7 describes the characteristic equation for the curve under consideration.

![Figure 6. Pullout time for solid particles along the height of the working chamber. Curves obtained with: $r_0 = 0.11; h_1 = 0.2; h_k = 1.2; y_0 = 4; L = 4000/3600; \rho_m = 900; \rho_g = 0.8; d = 0.005; G_m = 300/3600.$](image)

![Figure 7. The residence time of solid particles depending on their axial velocity $W_z$. The curve describes by the equation: $\tau_2 = 1/(0.028562 W_z + 0.064945)$](image)

5. Conclusion
Presented physical model of the process was developed based on preliminary physical experiments results. Creating a scientific experimental test-bed and physical experiments with the complex processes described above are associated with certain difficulties. Using the method of numerical investigation, we were able to determine the influence of the angle $\theta$ on other process parameters. The main task was to determine parameter value range of the process, ensuring the stability of intensified fluidized bed. It is therefore possible to characterize the features of numerical study results:

1. The influence of the angle $\theta$ on other process parameters, such as gases and solid particles velocities, hydraulic resistance of the gas suspension layer, and solid particles residence time in the...
sections of working chamber is determined. The rational values of the angle $\theta$ are determined and are in the range of 25–40 degrees.

2. The velocity of solid particles is significantly lost at the beginning of spouted bed action. This is due to the friction of particles among themselves in the lower part of the working chamber, where particles concentration is relatively higher. Change of $W_{20}$ value directly proportionally affects the general nature of particles current curves along the height of the working chamber.

3. To reduce the effect of hydraulic resistance on gas suspension sweep, it is necessary to increase the angle $\theta$ and reduce the height of the working chamber. In this case, it is possible to increase the number of sections of the working chamber.

4. By changing the gas velocity and angle $\theta$, conditions are created for controlling the residence time of solid particles in sections of the working chamber. Here it will be possible to set the diameter of the solid particles, to control their movement along the height of the working chamber. Residence timing control of solid particles in working chamber sections allows for better performance of thermal and physical processes, such as drying, gasification, burning, cooling and separation of solid particles of the processed mono- and polydisperse material.

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7. References

[1] Kovenskii V I Conditions for efficient combustion of solid fuel in fluidized-bed furnaces // Thermal Engineering. 2012. V. 59. N 8. P. 604-09. eLIBRARY ID: 17679855. https://elibrary.ru/item.asp?id=17845563

[2] Shemyakin V N and Karapetov A E Experience gained from mastering practical use of the fluidized bed technology in boilers for industrial and municipal power systems // Thermal Engineering. 2012. V. 59. N 6. P. 433-38. https://elibrary.ru/item.asp?id=17679855

[3] Ryabov G A and Litun D S Agglomeration during Fluidized Bed Combustion and Gasification of Fuels // Thermal Engineering. 2019. Vol. 66. N 9. P. 635-51. DOI: 10.1134/S0040363619090042. https://elibrary.ru/item.asp?id=39180234

[4] Belyaev A A Autothermal gasification of low-grade fuels in fluidized bed // Thermal Engineering. 2009. V. 56. N 1. P. 9-14. eLIBRARY ID: 11690730. https://elibrary.ru/item.asp?id=11690730

[5] Litun D S and Ryabov G A Three-zonal engineering method of heat calculation for fluidized bed furnaces based on data on commercial investigations of heat generation distribution during biomass combustion // Thermal Engineering. 2016. Vol. 63. N 2. P. 140-49. DOI: 10.1134/S0040363616020053. https://elibrary.ru/item.asp?id=25069612

[6] Ryabov G A, Folomeyev O M, Sankin D A and Khaneyev K V Cold flow model study on interconnected fluidized bed reactors for multigeneration systems and chemical looping processes // Proc. of the 10th Intern. Conf. on Circulating Fluidized Bed Technology. CFB-10. Sunriver, Oregon, USA, May 1-5, 2011. https://dc.engconfintl.org/cgi/viewcontent.cgi?article=1013&context=cfb10

[7] Korchevoy Yu P, Maistrenko A Yu and Topal A I Patterns of burning high-as coal in different modifications of the fluidized bed // Combustion and Plasma Chemistry. - 2006. T.4. N 3. - P.180-86.

[8] Tuponogov V G and Baskakov A P The influence of the gas-distributing grid diameter on the transition velocity and hydrodynamics of the bottom layer in circulating fluidized bed installations // Thermal Engineering. 2013. V. 60. N 11. P. 808-12. DOI: 10.1134/S004036361311012X. https://elibrary.ru/item.asp?id=20329155

[9] Baskakov A P, Munts V A and Pavlyuk E Yu Transients in a boiler with a circulating fluidized bed // Thermal Engineering. 2013. N 11. P. 4-9. DOI: 10.1134/S0040363613110039. https://elibrary.ru/item.asp?id=20329150
[10] Munts V A, Baskakov A P, Fedorenko Yu N and Kozlova Yu G The multiplicity of circulation in furnaces with a circulating fluidized bed // Thermal Engineering. 1990. N 4. P.30-34.

[11] Ryabov G A, Folomeev O M, Sankin D A and Mel'nikov D A Results of theoretical and experimental studies of hydrodynamics of circulation loops in circulating fluidized bed reactors and systems with interconnected reactors // Thermal Engineering. 2015. V. 62. N 2. P. 110-16. DOI: 10.1134 / S0040363615020083. https://elibrary.ru/item.asp?id=22840981

[12] Ryabov G A, Folomeev O M, Sankin D A and Mel'nikov D A Studies of boundary modes of solid material flow in circulation contours of power installations // Thermal Engineering. 2014. V. 61. N 11. P. 804-13. DOI: 10.1134 / S004036361411006X. https://elibrary.ru/item.asp?id=22020170

[13] Ryabov G A, Folomeev O M and Shaposhnik D A A study of systems for collecting and returning ash at installations with a circulating fluidized bed // Thermal Engineering. 2002. V. 49. N 8. P. 631-637. eLIBRARY ID: 28129610. https://elibrary.ru/item.asp?id=28129610

[14] Babakhodjaev R P Burning of Angren brown low-grade coal in an intensified fluidized bed // Burning Solid Fuel. Sat reports YI All-Russian conferences. Part 2. 2006. Novosibirsk. P.20-27.

[15] Babahodzhaev R Intensified fluidized bed burning of Angren brown coal containing an increased amount of ash // N. Syred and A. Khalatov (eds.), Advanced Combustion and Aerothermal Technologies. 2007. Springer. DOI https://doi.org/10.1007/978-1-4020-6515-6_6. https://link.springer.com/chapter/10.1007/978-1-4020-6515-6_6

[16] Babakhodjaev R P, Mirzaev D A, Eshkuvatov L M and Karimov A A An experimental study of the hydrodynamic processes of the intensified fluidized bed with model materials // IY All-Russian Scientific and Practical Conference Energy and energy saving: theory and practice. 2018. (TU Kuzbass). P.1091-95. http://science.kuzstu.ru/wp-content/Events/Conference/energ/2018/energ/pages/Articles/109.pdf

[17] Alekseenko S V, Burdukov A P, Dekterev A A, Markovich D M and Shtork S I Physical and mathematical simulation of aerodynamics and combustion in the furnace chambers of power installations // Thermal Engineering. 2011. V. 58. N 9. P. 779-85. eLIBRARY ID: 17057229. https://elibrary.ru/item.asp?id=17057229

[18] Dvoinishnikov V A and Larkin A V Mathematical simulation of working processes in the furnace of a circulating fluidized bed boiler // Thermal Engineering. 2009. Vol. 56. N 1. P. 41-45. eLIBRARY ID: 11690735. https://elibrary.ru/item.asp?id=11690735

[19] Babakhodjaev R P, Mukhidinov D N, Karimov A A, Shakirov A O, Khodjaev B A, Yusupov B V, Pulatova D M and Khujanov R A Installation for burning solid fuels or heat treatment of polydisperse materials. N IAP 04840. Patent for an invention. Intellectual Property Agency of the Republic of Uzbekistan. Official Bulletin. 2014. N 3. P.49. http://baza.ima.uz/upload/Bulletin/2014/03%20(155)%2031-03-2014/bul3-2014.pdf