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Створена комп'ютерна модель, яка дає можливість досліджувати роботу печі для обробки матеріалу заданого фракційного складу.

Досліджено роботу апарату з різними граничними умовами. Визначено траєкторію частинок в робочій зоні і час їхнього перебування в апараті, а також гідродинамічну структуру потоку. Отримані результати можуть бути використані для моделювання ефективності реакційних процесів, оптимізації конструкції печі та режимів її роботи

Ключові слова: чисельне моделювання, циклонна піч-декарбонізатор, розподіл частинок, потік газ-частинки, час перебування частинок

Создана компьютерная модель, которая дает возможность исследовать работу печи для обработки материала заданного фракционного состава.

Исследована работа аппарата с различными граничными условиями. Определена траектория частиц в рабочей зоне и время их пребывания в аппарате, а также гидродинамическая структура потока. Полученные результаты могут быть использованы для моделирования эффективности реакционных процессов, оптимизации конструкции печи и режимов ее работы

Ключевые слова: численное моделирование, циклоническая печь-декарбонизатор, распределение частиц, поток газ-частицы, время пребывания частиц

УДК 66.041: 666.90
DOI: 10.15587/1729-4061.2015.44168

DEVELOPMENT OF A NUMERICAL MODEL FOR GAS-SOLID FLOW IN THE INDUSTRIAL CYCLONE-CALCINER FURNACE

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1. Introduction

At this time one of the most promising directions of lime production is modernizing production using cyclone furnace for annealing finely dispersed limestone. This technology can significantly increase the production of a product, improve quality, reduce emissions of flue gases into the environment [1, 2].

The cyclone-calciner furnace is popular as a gas-solids contactor because it can handle large quantities of particles and gas on a continuous basis. In addition, it has no moving parts, requires limited amount of energy for its operation and exhibits good mass- and heat transfer characteristics.

The main physics-chemical processes taking place in the calciner furnace are combustion and the strongly endothermic calcination reaction of the raw materials and movement of solid phase.

At this time, there are many designs cyclone furnaces with a different way of the gas-solids enter. The authors propose a tangential supply of hot flow and central supply particles at the top of the device [3, 4]. Other authors propose input streams at the bottom of the device [5, 6]. All these constructions of furnaces have their advantages and disadvantages and can be used for calcination processes.

The effectiveness of such devices is highly dependent on the aerodynamics of the solid and gas phases motion in the device working area. Therefore, understanding the mechanisms of flow and transport phenomena in the calciner-furnace is very important for efficient lime production.

Using of experimental methods to investigate this phenomena is complex and expensive, thus the use of numerical techniques is more attractive way to obtain the necessary information about the flow and transport processes inside the cyclone furnace calciner. Moreover, CFD can be used to simulate and optimize mixing gas-solids processes, the phases distribution [7], for the prediction of the velocity, temperature and concentration fields of gases and of particle trajectories in calciner [8, 9]. In addition, heat transfer and chemistry in calciner can be modeled using CFD [10].

Thus, the results of modelling flow, the influence of solid particles and hydrodynamic flow in the industrial cyclone-calciner furnace will be presented in this paper.

2. Analysis of published data and problem statement

The choice of optimal work regimes of cyclone-calciner furnace is very important to maximize the work efficiency this device and the fuel consumption. This primarily concerns the definition of air mass flow rate for the gas combustion, distribution and transporting solid phase in the working area of the furnace [11].

It is very important that the particles are well distributed in work zone of cyclone-calciner furnace for better efficiency of the lime production. In addition, the residence time of the material particles should be sufficient for calcination and depends on gas flow too [12, 13].

In chemical engineering, the concept of particles residence time distribution is fundamental to furnace design. Currently, the main way to study aerodynamics furnace is experimental research using tracer elements or colored streams.

There are different theoretical and empirical equations to calculate the residence time of the particles needed for calcination. These equations show that the calcination time depends on a diameter of the particles, a temperature of the flow and a chemical composition of raw materials. According to these equations, the calcination time of the particles in the furnace and geometry of the calciner working area can be calculated [14, 15]. This approach to the definition of aerodynamics in the work zone of apparatus is not accurate and can't detect design flaws such as bypass and dead zones in furnace. Also, it should be noted that most of these equations are limited to the application and can not be used for a wide range of device designs.

Because of CFD is capable for predicting the complete velocity and particles distribution in a vessel, it provides an alternative, indeed, simpler means of determining the residence time distribution and aerodynamics of furnace.

The lack of a reliable method of the particles distribution calculation in devices of this type and the impact of operating and design parameters on the efficiency of the furnace needs the research in this area.

3. Purpose and objectives of the study

This study aim is to investigate the particles distribution in the industrial cyclone calciner-furnace. The main challenge of this project was to build a reliable CFD model based on the industrial calciner and a selection of boundary conditions according to industrial data, as well as the calculation of the optimal distribution of the air supply to the burner and additional flow. This additional flow should be sufficient to eliminate the particles falling in the region of the burner and to vortex generation by repeatedly circulating the gas-solids flow.

In accordance with the set goal the following research objectives are identified:

1. Creating a geometric model of the internal cavity of the furnace.
2. Building a mesh model of the furnace and discretization of the computational domain with the two versions of the boundary conditions.
3. Setting of gas-solids flow physical models and performing series of simulations.
4. Analysis of the particles distribution in the furnace and determining the optimal operating conditions of the furnace.

4. Materials and methods of gas-solid flow CFD-modelling in the cyclone-calciner furnace

4. 1. Cyclone-calciner furnace geometry

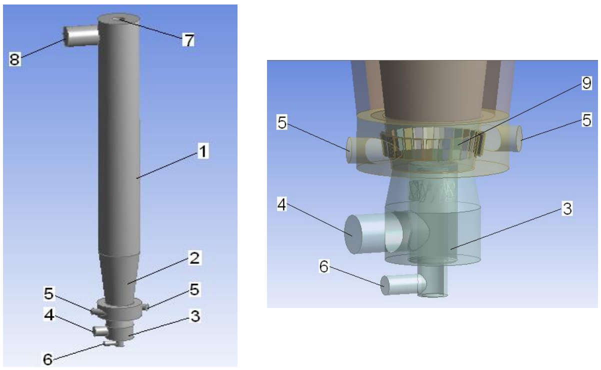
The modeled cyclone-calciner furnace is shown in Fig. 1, *a, b*. The calcinations processes take place in the work zone 1 of the furnace, consisting of a 0.8 m diameter cylinder with 4,4 m height and the combustion processes take place in a conical section 2.

The air is introduced into the calciner in two places. The primary air flow enters the burner 3 through the pipe 4 and additional flows enters the conical part of the calciner-furnace via two pipes 5 tangentially. The additional flows are inlet in the conical part of the calciner through the blades 9 where the air creats a swirling of the flow.

The fuel (methan) enters the burner through the inlet tube 6 which has a circular shape. Natural gas and air run into a burning chamber and mix up. In the burner burn fuel and gases are derived through a conical section 2 and cylindrical section 1. In this type of furnace, the burner "ГГВ-МГП-200" is used.

The $CaCO_3$ particles is introduced to the conical section of the work zone through the tube 7 in central part of the calciner-furnace. The products such as calcined CaO solids,

CO_2, and other gases go out through the outlet tube 8 with a diameter of 0.485 m. The total furnace volume is 3,4 m^3.



a *b*

Fig. 1. Cyclone-calciner furnace geometry: *a* — general view of furnace; *b* — burner location

The properties of the $CaCO_3$ particles used in the experiments are described in the next section. All the geometric data and the initial and boundary conditions were supplied by "Pustomyty lime plant", Ukraine.

4. 2. Model description and boundary conditions

ANSYS Fluent version 15 was used in this study to perform the simulation of the flow gases and particles $CaCO_3$ distribution in the industrial cyclone-calciner furnace.

Firstly, based on the drawings of the industrial furnace, geometric model of the internal flows of the apparatus was built. Then by means of the mesh generator a computational mesh was created for this model. The resulting mesh contains 157985 Nodes and 847224 Elements. All geometric transformations were done in a software module Design Modeler, and the mesh was created in ANSYS Meshing.

At the core of the CFD furnace model, there are the basic equations of hydrodynamics, namely the continuity equation (1), it expresses the law conservation of mass in the elementary volume, and the equation of momentum conservation (2). These equations represent the basic model of the medium flow [16].

$$\frac{\partial p}{\partial t}+\nabla(\rho\vec{v})=S_m, \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla(\rho\vec{v}\vec{v})=-\nabla p+\nabla(\vec{\tau})+\rho\vec{g}+\vec{F}, \qquad (2)$$

where ρ – density, ν – velocity, S_m – is the mass added to the continuous phase from the dispersed second phase, τ – stress tensor, p – static pressure, F – external body force, ρg – the gravitational body force.

To simulate the turbulence flow the "Realizable" k-ε model of turbulence was used. The realizable k-ε model contains a new formulation for the turbulent viscosity and a new transport equation for the dissipation rate, ε, that is derived from an exact equation for the transport of the mean-square vorticity fluctuation. [17]. An immediate benefit of the "Realizable" k-ε model is that it provides improved predictions for flows involving rotation, separation, and recirculation.

To simulate the particles distribution in cyclone-calciner furnace Discrete Phase Model was used. This model neglects the particle-particle interactions and the volume occupied by particulate phase. For each particle, the trajectory is calculated based on the forces balance equation acting on the particle [18].

$$\frac{du_p}{dt}=F_D(\vec{u}-\vec{u}_p)+\frac{\vec{g}(\rho_p-\rho)}{\rho_p}+\vec{F}, \qquad (3)$$

where u_p – velocity of particles, ν – velocity of fluid, F – additional external forces, ρ– density fluid, ρ_p – density of particles .

$$F_D=\frac{18\mu}{\rho_p d_p^2}\cdot\frac{C_D Re}{24}, \qquad (4)$$

where μ – molecular viscosity, d_p – diameter of particles, C_D – coefficient of resistance. Re is the relative Reynolds number which is defined as

$$Re=\frac{\rho d_p}{\mu}(u_p-u).ы \qquad (5)$$

The drag coeficient, C_D, can be taken from

$$C_D=a_1+\frac{a_2}{Re}+\frac{a_3}{Re^2}, \qquad (6)$$

where a_1, a_2, and a_3 are constants that apply for smooth spherical particles over several ranges of Re.

Size of the particles is a very important parameter when simulating multiphase systems. In this study, it is assumed that all the particles are spherical. According to the experimental data (Table 1) solids is composed of six different sizes of grains.

Table 1

The particle size data

Diametr range (μm)	Mass fraction in range
0–10	0.5
10–20	0.25
20–40	0.35
40–63	0.25
63–100	0.07
100–140	0.03

So, it is possible to use describe the particles distribution in Rosin-Rammler type. Parameters describing the Rosin-Rammler distribution of the $CaCO_3$ particles are listed in Table 2.

Table 2

The particle size data in terms of the Rosin-Rammler format

Diametr, d (μm)	Y_d	n
10	0.95	2,18
20	0.7	1,54
40	0.35	1,92
63	0.1	1,73
100	0.03	1,33
140	(0.00)	

Where, Y_d – the mass fraction of the particles of diameter greater than d; n – the size distribution parameter, which is constant.

The numerical value for n is given by:

$$n = \frac{\ln(-\ln Y_d)}{\ln(d/\bar{d})}, \qquad (7)$$

where $\bar{d}$ – is the mean diameter of the probe of solids measured; d – is the size constant;

The following parameters were defined for modeling: min. diameter 0.01 mm; max. diamter 0.14 mm; mean diameter 0.039 mm; spread parameter 1.74; No. of diameters 5. Rosin-Rammler curve fit is presented in Fig. 2.

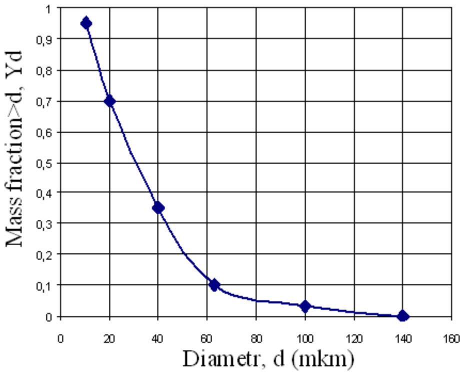


Fig. 2. Rosin-Rammler curve of the particles distribution

The simulations were run on the steady-state mode. Second Order Upwind discretization scheme was used to solve the governing equations with the pressure-based solver. The "Realizable " k–ε turbulence model was applied with the default settings.

The boundary conditions set in FLUENT are the same like those for the industrial work of the cyclone-calciner furnace. Productivity of furnace is 3000 kg/h and volumetric gas (methane) flow rate is 240 m^3/h. Main air flow inlet velocity changed from 17 to 22 m/s for all cases and additional air flow inlet velocity changed from 1 to 5 m/s for case 2.

The particle interaction with the walls of the furnace was controlled using the "reflect" boundary condition on all exterior faces.

It was assumed that the air and the particles $CaCO_3$ enter the cyclone-calciner with a uniform velocity profile and the wall of the calciner has a constant temperature of 300 K. Methane flow was modelled as air flow. The turbulent intensity at both inlets is 5 %. Approximately 2000 iterations were made for each simulation.

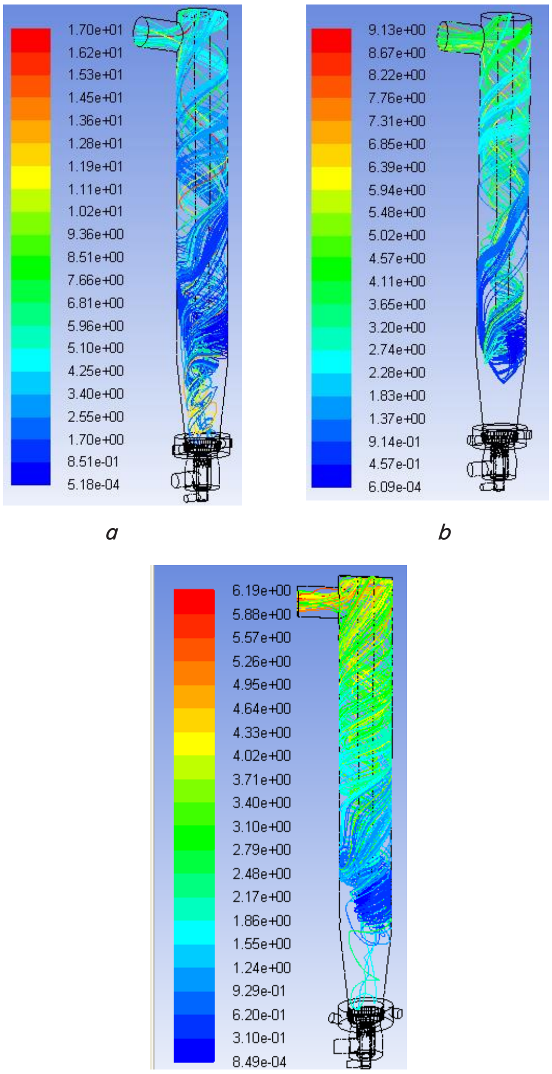
5. Results of gas-solid flow CFD-modelling in the cyclone-calciner furnace

5. 1. Particles distribution through the furnace

This chapter contains the description of a gas and particles flow in the calciner based on the simulations carried out in ANSYS FLUENT 15. Two cases (1 and 2) with different ratio of main and additional air flow and gas flow were analyzed.

First of all, it was tried to verify the effect of solid phase loading on the gas burner of the furnace. Moreover, it is interesting to see the solid phase distribution in the whole system with different operating conditions.

Initially, modelling was performed according to the operating data of the plant without additional air flow – case 1. Fig. 2, *a–c* represents the particles trajectories in the furnace when main air flow inlet velocity changed from 17 to 22 m/s. This air velocity is suitable for the most efficient combustion in the burner. Rational excess ratio by volume fuel-air for this type of burner is 1:11–12 and theoretical excess ratio by volume is 1: 9,7.



a *b*

c

Fig. 3. Particles distribution through the furnace (Case 1): *a* — main air flow inlet velocity = 17m/s; *b* — main air flow inlet velocity=20 m/s; *c* — main air flow inlet velocity=22 m/s

As it can be seen, when the time passes the particles start to circulate between the central pipe and the wall of furnace. Fig. 3 shows that there is higher concentration of the solid particles in the conical part of the furnace and above the burner. A certain amount of particles falls outside the burner. This is rather undesirable phenomena and has negative affect on the operation of the calciner furnace. These phenomena are observed even at the maximum velocity of the main air flow (Fig. 3, *c*).

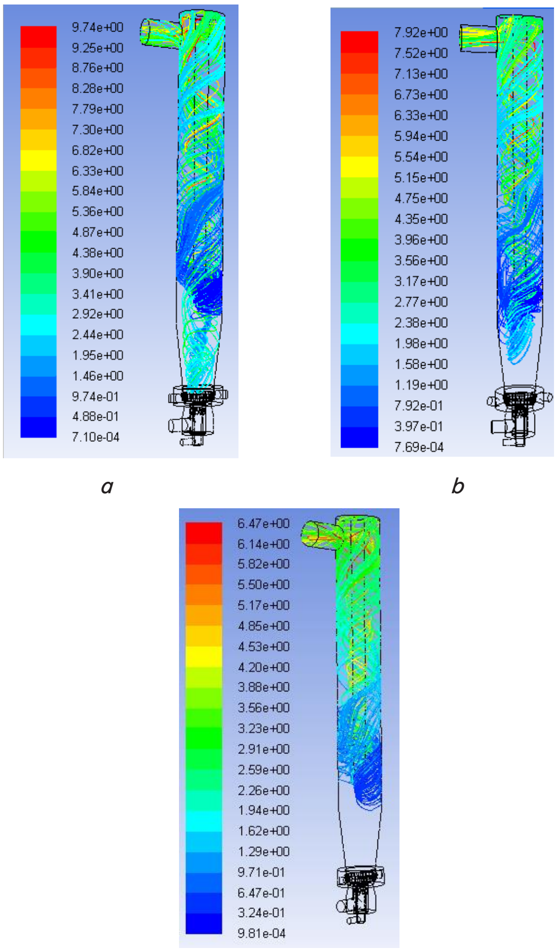
To reduce the load on the burner, it is necessary to increase the flow rate. Increasing the flow rate to the system results in lower residence time of the particles needed for calcination. Therefore, increasing the consumption of main air flow is impractical.

An additional method to improve the quality of particle distribution in the furnace was to change the operating condition and using additional air flow (case 2). This idea helps to improve the particles distribution in the furnace and to reduce the negative impact on the burner.

In this configuration of furnace geometry the particles must be forced up into the work zone with additional air flow instead of letting into the burner. But this method creates some complications in selecting an initial velocity for the additional air.

For that reason, the simulations provide two functions: determining an initial velocity for additional air flow and determining the effect this method has on the particle distribution.

To check the influence of the additional air in the furnace on the particles distribution, different initial velocities were used for the additional air flow according to the Table 2. Fig. 4, *a–c* shows the trajectory of particles with different ratios of the additional air/main air flow "f" for which the normal operation of the furnace is observed.



a *b*

c

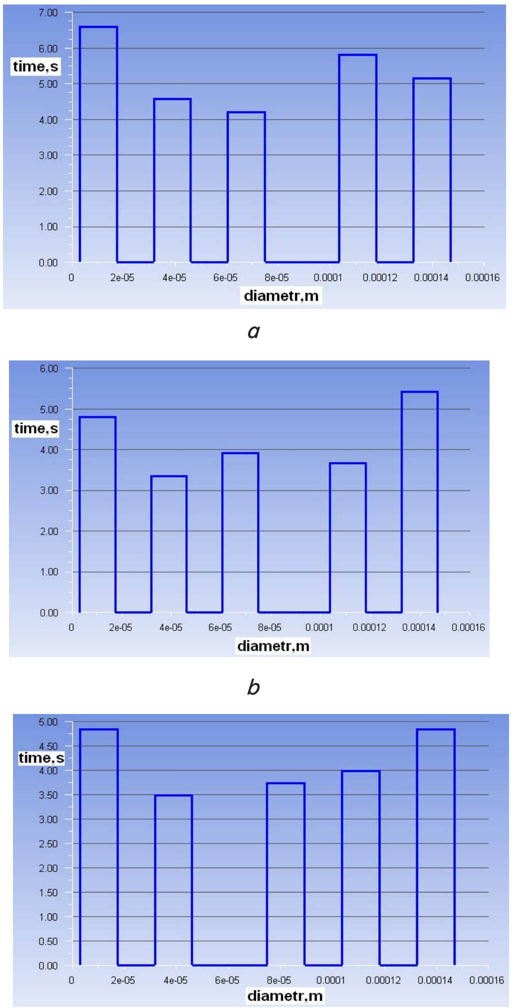
Fig. 4. Particles distribution through the furnace (Case 2): *a* — f=0,26; *b* — f=0,22; *c* — f=0,12

In comparison with the case 1 without additional air flow, the distribution, using an additional air flow, provides a significantly more normal distribution of the particles for all cases. The region of high concentration rises spirally in the same way as the flow pattern and the particles are not spread within the calciner in the lower parts – above the burner. In addition, the particles are not outside the boundaries of the burner.

5. 2. Particle residence time in the furnace

As mentioned before, particle residence time in the furnace should be sufficient for the calcination process. These parameters very strongly depend on the geometry and gas flows of the furnace and can be determined based on numerical modelling.

The residence time for both cases analyzed in this study is presented in form of histograms. The results presented in Fig. 5 and Fig. 6 comply with the conditions of the furnace work which are presented in Fig. 3, 4



a

b

c

Fig. 5. Particles residence time for case 1: *a* — main air flow inlet velocity =17 m/s; *b* — main air flow inlet velocity=20 m/s; *c* — main air flow inlet velocity=22 m/s

For both cases, the residence time is similar and for most of the particles is around 3–5 (s). However, in the case 1a there is a small amount of particles with the residence time slightly longer than 5 (s). The reason is low speed main airflow for this case and probably the low-velocity region is created in the work zone of furnace. There are few particles in this zone and thus, the residence time is up to 7 (s). This supports the results of the simulation flow rate presented below.

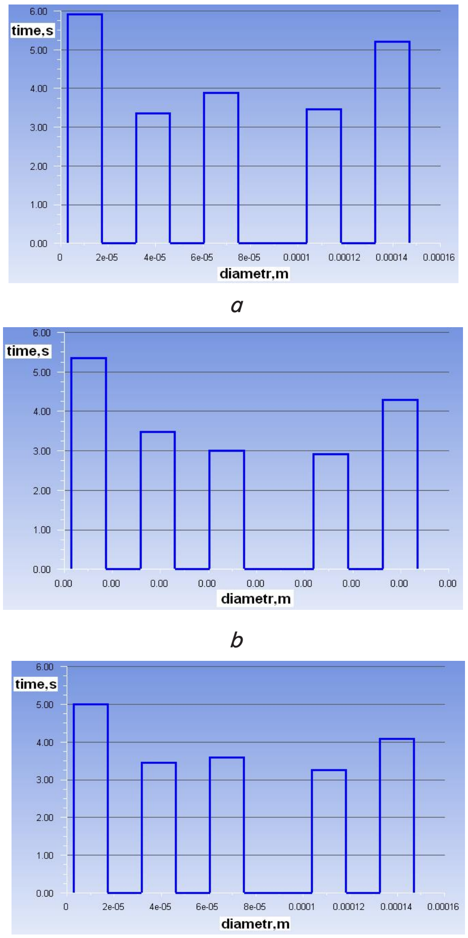
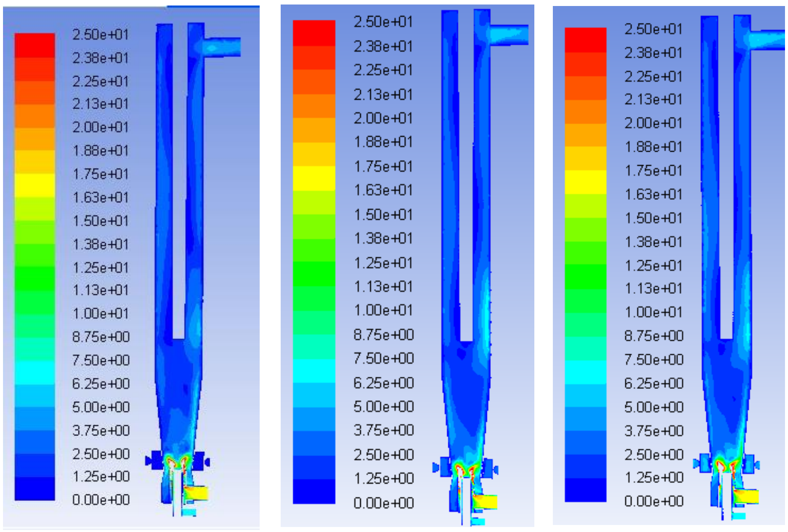


Fig. 6. Particles residence time for case 2: *a* — f=0,26; *b* — f=0,22; *c* — f=0,12

5. 3. Distributions of flow velocities

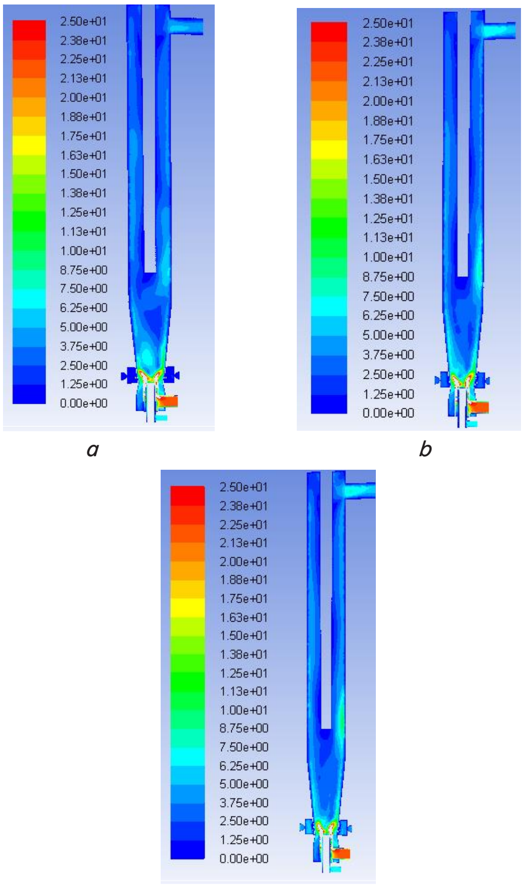
The distribution of flow velocities are present on Fig. 7, 8.

The Fig.7 and Fig.8 shows that the air flow is quite different in both cases.



a *b* *c*

Fig. 7. Distributions of flow velocities for case 1: *a* — main air flow inlet velocity =17 m/s; *b* — main air flow inlet velocity=20 m/s; *c* — main air flow inlet velocity=22 m/s



c

Fig. 8. Distributions of flow velocities for case 2: *a* — f = 0,26; *b* — f = 0,22; *c* — f = 0,12

For the case 1 in the centre of the bottom part of the calciner, the velocity magnitude is low. The region of low velocities decreases in the middle of the lower conical part of the calciner, for the case 2 when additional air flow is introduced. The additional air flow entering the calciner smoothes the flow velocity in this region. It should be noted that increasing the additional flow velocity increases the tangential velocity and increases concentration of particles near the wall in the center of the furnace. This phenomenon can adversely affect the calcination process of the particles.

6. Discussion of the gas-solid flow CFD-modelling results

The results of numerical simulations presented in this paper show that the aerodynamic flow structure is highly heterogeneous and depend from the inlet boundary conditions.

Using additional flow in the furnace reduces negative impact on the burner, but the material particles move mainly along the outer wall of the furnace in the form of “strip” that is curved along the lines twist the gas flow. This phenomenon could adversely affect the calcination process particles in the furnace, because the temperature flow in the periphery of the furnace is low.

Particular attention should be paid to the core flow over the burner where there is a zone of low speed (Fig. 7 and Fig. 8). Possible cause is a bad device geometry blade vortex burner. This fact may serve in the future for additional research to optimize the design of blades and modernization of furnace design.

Comparison of actual furnace work and model shows that for the case 1, without additional air flow, localization of the particles at the bottom of the furnace is similarly. This suggests that the developed computer model is adequate.

But quantification of solids accumulation at the bottom of the furnace (especially for case 2) shows that the rate of solid phase formation is higher for actual furnace. However, we believe this result is logical, because the model is created with a number of assumptions. Specifically excluded number of important processes such as combustion and calcination processes and gas flows are modeled as air.

We must pay attention to the simulation results of the particle residence time in the apparatus represented in Fig. 5 and Fig. 6, respectively.

Established fact that the use of additional flow does not reduce significantly the residence time of particles, and it opens the possibility for effective regulation of the furnace in industrial production.

So, using the additional air flown can be a viable way to get more normal distributions of particles when the furnace design can not be easily changed.

According to the present results, we can recommend additional intake air flow in the range of 3–5 m/s. The final selection will be done based on the analysis of combustion processes and chemical kinetics in the working area of the furnace. The results of this simulation in the following study will be presented.

7. Conclusions

The aims of this work were to study distributions of gas flow and trajectories of particles in the industrial cyclone-calciner furnace as well as developing reliable modelling tools for the next simulation of combustion processes and chemical kinetics between two-phase flows.

Two cases were studied in present work: case 1 is the flow of particles $CaCO_3$ in the calciner-furnace without inlet additional air flow and case 2 is the flow of particles with additional air flow.

According to the presented results based on the numerical simulations, for both cases were defined the hydrodynamic structure of flows, a residence time and a particles distribution in calciner-furnace.

The results show that the case 1, in comparison with the case 2 provides better mixing and distribution of particles $CaCO_3$ in the calciner-furnace but high solids phase concentration was observed in the vicinity of the burner for this case. In addition, some solid phases fall outside the burner. This is rather undesirable phenomenon and have negatively affect on the operation of the calciner-furnace.

In the case 2, the entire flow moves up without significant negative effects on the burner. It means that high swirling additional air does ensure high turbulence of the flow, especially in lower parts of the calciner-furnace. On the other hand, high particles concentration was observed in the vicinity of the walls for the case 2. It should be noted that a vortex resulting from the high swirling flow is beneficial to ensure full heat transfer between the air and the particles and good dispersion of the solid phase.

Therefore, CFD-modelling of multiphase flows presented in this work allows a deeper understanding of the processes under study and can be used for the optimization of lime calciner-furnace geometry and operating conditions.

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УДК 621.438.629.12
DOI: 10.15587/1729-4061.2015.43465

ТЕРМОДИНАМИЧЕСКИЙ АНАЛИЗ ЭНЕРГЕТИЧЕСКОЙ ЭФФЕКТИВНОСТИ ДВУХТОПЛИВНЫХ МОНАРНЫХ ГАЗОПАРОВЫХ УСТАНОВОК

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Наводяться матеріали щодо розробки та аналізу енергетичної ефективності двопаливних монарних парогазових установок з форкотлом, що працює на паливах-замінниках природного газу низької або середньої калорійності. Розглядаються технологічні схеми даних установок, які відповідають роботі теплоутилізаційного контуру в режимі підігріву живильної води та в режимі її підігріву та випаровування

Ключові слова: двохпаливна монарна газопарова установка, форкотел, палива – замінники природного газу

Приводятся материалы по разработке и анализу энергетической эффективности двухтопливных монарных парогазовых установок с форкотлом, работающим на топливах-заменителях природного газа низкой или средней калорийности. Рассматриваются технологические схемы данных установок, соответствующие работе теплоутилизационного контура в режиме подогрева питательной воды и в режиме ее подогрева и испарения

Ключевые слова: двухтопливная монарная газопаровая установка, форкотел, топлива – заменители природного газа

1. Введение

Одним из перспективных направлений развития газотурбинных установок (ГТУ) является, как известно, совершенствование монарных газопаровых технологий. Среди различных путей такого совершенствования выделяется разработка схемных решений, ориентированных на сокращение потребления дефицитных, высококалорийных энергетических топлив (природный газ и специальные марки жидких газотур-