Modeling the Technological Process of an Exhaust Gas Purification System in a Pyrolysis Plant for Waste Disposal

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Abstract

A study was conducted using the method of mathematical modeling to analyze the physical processes involved in the separation of solid dispersive particles from the exhaust gas in the technological process of pyrolysis waste disposal. The design of a pyrolysis waste disposal installation was developed, incorporating a two-stage exhaust gas purification system. The focus of the study is on the first stage of waste gas purification, specifically a system of cyclones designed to separate solid dispersed particles from the exhaust gases. To facilitate the research, a computer modeling method for aerodynamic processes in the flue gas purification system was developed. This method is based on a CAD system and a low-level programming language. A mathematical model of the dynamics of hot gas movement was also developed to study the processes occurring in the flue gas purification system. This mathematical model comprises systems of partial differential equations that describe the movement of the carrier and dispersed media (in the form of Lagrangian particles). The study yielded working relationships describing the distribution of exhaust gas velocity and the concentration of dispersed polluting particles in various planes of the cyclone system within the waste disposal plant. The design and operational parameters of the cyclone system were determined through mathematical modeling methods to ensure effective cleaning of flue gases in the pyrolysis plant for waste disposal.

Keywords

Separation, Cyclone, Pyrolysis, Mathematical model, Utilisation, Dispersed particle

1. Introduction

Waste disposal is one of the significant challenges facing modern civilization [1]. Production and consumption waste act as sources of anthropogenic pollution on a global scale, arising as an inevitable consequence of consumer behavior and low utilization rates of natural resources. In this context, a method and engineering design for a system have been proposed to efficiently dispose of waste with minimal environmental impact, along with reduced economic and technological costs for disposal. The system also allows for the subsequent effective utilization of thermal energy [2]. The proposed method is founded upon the pyrolysis process, which involves high-temperature decomposition and oxidation of toxic waste components. This is followed by the purification of the resulting flue gases and ash, which become practically non-toxic or low-toxic. The protection of atmospheric air from pollutants generated during waste disposal is a critical issue in the present era [3]. It is well-known that any pollutants released into the atmosphere undergo secondary physical and chemical transformations over time. These transformations occur due to various factors such as sunlight, electrical discharges, air oxygen, and rain. Eventually, the pollutants are deposited in the form of precipitation into the soil and water bodies.

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Therefore, the protection of atmospheric air from pollutants simultaneously protects other components of the biosphere – the lithosphere and the hydrosphere. Apparatus for cleaning waste gases from solid and liquid impurities play a key role in the equipment used for technological utilization in various branches of production [1-3]. One of the most common methods of primary cleaning of exhaust gases is ash capture, which allows for the cleaning of exhaust gases from combustion products of the coarse fraction. In order to implement this method, inertial separators in the form of a system of cyclones [1] have become the most widely used, as they allow for a high degree of separation with low energy consumption. Existing cyclone systems allow for high separation coefficients (k_c=0,8 and higher), but their operation is not reliable (slagging, erosive wear of the flow part) and not economical (large leaks, hydraulic resistance). Therefore, the development of new, effective designs of inertial systems for cleaning waste gases based on cyclones, which work as part of modern power plants, is an urgent task.

Solving the aforementioned issues is impossible without comprehensive scientific research to choose the optimal and well-founded technical solution. Conducting this kind of research is based on mathematical modeling methods with calculations using computer systems [4]. This makes it possible to prevent an unnecessarily large number of complex and expensive experimental studies, to significantly reduce the time and cost of design work, and to carry out qualitative and quantitative assessments of physical phenomena with sufficient accuracy for engineering practice. In this context, it is worth noting the great impact on the professional activity of the authors of this article by professor Ivan Kuzmin. Indeed, within the scope of the Ivan Kuzmin Scientific School in the field of "Creation of theory, mathematical models, methods and algorithms for the synthesis of complex systems of control, diagnostics and management in industry, aerospace and defense," significant results were achieved that are still used in scientific research.

In the scientific work [5], the influence of using cyclonic spiral inlets on the airflow pattern and the process of separating bioparticles was investigated. This was done through the assistance of finite element (FEM) calculations and fluid dynamics (CFD) software systems. The study involved designing and testing six separate cyclone separators with different inlet sizes and locations. Heterogeneous biogranular flow was used in both experiments and numerical simulations. The findings of the study highlight the crucial role of inlet type and design in determining cyclone performance. This is evidenced by variations in cyclone airflow pressure, velocity, and turbulence parameters. One drawback of this study is that it does not take into account the high air temperature, which is the main pollutant in the process of separating dispersed particles.

In scientific work [6], a mathematical model of a dense discrete phase in combination with an agglomeration model was used to simulate the operation of industrial cyclones with a high content of solids. The disadvantage of this approach is the low performance of the computer system, which is affected by the general parameters of the mathematical model.

Currently, mathematical modeling of physical processes is widely used [7], which allows the study of the influence of structural and mode factors on the main characteristics of the cleaning system. This enables the identification of specific ways to improve these systems while reducing the need for extensive experimental research [8]. Although the calculations involved and the assumptions made in the mathematical description of the work process are complex, these models hold clear prospects for the development of designs of inertial systems for cleaning waste gases based on cyclones [1].

The purpose of the work is to improve the efficiency of waste gas purification of a pyrolysis plant for waste disposal, by determining the structural and operational parameters of cyclone systems using mathematical modeling methods.

To achieve the goal, the following tasks were solved:

– to develop a method of computer modeling of aerodynamic processes in the flue gas cleaning system;

- to develop a mathematical model of the dynamics of hot gas movement for the study of work processes occurring in the flue gas cleaning system;

- on the basis of the developed mathematical model, obtain operational dependencies for determining the effective design and operational parameters of the cyclone system.

2. Materials and methods of research

2.1. Object of research

At Vinnytsia National Technical University, a pyrolysis plant (Fig. 1) [1] has been developed. This plant enables the efficient disposal of household waste with minimal economic and technological costs, as well as the efficient utilization of thermal energy. The device consists of a pyrolytic combustion chamber 1 and an exhaust gas cleaning unit, which includes a system of cyclones 2 and a system of catalytic filters 3. These components are interconnected by pipelines, forming a unified system for the flow of gas.

a)

b)

Figure 1: General view of the pyrolysis plant for the disposal of household waste
a – view from the left; b - view from the right

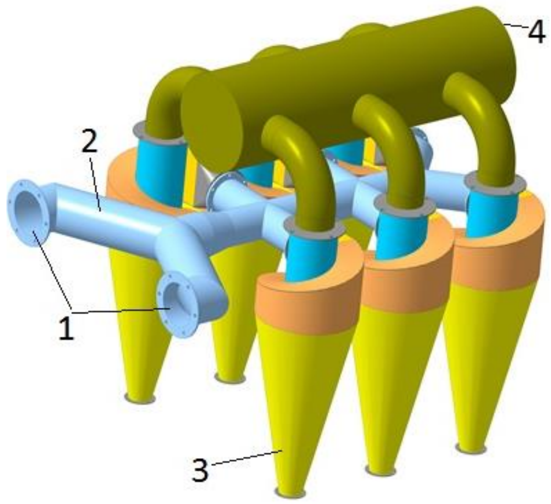


Figure 2: General view of the design of the cyclone system

Cyclone system 2 (see Fig. 1) is one of the main components of the pyrolysis plant, which is responsible for the rough cleaning process of waste gases. The exhaust gas cleaning system, which utilizes cyclones (Fig. 2), operates as follows. Hot gases containing solid pollutant particles enter the cone-shaped container 3 through opening 1 of the pipelines 2. The velocity vector of the container 3 is perpendicular to the generating plane [9]. When the gas flow enters the cyclone 3 at a high speed, a vortex (tornado) is formed in the conical cylinder due to the eccentric entry of the gas flow and the spiral design of the walls of the upper cover. Dispersed particles carried by the gas flow hit the walls of the cylinder 3 under the influence of centrifugal force, after which they settle at the bottom of the cyclone 3 due to gravity. The purified gas then passes through collector 4 and enters the fine purification system.

2.2.Research methods

For a deep and comprehensive study of work processes aimed at designing effective technological machines, a computer modeling method [10] of aerodynamic processes (Fig. 3) was developed for the flue gas cleaning system (FGCS).

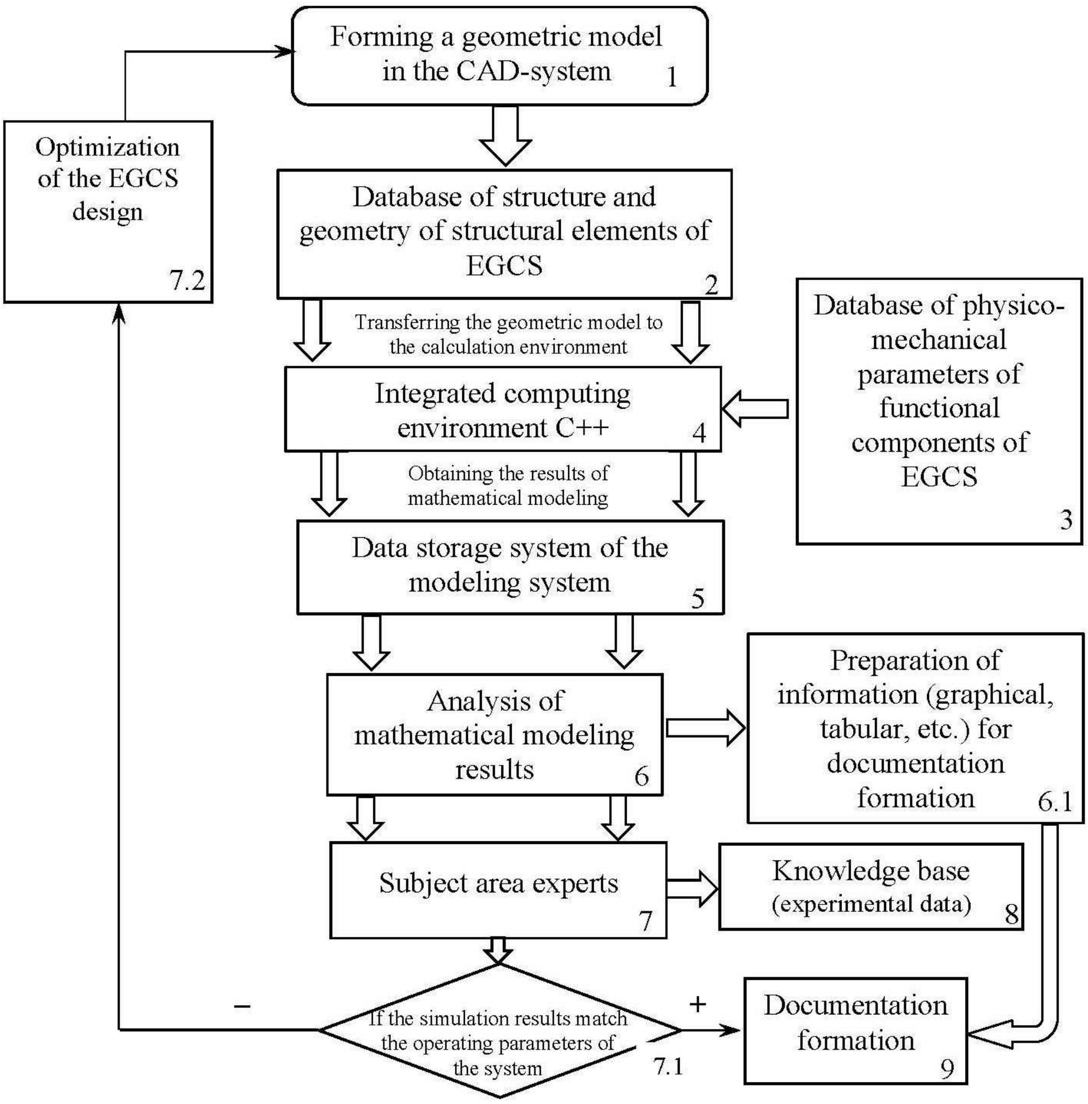


Figure 3: Structural diagram of the methodology for computer modeling of aerodynamic processes in EGCS

At the beginning, databases are created in CAD systems [11] using an array of coordinate values of a set of surface points of EGCS structural elements (unit 1 and 2) in the format of STL, M3D, WRL files [12]. At the same time, CAD systems, as a basic element of computer-aided design (CAD) systems, allow for the creation of design documentation for this research object, for example, in SPW file format [13]. In parallel, a database (unit 3) of physical and mechanical parameters of functional constituent elements (parts and nodes, technological environments) of EGCS is being formed in the format of TXT, XLS or API files [11–13].

At the next stage, the database of the structure and geometry of the structural elements (unit 2) and the physical and mechanical parameters of the functional component elements (unit 3) of the EGCS is exported to the integrated environment (unit 4) of numerical modeling in the C++ programming language. Upon completion of work in the integrated numerical modeling environment in the C++ programming language (unit 4), the results of the calculation (numerical simulation) are transferred to the data store of numerical simulation results (unit 5). Simulation results can be presented using multimedia formats (MP4, AVI files), as well as graphical images (PNG, JPEG, BMP files) combined with discrete data (TXT, XLS, API files).

At the next stage, the analysis of modeling results (unit 6) is performed with the help of experts in the subject area (unit 7) based on the knowledge base (block 8), which was formed on the basis of experimental data of EGCS operation for various technological processes [14]. Based on the results of the experts' conclusions, a decision is made on the acceptability of the numerical modeling results. If the initial results of the numerical modeling (general technological characteristics of the cyclone) correspond (unit 7.1) to the initial data of the technical task for the design of equipment for a certain technological process (pyrolytic combustion), then project documentation is formed (unit 9). If the results of the numerical simulation do not correspond (unit 7.2) to the initial data of the technical task, a change is made to the design of the technological equipment by optimizing the design of the EGCS (unit 10) and proceed to the initial block 1 of information technology modeling.

At the same level as the well-known monolithic approach [15] to solving multiphysics problems of numerical modeling of dynamic processes and Fluid Structure Interaction (FSI) systems [16], the developed technique (see Fig. 3) performs joint numerical modeling using separate algorithms [17]. Each algorithm is responsible for solving separate systems of differential equations that describe a specific physical process occurring in a particular technological system [1, 14].

A mathematical model describing the dynamics of hot gas movement, incorporating two distinct phases, has been developed for the theoretical examination of exhaust gas purification processes in Electrostatic Gas Cleaning Systems (EGCS). In this model, the carrier medium is represented as an incompressible fluid [18], while the dispersed medium is characterized by small solid spherical carbon particles [19].

1) The mathematical model of the motion of the bearing medium consists of:

– continuity equation of a continuously compressed medium

$$\frac{\partial \rho_g}{\partial t} + \bar{\nabla} \cdot \left(\rho_g \bar{V}_g \right) = Q^p_{mass}, \tag{1}$$

where Q^p_{mass} – relative mass flow rate of hot gas per unit time; ρ_g – density of a continuous carrier gas medium; $\bar{V}_g$ – velocity vector of a solid bearing medium;

– equation of mass conservation

$$\frac{\partial \left(\rho_g Y_1 \right)}{\partial t} + \bar{\nabla} \cdot \left(\rho_g Y_1 \bar{V}_g \right) = \bar{\nabla} \cdot \left(\left(\rho_g D_1 + \frac{\mu_t}{Sc_t} \right) \bar{\nabla} Y_1 \right) + Q^p_{mass}, \tag{2}$$

where Sc_t=1,0 – turbulent Schmidt number; Y_0 – mass concentration of the dispersed media; Y_1=1-Y_0 – mass concentration of the carrier medium; $\mu_t = C_\infty \rho_g \frac{k^2}{\varepsilon}$ – turbulent viscosity of a continuous carrier medium of the standard k-ε turbulence model [20]; k – turbulent energy; ε – dissipation rate of turbulent energy [9]; C_∞=0,09; D_1 – effective molecular diffusion coefficient of the exhaust gas substance (is calculated as the binary diffusion coefficient of the exhaust gas substance in nitrogen) [21];

– equation of conservation of momentum

$$\frac{\partial \left(\rho_g \bar{V}_g \right)}{\partial t} + \bar{\nabla} \cdot \left(\rho_g \bar{V}_g \otimes \bar{V}_g \right) = -\bar{\nabla} P + \bar{\nabla} \cdot \bar{\hat{\tau}}_g + \rho_g g + \bar{Q}^p_{mass}, \tag{3}$$

where $\bar{P}$ – full pressure of the carrier medium; $\bar{g}$ – free fall acceleration vector; $\bar{\hat{\tau}}_g$ – vector of the effective viscous stress tensor in a continuous bearing medium..

2) Mathematical model of the motion of a dispersed medium in the form of Lagrangian particles [4, 10]:

– equation of motion of the dispersed particle

$$\begin{cases} \dfrac{d\overline{x}_p}{dt} = \overline{V}_p; \\ \dfrac{dV_p}{dt} = \dfrac{\pi d^2}{8m} C_D \rho_g |V_r| V_r + g\left(1 - \dfrac{\rho_g}{\rho_P}\right), \end{cases} \tag{4}$$

where x_p – change in the coordinate of the dispersed particle during movement; V_P – change in the velocity of the dispersed particle during movement; m – mass of a dispersed particle; ρ_g – density of a dispersed particle; $\overline{V}_r = \overline{V}_g - \overline{V}_p$ – velocity of the dispersed particle relative to the carrier medium; d – diameter of a dispersed particle; $C_D = \dfrac{24}{\mathrm{Re}} + 0,44$ – particle drag coefficient [22]; Re – Reynolds number [8]; $V_g = \langle V_g \rangle + V_g'$ – carrier phase velocity; $\langle V_g \rangle$ – average velocity of a dispersed particle; V_g' – pulsating component of the dispersed particle velocity.

On the basis of the technical drawings of the pyrolysis plant in the CAD system, a three-dimensional CAD model (see Fig. 2) of the design of the cyclone system was developed. This, in turn, made it possible to use the geometric area (Fig. 4) in which the movement of the gaseous medium takes place (exhaust gases).

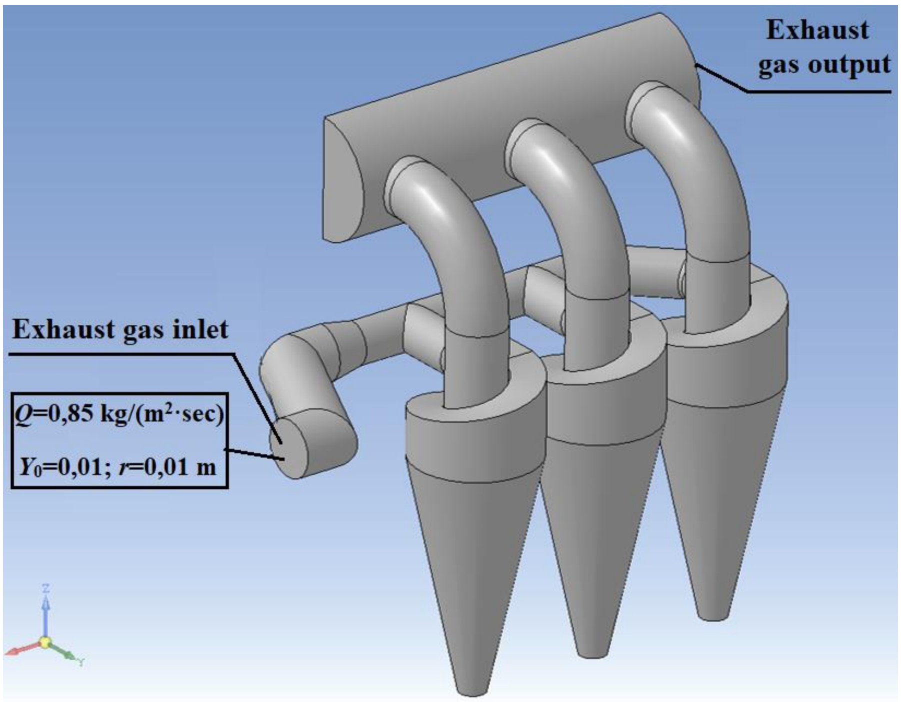


Figure 4: The calculated area of the internal cavity of the cyclone cleaning system

The internal cavity of the cyclone cleaning system is taken as the calculation area, and it is enough to take only one of the sides of the calculation sub-area, for example the right (left), since the model is symmetrical with respect to the plane of the intake pipe. Inside the calculation area, the main studied gas-dynamic processes take place [23]. The basic initial data are determined on the three-dimensional model of the geometric area, which in turn will be the boundary conditions for calculating the combustion process (see Fig. 4). The gaseous environment is composed of combustion products of natural gas and air. The dispersed medium is made up of carbon, with the relative volume of the dispersed phase being Y_0=0,01 of the total volume of the gaseous medium. The model used for the collision of particles with cyclone walls is one that incorporates partial velocity damping [24]. It is also assumed that the dispersed particles interact with each other, while introducing the average particle movement resistance coefficient CD (see 4).

In this geometric area, the model of turbulent flow in a weakly compressed two-phase medium serves as the basis [24]. At the entrance to this area, an air-gas mixture (carrier medium) is supplied, with the following parameters (boundary conditions) [4, 18]: volume of solid pollutant particles in the form of spherical dispersed particles with a diameter of d=0,20 mm; consumption of the carrier gas medium Q=0,85 kg/(m^2·sec); exhaust gas temperature T=6930,0 K; initial pressure P=101325,0 Pa; coefficient of gas and air input flow pulsation b=0,03; turbulence scale I=0,01 m. The condition of flow with a boundary layer, characterized by the logarithmic law of change of the tangential component of velocity, is observed on the inner walls of the cyclone chambers [25]. The boundary condition at the exit is set as zero flow.

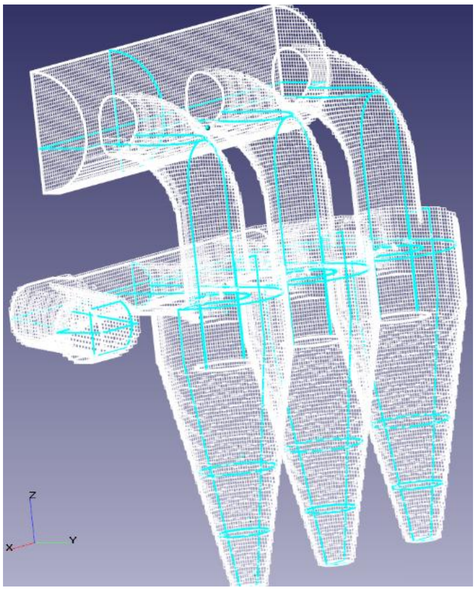


Figure 5: The scheme of the finite-volume calculation grid

Since the aerodynamic process is calculated using the finite element method [6, 18, 26], it is necessary to construct a finite volume calculation grid for further calculations. This grid should take into account the flow near the characteristic elements of the burner design, which can create local vortices [20, 27-30]. The initial calculation grid (Fig. 5) was initially made uniform throughout the calculation area and then adapted to different levels on the surface.

For this stationary problem of aerodynamics, a constant time step is chosen based on 1/10 of the flight time for the characteristic size of the problem. In this case, the typical size is the length of the cyclone system pipeline, L_m=2,0 m. Time of flight refers to the time required for a hypothetical particle moving with an average flow speed of V≈1,0 m/sec (the speed of dispersed particles and hot gases are approximately equal to each other) to overcome the characteristic size, τ_m=0,1(L_m/V)=0,1(2,0/1)=0,20 sec. Therefore, to obtain adequate calculation results, a constant calculation time step of τ = 0,2 sec is adopted.

2.3. Results of the research

Using the methods of numerical solution [14, 17] for systems of partial differential equations, the mathematical model (1)–(4) was solved in an integrated numerical environment based on the C++ programming language. The calculation of the above equations resulted in the distribution of the concentration of dispersed particles (carbon particles) in the cavity of the cyclone system (Fig. 6).

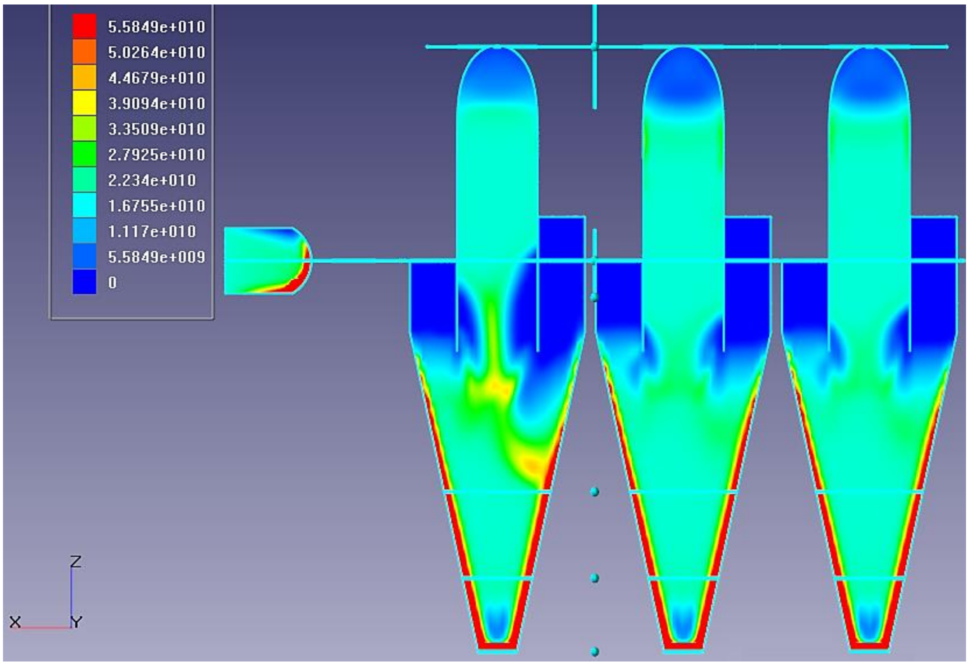
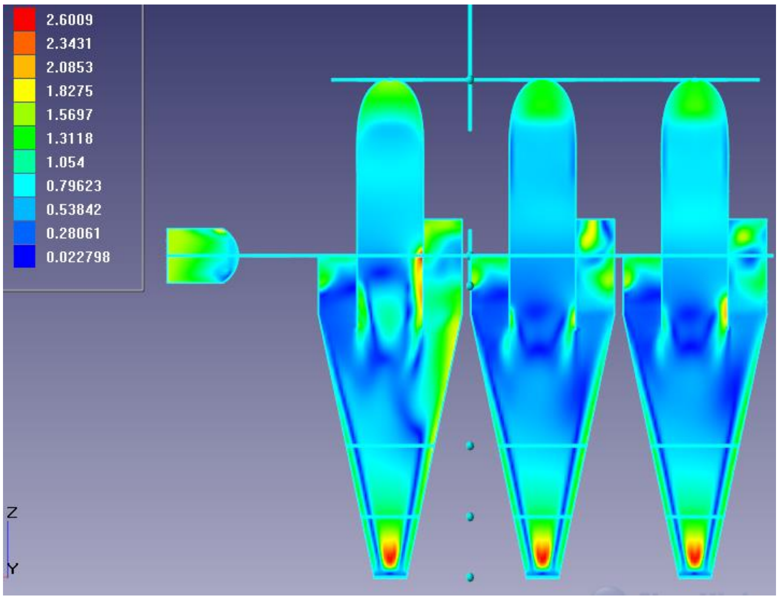
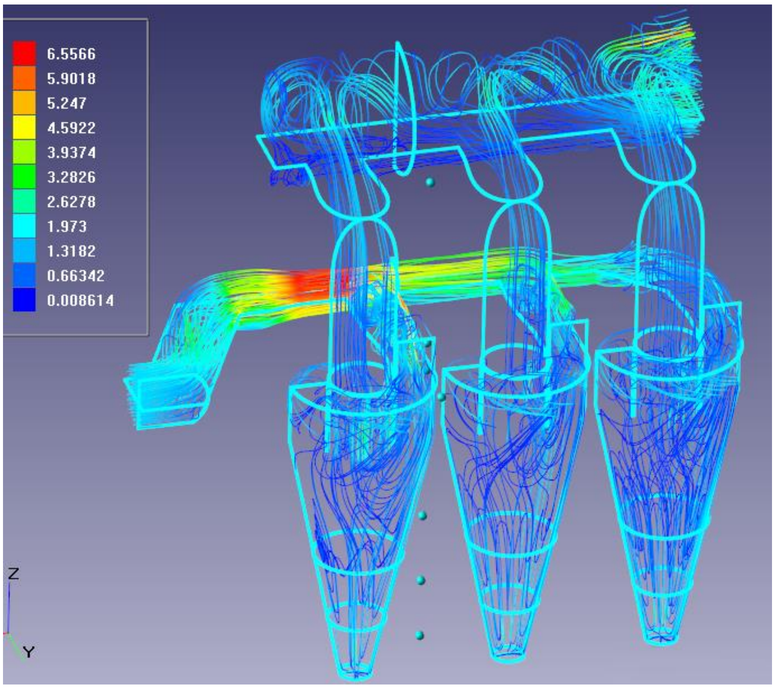


Figure 6: Concentration distribution of dispersed pollutant particles in the XOZ plane

The result of the calculation of hydrodynamic processes is also the distribution of exhaust gas flow velocities in the cyclone system cavity (Fig. 7).



a)



b)

Figure 7. Velocity distribution of exhaust gases in the cyclone system cavity of a waste treatment plant

a) – in the XOZ plane; b) – by cavity volume of the cyclone system

2.4. Discussion of the study results

Analyzing the distribution of the concentration of dispersed particles (carbon particles) in the cyclone system cavity (see Fig. 6), it is clear that the highest concentration of coarse pollutants is generally located in the cone-shaped cavity of the cyclones. Moreover, the highest concentration of dispersed particles is located on the inner walls of the cyclones ($5{,}56 \cdot 10^{10}$ units), which confirms the effectiveness of using centrifugal force to clean the large fraction of flue gases [29].

It can also be noted that the thickness of the wall layer of dispersed particles increases as it approaches the height of the cone, which, in turn, confirms the effectiveness of using external gravity to settle the separated large pollutants. It should be noted that an insignificant amount of dispersed particles enters the outlet collector 4 ($2{,}23 \cdot 10^{10}$ units), which confirms the need to use an additional system of fine exhaust gas cleaning. The use of cyclones installed in series contributes to additional purification of exhaust gases from larger pollutants, as evidenced by a decrease in the concentration of dispersed particles at the collector inlet ($2{,}23 \cdot 10^{10}$ units) and the resulting separation coefficient k_c=0,83.

Analyzing the distribution of velocities (see Fig. 7, a) in the cavity of the cyclone system, one can note the presence of extreme velocity values (2,60 m/sec) at the top of the cyclone cone (lower base), which indicates the presence of an optimal design of the cyclone system. There is also a velocity gradient along the vertical axis of the cyclone cavity (1,40 m/sec), which indicates the presence of a vortex (tornado) phenomenon. This, in turn, causes the emergence of centrifugal forces that move large pollutants to the cyclone walls. It should be noted that there is a wall flow of exhaust gases (1,30 m/sec), which causes the emergence of an additional centrifugal force that increases the efficiency of separation from dispersed particles. Analyzing the distribution of the current lines of velocity vectors in the cavity of the cyclone system (see Fig. 7, b), it is possible to note extreme velocity values (6,56 m/sec) at the inlet to the first (left) conical tank of the cyclone system. This negative phenomenon can be avoided by locally increasing the diameter of the inlet pipe 3 (see Fig. 2) at the cyclone connection. The uneven velocity values (see Fig. 7, a) at the inlet to the cyclone system outlet manifold (1,30 m/sec), as well as extreme values of the concentration of dispersed pollutant particles ($3{,}90\cdot10^{10}$ units), can be avoided by structurally changing the size of the cyclones (increasing the overall size of the left cyclone will allow for the equalization of exhaust gas velocities).

3. Conclusions

1. A methodology for computer modeling of aerodynamic processes in the flue gas cleaning system has been developed. This methodology is based on a CAD-system for computer-aided design and an integrated calculation environment that uses the C++ programming language.
2. A mathematical model of the dynamics of exhaust gas flow has been developed. This model describes the motion of the carrier and dispersed media in the form of systems of partial differential equations.
3. The operational dependencies of the distribution of exhaust gas velocity and the concentration of dispersed pollutant particles in different planes of the cavity of the cyclone system of the waste disposal unit were obtained.

Based on the results of numerical modelling of the exhaust gas purification process of a pyrolysis unit for waste disposal, a value of the separation coefficient k_c=0,83 was obtained for the minimum size of a dispersed particle of carbon-type pollutants d=0,20 mm for an average velocity of exhaust gases in the pipeline v=1,0 m/sec. The developed design of the inertial exhaust gas cleaning system of a pyrolysis plant for waste disposal consists of six cyclones with a diameter of D_c=0,50 m and a nominal diameter of d_y=0,05 m. The results obtained from numerical modeling of the inertial exhaust gas cleaning system of the waste disposal unit showed the advantages of the chosen modeling approach and also proved the effectiveness of the developed cyclone designs.

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