Simulation of fractional efficiency of direct-flow cyclone with intermediate dust collector

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Abstract. By means of numerical modeling in the program ANSYS Fluent CFX the evaluation of fractional efficiency in a direct-flow cyclone with intermediate dust collector has been carried out. The boundary conditions were as close as possible to the experimental ones. As a gas phase, the authors take the air under normal conditions, as the solid phase – spherical particles of 30 and 80 microns in size. In order to evaluate the adequacy of the calculation model, a laboratory installation of a DCIC with two separate chambers for the selection of collected particles was made. This design allowed estimating the fractional efficiency of both individual chambers of a direct-flow cyclone DCIC and the apparatus as a whole. The results of the experiments carried out on different types of dust (fly ash, cement) showed a good convergence with the design model

1. Introduction

To date, along with increasing production growth rates, the world is facing pressing environmental issues, in particular the protection of atmospheric air from pollution. The efficiency of new gas treatment plants under development largely depends on the right equipment and the accuracy of engineering calculations in the design of gas treatment equipment. One of the effective elements of a gas processing plant is centrifugal separation in a direct-flow cyclone with an intermediate dust collector (DCIC) [1].

The development of direct-flow cyclones requires a special approach in the calculation of the dust-gas-air mixture motion in separation chambers, which largely determines their efficiency and geometric dimensions [2, 3]. Adequate forecasting of efficiency is very important for the large-scale transition at the stage of design of dust-cleaning equipment, but in the literature on dust collection by now there is no single approach to calculate the efficiency of cleaning in direct-flow cyclones of various designs.

One of the main estimates in calculating the efficiency of gas purification in cyclones is the fractional degree of purification – the ratio of the number of particles collected in the device to the number of incoming dust particles of the same fraction.

The known methods of cyclone efficiency evaluation based on empirical probabilistic functions of fractional efficiency and dust dispersion composition have low accuracy.

For example, the method of calculating the fractional efficiency proposed by the researchers in the works [4–6] assumes a multistage approach, which complicates its use. Each efficiency forecasting method involves certain assumptions and the availability of input data.
Probabilistic and energy method of evaluating the cyclones efficiency [7, 8], assumes subordination of the dust input composition and fractional efficiency of dust collection to the log-normal law of distribution and efficiency evaluation of a gas cleaning apparatus on the probability integral:

$$\eta = \frac{1}{2\pi} \int_{-\infty}^{x} \exp \left( -\frac{x^2}{2} \right) dx = f(x),$$  

(1)

where $f(x)$ is a function of normal Gaussian distribution and the parameter $x$ is:

$$x = \frac{\lg(\delta_m/d_{50})}{\sqrt{\lg^2 \sigma_v + \lg^2 \sigma_\eta}},$$  

(2)

where $\delta_m$ is the mass-mediated particle diameter, $\lg \sigma_v$ is the standard deviation of particle diameters logarithms, $\lg \sigma_\eta$ is the value determined by the type of dust collector. Parameter $d_{50}$ is the diameter of particles separated in cyclone by 50 % is based on the result of experimental studies.

According to the NIIOGAZ method [9] the calculation of the cyclones separation efficiency takes into account the influence of the flow velocity $w$, the dynamic viscosity $\mu$ of the stream, the dust density $\rho_\delta$, and the diameter of the cyclone $D$, in the terms of particle diameter $d_{50}$, separated by 50 %, working on the technological parameters of the cyclone according to the known operating parameters (T) by the formula:

$$d_{50} = d_{50}^T \sqrt{\frac{D}{D^T} \frac{\rho_\delta^T}{\rho_\delta} \frac{\mu}{\mu^T} \frac{w}{w^T}},$$  

(3)

According to this method, the calculation of the $d_{50}$ parameter for any dust collector requires a special experiment on dust with different fractional compositions, as well as the use of such dependencies, which often do not adequately describe the experimental data.

The work [10] proposes to recalculate the cleaning efficiency of $\eta$ by dust slippage $\varepsilon$ from the base cyclone (index 0) to the geometrically similar calculated (index $p$) at the same average flow rate $w$ in terms of the cyclone, according to the equation:

$$\varepsilon = \frac{(1-\eta_p)}{(1-\eta_0)} = \prod_{i} \frac{K_{ip}}{K_{i0}},$$  

(4)

where $K_i$ is the relative entrainment coefficients.

The method is based on the assumption of independence of the cyclone diameter influence $D$, mass-mediated particle diameter $\delta_m$ and dust flow $z$ on the relative dust slip $\varepsilon$. It is universal, i.e. applicable to any type of cyclones: counter flow, direct flow and counter-rotating flows; does not depend on the dispersion distribution of particles in terms of size and fractional cyclone cleaning parameters.

The work [11] proposes a universal method of evaluating the efficiency of geometrically similar cyclones based on the formula (4). The method takes into account the influence of the average flow rate $w$, cyclone diameter $D$, dust concentration $z$, as well as the joint influence of the mass-mediated particle diameter $\delta_m$ and particle density $\rho_\delta$ on the relative slip $\varepsilon$ – carry-over coefficient $K_\rho$. The disadvantages of this method are the narrow range of applicability of the cyclone diameter: from 100 to 600 mm. In addition, the average rate of dust flow is not taken into account.

Thus, the literature does not yet provide a generally accepted method of predictive calculation of the separation efficiency of projected cyclones. Since more than 80 % of all collected industrial dust is deposited in cyclones of different types, the development of universal method of separation efficiency predictive calculation is very important.

In order to carry out further studies of fluid dynamics processes in dispersed systems, modern tools of mathematical modeling by the finite element method (FEM) are indispensable.
2. Materials and methods

Experiments to determine the fractional efficiency were carried out on a transparent test device of the DCIC direct-flow cyclone with two separate dust collectors: Intermediate Dust Collector (IDC) and Main Dust Collector (MDC) in Figure 1.

![Diagram of test device direct-flow cyclone with intermediate dust collection](image)

Two types of dust were used in the experiment: fly ash CHP ($\rho_\delta = 1950 \text{ kg/m}^3$) and cement 32.5B ($\rho_\delta = 3170 \text{ kg/m}^3$) (Figures 2). To determine the exact grain-size composition of the initial and collected dust, we used the method of laser diffraction on the Microtrac S3500 laser diffraction analyzer. The laser analysis system complies with international standards of particle size measurement and is certified in accordance with ISO 13320-1 (International Organization for Standardization). The device is included in the State Register of Measuring Instruments (US.E.27.001.A № 23120), the measuring range – from 0.021 to 2816 microns.

The initial dispersion composition of two dust samples was obtained by laser diffraction. Then the data on the log-normal distribution law were approximated:

$$f(\delta) = \exp\left(-\frac{\ln \delta - M}{\sigma^2}\right) \cdot \frac{1}{\delta \sigma \sqrt{2\pi}}.$$  

(5)

The curved lines of the log-normal distribution of particles by size are presented in Figure 2.
The integral curved lines of particles distribution: a – fly ash; b – cement 32.5B.

The calculated mass-median diameter $\delta_m$ and standard deviation $\sigma$ are presented in Table 1.

### Table 1. Results of the initial dust dispersal analysis.

| Material   | Density $\rho_s$, kg/m³ | Mass-median diameter $\delta_m$, µm | RMS logarithm deviation $\sigma$ |
|------------|--------------------------|-------------------------------------|----------------------------------|
| Fly ash    | 1950                     | 27.27                               | 1.026                            |
| Cement 32.5B | 3170                     | 25.29                               | 1.019                            |

3. **Fractional efficiency studies on the DCIC direct flow cyclone test device**

Experiments were carried out on the parameters indicated in Table 2. The efficiency of separation of the intermediate dust collector ($\eta_{idc}$), the main dust collector ($\eta_{mdc}$) and the entire DCIC direct-flow cyclone was determined:

$$\eta_{idc, mdc} = \frac{m_{caught}}{m_0}$$  \hspace{1cm} (6)

$$\eta = \eta_{idc} + \eta_{mdc}$$  \hspace{1cm} (7)

where $m_0$ is the initial mass of dust, $m_{caught}$ is the mass of collected dust.

### Table 2. Parameters and results of experiments.

|             | $T$, °K | $P_{atm}$, mm Hg | $\Delta P$, Pa | $w_{cp}$, m/s | $Q$, m³/h | $z$, g/m³ | $m_0$, kg/h | $\eta_{idc}$, % | $\eta_{mdc}$, % | $\eta$, % |
|-------------|---------|------------------|----------------|--------------|-----------|------------|-------------|-----------------|-----------------|---------|
| Fly ash     | 290     | 730              | 2500           | 7.99         | 293.7     | 21.1       | 6.2         | 48.06           | 31.58           | 79.64  |
| Cement 32.5B | 288     | 730              | 2450           | 7.99         | 293.7     | 26.1       | 7.7         | 47.23           | 40.16           | 87.38  |

Particles collected in the intermediate and main dust collector were examined by laser diffraction. Then, using formula (5), we determined the integral functions of particle distribution and found $\delta_m$ and $\sigma$ (Table 3).

### Table 3. Results of the disperse analysis of the collected dust.

| Material   | Dust collector | Mass-median diameter $\delta_m$, µm | RMS logarithm deviation $\sigma$ |
|------------|----------------|-------------------------------------|----------------------------------|
| Fly ash    | IDC            | 40.75                               | 0.832                            |
|            | MDC            | 22.03                               | 0.915                            |
| Cement 32.5B | IDC            | 37.15                               | 0.730                            |
|            | MDC            | 23.77                               | 0.947                            |
On the basis of the obtained integral particle distribution functions, the fractional efficiency in the intermediate and main dust collector and the total fractional efficiency of the DCIC direct-flow cyclone were determined by the formula:

$$\eta(\Delta \delta) = \frac{F_{catch}(\Delta \delta)}{F_0(\Delta \delta)} \eta$$ (8)

where $\Delta \delta$ is the difference between the largest and smallest particle sizes nearby, $\eta$ is the efficiency of dust collectors.

Figure 3 shows the fractional efficiency of the intermediate and main dust collector. Figure 4 shows the total fractional efficiency of the DCIC direct-flow cyclone.

**Figure 3.** a – fractional efficiency of the intermediate dust collector on ash; b – fractional efficiency of the main dust collector on ash; c – fractional efficiency of the intermediate dust collector on cement; d – fractional efficiency of the main dust collector on cement.
Table 4 shows the experimentally obtained parameters of fractional efficiency $d_{50}$ for the DCIC direct-flow cyclone test device with two separate dust collectors.

**Table 4.** Parameters of fractional efficiency $d_{50}$ of DCIC direct-flow cyclone.

| Dust collector | $d_{50}$, µm | RMS logarithmic deviation $\sigma$ |
|----------------|--------------|-----------------------------------|
| **Fly ash**    |              |                                   |
| IDC            | 11.025       | 11.025                            |
| MDC            | 19.72        | 19.72                             |
| DCIC           | 6.481        | 6.481                             |
| **Cement 32.5B**|              |                                   |
| IDC            | 15.12        | 15.12                             |
| MDC            | 20.18        | 20.18                             |
| DCIC           | 6.93         | 6.93                              |

Table 4 shows that the parameter of fractional efficiency $d_{50}$ varies depending on the density and dispersion composition of the dust.

4. Numerical simulation of the fractional efficiency of DCIC direct flow cyclone by the finite element method (FEM)

The document shows a three-dimensional stationary mathematical model, which allows making the analysis of the motion of particles in a direct-flow cyclone. To solve the problem, we use the CFD calculation software ANSYS CFX, it allows one to model disperse systems. The appearance of the investigated computational model is shown in Figure 5.

![Layout of the studied computational model](image)

**Figure 5.** Layout of the studied computational model.

4.1. Setting up the CFD software

In the CFD program ANSYS CFX, the dispersion system modeling is implemented using the models:
- media interaction model;
- model of the exchange of the quantity of motion between the particle and the gas medium;
- model of the motion of the gaseous medium.
4.1.1. Media interaction model. In the computational model, the dispersed system consists of two phases: gas and solid particles. A simulation of the dispersed system in ANSYS CFX is performed using Euler-Euler media interaction model.

Euler-Euler model — in this model, the phases are regarded as interpenetrating continua; the interaction of media through pressure and interphase exchange coefficients is calculated, taking into account the calculation of Euler variables [12].

4.1.2. Model of the exchange of the quantity of motion between the particle and the gas medium. The choice of other computational models in the cyclone simulation is simpler, but no less important. The Schiller-Naumann model should be used to describe the exchange of the quantity of motion between the particle and the gas medium [13]. According to the model, the drag coefficient of particles is determined in accordance with the following formula:

$$C_D = \frac{24}{Re} \cdot (1 + 0.15 \cdot Re^{0.687})$$

where $Re$ is the particle Reynolds number, which is determined based on the following relation:

$$Re = \frac{\rho_\beta |U_\beta - U_\alpha| d_\beta}{\mu_\alpha}$$

where subscript $\alpha$ denotes that the variable belongs to the main phase (mixture of gases), $\beta$ belongs to the solid phase.

4.1.3. Model of the motion of the gas medium. The motion of solid particles can be traced taking into account the turbulence of the gas phase.

As a model of turbulence, the RNG (renormalization groups) version of the $k$-$\epsilon$ model is used. Of all the CFX turbulence models, it is the most suitable for simulating flow with highly curved particle trajectories [14].

4.1.4. Boundary and initial conditions. The computational geometry with the arrangement of boundary conditions shown in Figure 5 consists of:

- the node of the main selection of particles;
- particle intermediate particle assembly;
- flow swirl;
- entry areas gas and particles inlet;
- purified gas outlet area.

The input parameters for the dispersion medium are shown in Table 5.

| Parameter description | Value and dimension |
|-----------------------|---------------------|
| Mass flow rate ash solids of 30 micron | 4.2 [kg/h] |
| Mass flow rate ash solids of 80 micron | 1.8 [kg/h] |
| Inlet gas velocity | 10 [m/s] |

4.1.5. Computational grid. The computational domain is a part of the cyclone design under consideration. On the basis of the preliminary analysis of convergence, a grid mathematical model was constructed in Figure 6, consisting of 7,855,345 tetrahedral elements. The size of the elements in the near-wall layers was set taking into account the criterion $y^*$, which must satisfy the condition $30<y^*<300$ as the gas mixture moves in a highly developed turbulent flow.
4.1.6. Conducting a numerical solution. Before starting the calculation, some settings were specified to control the numerical solution scheme:

- First order advection scheme (High Resolution). The advantage of this scheme is its stability and good rate of convergence.
- The time scale was set by a piecewise linear function, which gradually decreases while the iteration number increases (Table 6).

| Iteration number | 0-100 | 100-200 | 200-300 | 300-400 | 400-500 |
|------------------|-------|---------|---------|---------|---------|
| Timescale, sec   | 0.15  | 0.10    | 0.08    | 0.06    | 0.04    |

This technique is caused by a significant difference in the scale of the simulated processes in the various structural elements. The large scale at the beginning of the solution helps to accelerate the convergence of the equations [15].

The system of equations was solved iteratively. The values of the calculated variables in each calculation cell were changed from a certain initial distribution (based on the given initial conditions) to the desired distribution.

In the course of the solution process, two main indicators of the convergence level were monitored:

- the RMS residuals of the calculated variables;
- the global imbalances of the calculated variables.

The solution process was stopped when all the indicators met the convergence criteria (residuals < $10^{-3}$...$10^{-5}$, imbalances <1 %, the target parameters do not change during the last 100 iterations by more than 1 %).

4.2. Results

As a result of the calculations, the pressure of the gaseous medium and the changes in the volume fractions of solid particles in the computational model were determined. The color map of the pressure distribution of the gas mixture in the cross section of the calculated geometry for a fragment of the calculation model is shown in Figure 7.

As can be seen from the color map of the pressure distribution of the gas mixture for the Euler-Eilor model, ash particles in the region of the location of the intermediate selection unit have a disturbing effect on the gas medium in the extreme regions of the computational model.

Figure 8 shows color maps of changes in the volume fraction of solid particles in the cross section of the calculated geometry.
Figure 7. Color maps of the gas mixture pressure distribution

Figure 8. Color maps of the changes in the volume fraction of solid particles: a – distributions of the volume fraction of solid particles 30 microns in size after the swirler; b – distributions of the volume fraction of solid particles 80 microns in size after the swirl; c – volume fraction of solid particles with a size of 30 microns in an intermediate particle extraction unit; d – volume fraction of solid particles with a size of 80 microns in an intermediate particle extraction unit.
The color maps shown in Figure 6 show that the particles after the swirler to the intermediate node for the selection of particles and after it move near the surface of the walls. When it enters the node of the intermediate selection, particles of 80 microns in size move in the direction of the base of this area, and particles of 30 microns in size are evenly distributed throughout the volume, without causing significant disturbances to the gas medium.

5. Conclusion

Numerical modeling of the fractional efficiency of the direct-flow cyclone test device DCIC allowed us to establish that 70% of the particles 80 microns in size after the swirler fall into the node of the intermediate dust collector, which in turn correlates well with the experimental data.

The developed mathematical model of the flow of dispersed media allows estimating local disturbances associated with the distribution of solid particles in the geometry of a direct-flow cyclone DCIC, and significantly reduces the number and time of experiments at the design and calculation stages using a known method for evaluating the efficiency of dust collectors.

The using of the ANSYS CFX software package will make it possible to further carry out various simulations with different streams of the disperse medium. Thus, specifying in advance the fractional degree of purification and operating parameters of the cleaned dust stream on the test device of a direct-flow cyclone DCIC, and having reliable settings for the model solver in FEM systems, you can accurately calculate the number and diameter of designed direct-flow cyclones with an intermediate dust collector for gas cleaning systems.

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