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Experimental studies of two-stage centrifugal dust concentrator

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Abstract. The article presents data of experimental results of two-stage centrifugal dust concentrator, describes its design, and shows the development of a method of engineering calculation and laboratory investigations. For the experiments, the authors used quartz, ceramic dust and slag. Experimental dispersion analysis of dust particles was obtained by sedimentation method. To build a mathematical model of the process, dust collection was built using central composite rotatable design of the four factorial experiment. A sequence of experiments was conducted in accordance with the table of random numbers. Conclusion were made.

1. Introduction

A cyclone separator is the most common and easy-to-use equipment for cleaning air from dust particles, working on the principle of ejection of particles from the steam-and-gas mixture by the centrifugal force [1].

One of the directions of improvement of the cyclone separator is its upgrade to the two-stage dust concentrator. The source information for the development of this equipment was obtained through the study and research of aerodynamics and the dust dynamics system with forced recirculation of the aspirated air.

2. Design construction of two-stage dust concentrator

The cyclone two-stage dust concentrator (Figure 1) consists of cylindrical body 1, equipped with tangential pipe 2, which is supplied to the cleaning steam-and-gas mixture, cylindrical insert 4 with target sleeve 5 and shutter 6; on the cover of cyclone separator 3, there is fixed exhaust pipe 7 with volute for detwisting moving stream. The construction of dust concentrator is made in the form of a cyclone chamber with the annular selection steam-and-gas concentrate (the first stage of filtration) on the axis, which is a counter flow cyclone (the second stage of filtration).

Through inlet pipe 2 in the cyclone part of the dust concentrator between body 1 and cylindrical insert 4, unclean steam-and-gas mixture Q_a is fed. Due to the action of centrifugal force, dust particles impact on the wall of body 1 are carried to internal cavity TSDC airflow Q_r through annular cavity, and then enter the recirculation line. The part of air flow Q_v , remaining after the first stage of filtration, through the annular pit between the upper butt end of cylindrical insert 4 and cover 3 is directed in a counter flow cyclone for a second stage of filtration.



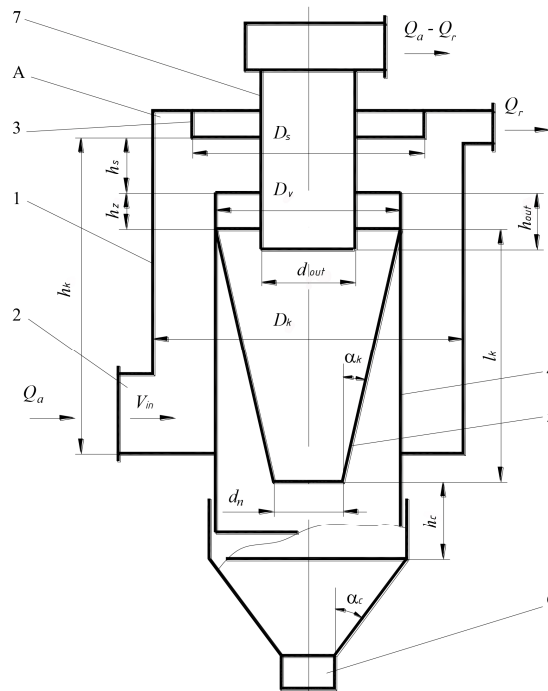


Figure 1. The scheme of the two-stage dust concentrator: 1 – body; 2 – inlet pipe; 3 – cover; 4 – cylindrical insert; 5 – target sleeve; 6 – shutter; 7 – exhaust pipe

3. The methodology of experimental studies

The target of experimental research TSDC:

1. The definition of modal, structural parameters of TSDC and deducing mathematical relationships that affect the collection efficiency of dust particles and water resistance of TSDC.
2. Optimization of constructive and regime parameters.
3. The definition of fractional efficiency of dust collection and water resistance of construction TSDC.

Table 1. The results of the dispersion analysis of the experimental dusts

Size, μm	Mass content, %				
	QD-1	QD-2	QD-3	Ceramic	Slag
<2.5	18.4	6.5	5.5	9.1	7.1
2.5-4	9.6	6.2	6.8	7.0	9.5
4-6.3	13.5	9.1	7.2	11.2	14.1
6.3-10	12.5	17.5	10.8	9.3	17.9
10-15	11.2	11.2	8.2	7.9	10.4
15-20	8.5	10.1	7.9	9.3	10.6
20-25	7.2	8.0	4.3	4.9	6.0
25-30	3.6	5.5	4.6	5.8	7.1
30-40	5.2	8.8	7.8	9.2	6.2
40-60	5.9	7.8	11.0	12.1	5.4
>60	4.2	9.6	25.5	14.0	5.5
$d_m, \mu\text{m}$	9	15.5	24	17	12
$\lg[\sigma]_d$	0.523	0.491	0.535	—	0.477
$\rho_d, \text{kg/m}^3$	2620	2620	2620	2440	2350

After processing the results [2], the research has developed a method of engineering calculation design cyclone of the two-stage dust concentrator.

Laboratory studies of TSDC were carried out on an experimental stand, which was open air and dusty. The air that is sucked into the system after one use went in the exhaust ventilation system. This allowed us to conduct experiments in the isothermal process that enormously simplified the processing of the results.

The time for one of experiments made 11-19 min; minimal subsample – 350 g. The subsample, which was necessary for the experiment, was determined by the dust concentration, airflow and time of the experiment.

For experiments, the authors used steam-and-gas flow, quartz (QD-1, QD-2, QD-3), ceramic dust and dust of blast-furnace slag. Experimental dispersion analysis of dust particles was conducted by the sedimentation method with the help of pipette equipment [3, 4]. The results of the experiment are shown in table 1.

The ceramic dust 4 (Fig. 2) was taken from the dust mass of construction production of Eltinskiy Building Materials Plant and further sifted through a sieve with a mesh of 150 μm . Dust of blast-furnace slag 5 and quartz dust 1-3 (Fig. 2) were obtained by grinding the source material in vibratory ball mill VNINKSM-10.

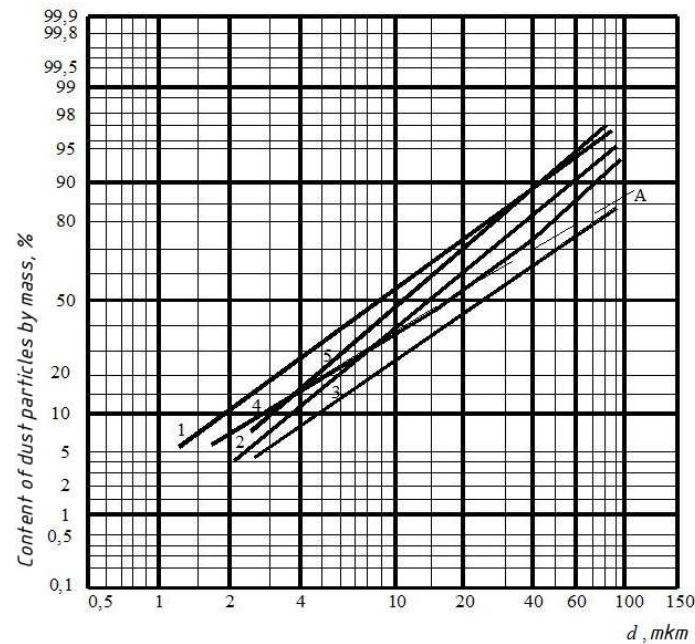


Figure 2. Disperse composition of experimental dusts

4. The basic constructive and regime parameters that influence the efficiency of dust collecting

When the authors were conducting major experiments of fractional efficiency of dust collection and water resistance of construction of the dust concentrator, the following parameters were measured:

- barometric pressure;
- temperature;
- the relative humidity in the zone of suction in the system;
- the costs of filtrating and recirculating airflows;
- static pressure in the input and output pipelines TSDC;
- the weight of the dust fed palpitates and caught the respective steps of purification;
- the time of the experiment.

The weight of the dust that was caught by the first step of TSDC₁ was determined as the weight of the dust collected by the bag filter. The weight of the dust, unloaded from the hopper counter of the

flow cyclone (Fig. 1), corresponded to the value of G_{II} . The weighting was done on an assay balance VLKT-500-M, the two-stage centrifugal dust concentrator with sensitivity is 10 mg per 1/2 division.

Filtering efficiency of the first stage η_I was calculated by the formula:

$$[\eta]_I = \frac{G_I}{G_p}; \quad (1)$$

of the second stage:

$$[\eta]_{II} = \frac{G_I}{G_p - G_I}. \quad (2)$$

The water resistance TSDC was calculated as the difference between full pressure in the inlet tangential pipe of dust concentrator 2 (Figure 1) and in the output of the second stage.

A series of parallel experiments was carried out at constant parameters of the atmospheric air (temperature, barometric pressure, relative humidity) [5].

Table 2. Table of levels of factors and effects

Code	Factors	The levels of factors			a_i	Significant
		-	0	+		
X_1	Internal diameter of annular pit D_r , m	0.3	0.32	0.34	0.125	Not
X_2	The height of the cylindrical part of the second stage h_c , m	0.2	0.275	0.35	0.24	Not
X_3	Diameter of dust ventage d_n , m	0.05	0.065	0.08	-0.243	Not
X_4	The dust concentration at the inlet, g/m^3	0.5	3	5.5	0.088	Not
X_5	The height of the hopper h_n , m	0.2	0.25	0.3	0.323	Not
X_6	Number of inlet pipe output of steam-and-gas concentrate, pieces. The depth of immersion of the exhaust pipe	1	0	2	0.468	Yes
X_7	h_{out} , m	0.1	0.2	0.3	1.028	Yes
X_8	Height of body h_k , m The height of the entrance pit in the II stage	0.75	0.875	1	0.153	Not
X_9	h_s , m	0.05	0.1	0.15	1.613	Yes
X_{10}	The flow of filtered air Q_a , m^3/sec The relative flow rate of recirculated air	700	850	1000	4.313	Yes
X_{11}	$q=Q_p/Q_a$	0.3	0.4	0.5	1.568	Yes
X_{12}	Fictitious	—	—	—	0.098	—
X_{13}	Fictitious	—	—	—	0.113	—
X_{14}	Fictitious	—	—	—	0.158	—
X_{15}	Fictitious	—	—	—	0.108	—

Factors that affect the efficiency of dust collecting were established as in the analysis of mathematical and experimental research. So the factors that influence the degree of filtration of airflow from the dust of TSDC were deduced with plans by Plackett–Burman. That made it easy to process the results, to calculate the effects independently from each other and to vary the factors at two levels.

For the application of plan type N=16 for 15 factors (N-1) to 11 valid factors, the authors added an additional 4 dummy (Table 2), which allow them to estimate the variance of observation errors. According to [5] for each of the factors that was included in the plan of the experiment, the effects and the corresponding values of coefficients a_i were determined by assessment (Table 2), as well as the condition of importance $a_i \geq 0.338$. As one can see, important factors are $X_6, X_7, X_9, X_{10}, X_{11}$ [4].

This series of experiments allowed one to establish the efficiency of the dust of the TSDC and the predominant effect, the flow of filtered air (X_{10}), the relative flow rate of recirculated air (X_{11}), the height of the entrance pit in the II stage (X_9), the depth of immersion of the exhaust pipe (X_7), the number of inlet pipe output of the steam-and-gas concentrate (X_6) [5].

The value of coefficient $a_6 = 0.468$ of factor X_6 exceeds the level of significance at 38%. The excess of the significance level for the other factors are, %: $X_7 - 205$, $X_9 - 377$, $X_{10} - 1176$, $X_{11} - 363$. Other factors X_2 , X_6 , X_8 were fixed at the lower levels, factors X_4 , X_5 – at middle; and X_1 , X_3 – at the upper levels (Table 2).

Factor X_6 has a minimal effect on the efficiency of dust collecting; therefore, in subsequent experiments the authors took into account only factors X_7 , X_9 , X_{10} , X_{11} .

The water resistance of the two-stage dust concentrator was determined by the plan of Plackett–Burman, losses which depend on the same factors X_7 , X_9 , X_{10} , X_{11} . The strongest influence on the pressure loss was exerted by the flow of filtered air.

5. The construction of the mathematical model of the process dust collection

A mathematical model of the process dust collection was built as a composite rotatable design (CCRD) of the four factorial experiment. Five levels of variation factors were established. The new code of factors and the variation levels are presented in table 3.

Table 3. Region of the factor space CCRD

Code	Factors	Step	The variation levels				
			-2	-1	0	+1	+2
X_1	The height of the entrance pit at the II stage, mm	50	20	70	120	170	220
X_2	The depth of immersion of the exhaust pipe, mm	50	0	50	100	150	200
X_3	The flow of filtered air, m ³ /hours	100	700	800	900	1000	1100
X_4	The relative flow rate of recirculated air	0.1	0.2	0.3	0.4	0.5	0.6

The following was determined as the response function:

- $[\eta]_{TSDC}$ - the overall efficiency of dust collection TSDC;
- $[\eta]_I$ - the efficiency of the first stage of filtering (cyclone chamber);
- $[\eta]_{II}$ - the efficiency of the second stage of cleaning (a counterflow cyclone).

Water resistance of cyclone ΔP_{TSDC} was determined in the process of pilot experiments and calculated as the difference between full pressure, the first input and the output of the second stages of the dust concentrator.

A sequence of experiments was conducted in accordance with the table of random numbers [6] that compensate for systematic errors in the experiment [7]. The value of the coefficients in the regression equations was obtained in the computer program. Validity check of the obtained results of the experiment equations was performed using F-test and the significance of the coefficients by Student's criterion [8]. The final form of the equations is presented in formulas 3, 4, 5 and 6:

$$[\eta]_{TSDC} = 91.15 - 0.18 \cdot X_1 + 0.26 \cdot X_2 + 1.08 \cdot X_3 + 0.29 \cdot X_4 + 0.22 \cdot X_1 \cdot X_2 - 0.88 \cdot X_1 \cdot X_4 - 0.79 \cdot X_{12} - 0.5 \cdot X_{22} - 0.44 \cdot X_{42} - 0.13 \cdot X_{42} \quad (3)$$

$$[\eta]_I = 89.0 - 0.74 \cdot X_1 + 1.05 \cdot X_3 + 1.01 \cdot X_4 + 0.19 \cdot X_1 \cdot X_2 + 0.37 \cdot X_3 \cdot X_4 - 0.44 \cdot X_{12} - 0.6 \cdot X_{32} - 0.12 \cdot X_{42} \quad (4)$$

$$[\eta]_{II} = 56.94 - 5.18 \cdot X_1 + 1.73 \cdot X_2 + 4.01 \cdot X_3 + 1.6 \cdot X_4 + 3.79 \cdot X_1 \cdot X_4 - 1.6 \cdot X_3 \cdot X_4 - 5.45 \cdot X_{12} - 4.16 \cdot X_{22} - 1.37 \cdot X_{32} - 2.73 \cdot X_{42} \quad (5)$$

$$\Delta P_{TSDC} = 1605 - 64 \cdot X_1 + 66 \cdot X_2 + 532 \cdot X_3 - 71 \cdot X_4 + 69 \cdot X_{12} + 62 \cdot X_{22} + 78 \cdot X_{32} \quad (6)$$

6. Conclusions

The flow of filtered air (X_3) is having a global impact on the main part of the capture efficiency TSDC; moreover, the value of $[\eta]_{TSDC}$ with increasing X_3 increases due to the first and second stage of filtration. The growth efficiency of dust collecting the first $[\eta]_I$ and second $[\eta]_{II}$ stage of filtration with increasing the flow of filtered air influences positively the process of separation of dust particles effect t . This can be explained by the increase of velocities of the gas [9, 10]. The increase factor, the relative flow rate of recirculated air X_4 at the first stage of filtrating $[\eta]_I$ the efficiency of air filtration increases due to the lower velocity of the gas flow at the second stage of filtrating $[\eta]_{II}$, the filtrating efficiency is reduced. The increase in geometric characteristics X_1 (the height of the entrance pit in the II stage) and X_2 (the depth of immersion of the exhaust pipe) can cause an erratic decrease or increase of overall efficiency of the two-stage dust concentrator. A decrease of flow of filtered air (X_3) decreases water resistance $TSDC \Delta P_{TSDC}$ at the first stage and reduced at the second stage of filtrating. Therefore, the use of factors X_1 , X_2 and X_3 limits the overall effectiveness of the two-stage dust concentrator [5].

The resulting regression equation allowed optimization of the dust collection process.

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