This article presents experimental research results data and optimization of a two-stage cyclone-type dust concentrator and the design and operating parameters data. To resolve the assigned optimization task, SUMT (Sequential Unconstrained Minimization Technique) was applied. The Davidon-Fletcher-Powell method was used to find the minimum of a function, afterwards the iterative procedure was realized. The results were processed using joint analysis of the characteristic curve with regression equation of dust collecting efficiency and liquid resistance.

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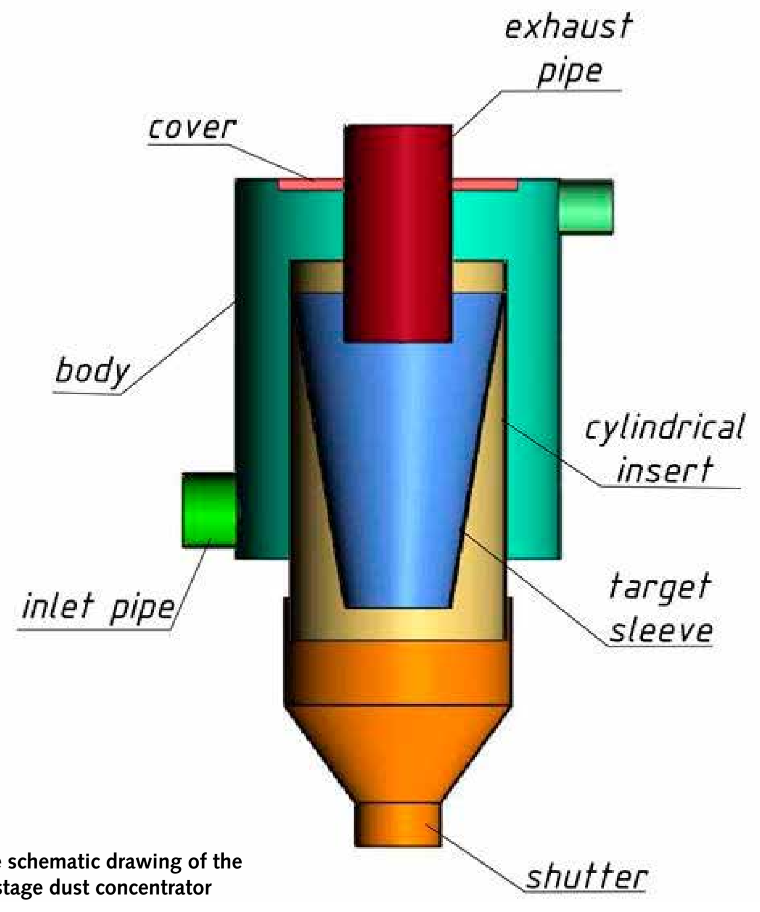
Optimization of the two-stage cyclone-type dust concentrator – design and operating parameters



1 The schematic drawing of the two-stage dust concentrator

All authors

1 Introduction

A large part of the technological processes of building materials enterprises, as well as a number of other branches of industry are the mechanical manipulation and material handling processes, related to the gravity flow of large amounts of granular materials on closed gutters and accompanied by intensive release of dust.

Traditional aspiration systems, characterized by volumetric emission of dusty air, are widely used for localization of sources of dust emissions. Reduction of the power consumption and the dust emission of the system can be achieved as a result of purification of the aspirated air in centrifugal dust concentrators – cyclones, the conclusion of the trapped dust of which is carried out with part of the carrier gas stream [1].

The working principle of the two-stage cyclone-type dust concentrator is ejection of particles from the gas-dust flow by centrifugal force (Figure 1). Through the inlet pipe into the cyclone part of the dust concentrator between the body and the cylindrical insert a polluted gas and dust stream is fed. Particles of dust by centrifugal force hit the walls of the body and are carried out from the internal cavity of the two-stage dust concentrator by the air flow through the annular cavity and then enter the recirculation line. Part of the air flow, which remained after the first stage of purification, is directed to the countercurrent cyclone for the second stage of purification through the annular gap between the upper end of the cylindrical insert and the lid.

2 Methodology of determination of the two-stage cyclone-type dust concentrator optimal design parameters

As a result of the experimental research, it was found that the flow rate of the air supplied for cleaning exerts a global influence on the main part of the efficiency of the two-stage dust concentrator capture and the value of η_{TSDC} increases with the growth in the flow rate of the filtered air due to the first and second stages of purification. Increase in dust collection efficiency of the first h_I and second η_{II} stages of purification with a growth in the flow rate of the gas supplied for purification have a positive impact on the dust separation process [2, 3].

Growth of the factor of the relative consumption of recirculation air in the first stage of cleaning h_I increases the efficiency of air purification, the cleaning efficiency is reduced due to the decrease in the velocity of the gas flow in the second stage η_{II}. Increase the geometric characteristics of the height of the entrance pit in the second stage and the depth of immersion of an exhaust pipe can induce a random decrease or increase in the overall efficiency of the two-stage dust concentrator. Growth of the flow rate of the filtered gas increases the hydraulic resistance of the two-stage dust concentrator in the first stage and lowers in the second stage of purification. Therefore, the use of factors X_1, X_2 and X_3 limits the overall efficiency of the two-stage dust concentrator [4].

Optimization of the two-stage dust concentrator design and operating parameters was reduced to the determination of the values of the factors entering into the regression equation (1), when the maximum value of the response function is achieved – the efficiency of dust collection of the two-stage dust concentrator [5].

$$[eta]_{TSDC} = 91.15 - 0.18 \cdot X_1 + 0.26 \cdot X_2 + 1.08 \cdot X_3 + 0.29 \cdot X_4 + 0.22 \cdot X_1 \cdot X_2 - 0.88 \cdot X_1 \cdot X_4 - 0.79 \cdot X_{12} - 0.5 \cdot X_{22} - 0.44 \cdot X_{12} - 0.13 \cdot X_{42} \quad (1)$$

However, the maximum possible efficiency of dust collection of the two-stage dust concentrator can take place at the values of the factors X_1, X_2, X_3, X_4, which are unacceptable for the operation conditions for the following reasons:

1. Optimal relative recirculation airflow rate (X_4) in most cases, in practice, will not correspond to the required flow rate in the recirculation line of the aspiration system.
2. Optimal values of factors may be unacceptable, because they can create the unacceptably high hydraulic resistance of the machine. This, above all, refers to the flow of filtered air (X_3), which exerts a dominant influence both on the cleaning efficiency (1), and on the hydraulic resistance (2) of the two-stage dust concentrator:

$$\Delta P_{TSDC} = 1605 - 64 \cdot X_1 + 66 \cdot X_2 + 532 \cdot X_3 - 71 \cdot X_4 + 69 \cdot X_1^2 + 62 \cdot X_2^2 + 78 \cdot X_3^2 \quad (2)$$

Therefore, in the future factor X_4 was excluded from consideration and fixed at certain levels of variation. And the optimal values of the factors X_1, X_2, X_3 were limited to the maximum possible level of the hydraulic resistance of the machine [4].

3 Optimization task solution

To resolve the assigned optimization task, SUMT (Sequential Unconstrained Minimization Technique) was applied firstly proposed by Carroll [6] and which has been developed further by Fiacco and McCormick [7, 8], which is based on the idea of converting the task of minimizing a function:

$$z = f(\vec{x}) \quad (3)$$

with the appropriate restrictions imposed on x, in the problem of finding the minimum without constraints of the function:

$$Z = f(\vec{x}) + P(\vec{x}) \ldots \quad (4)$$

The function P(x) is a penalty function. It is necessary that, in violation of restrictions, it "fine" the function Z, increasing its value. In this case, the minimum of the function Z will be within the constraint area.

The penalty function P(x) is written as follows:

$$P(x) = r \sum_{j=1}^{m} \frac{1}{C_j(\vec{x})} \quad (5)$$

where $C_j(x)>0$ – the constraints imposed on x,
m – number of constraints,
r – the positive value.

If the imposed constraints are of the form $h(x) \leq 0$, then they are written as $-h(x) \geq 0$.

With allowance for (5), the function $Z=\varphi(\vec{x}, r)$ takes the form:

$$Z = \varphi(\vec{x}, r) = f(\vec{x}) + r \sum_{j=1}^{m} \frac{1}{C_j(\vec{x})} \quad (6)$$

If $\vec{x}$ takes valid values for which $C_j(\vec{x}) \geq 0$, then Z takes values that are greater than the corresponding values of $f(\vec{x})$, and the difference can be reduced by the fact that r can be a very small value. But if x takes a value that, while acceptable, is close to the

Table 1 The range of the factor space of the central composite rotatable plan of the four factor experiment

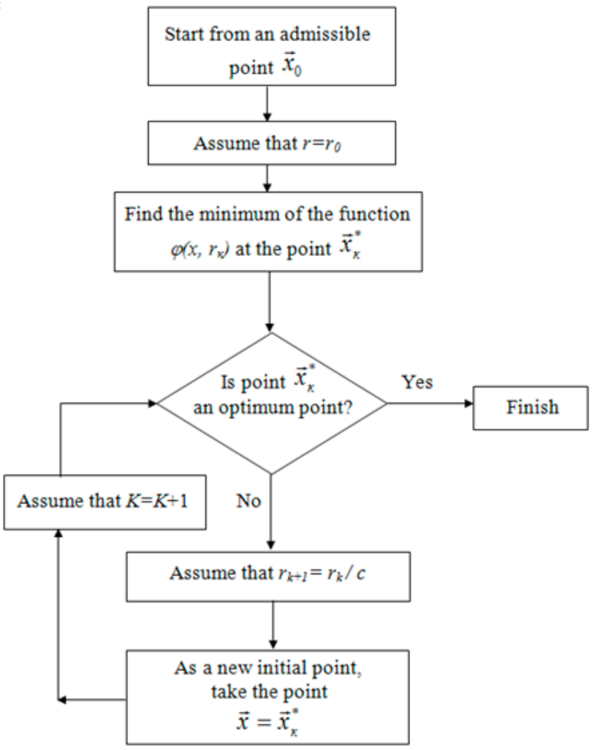
Code	Factors	Step	Variation levels				
			-2	-1	0	+1	+2
X_1	Height of the entrance pit in the II stage [mm]	50	20	70	120	170	220
X_2	Depth of immersion of an exhaust pipe [mm]	50	0	50	100	150	200
X_3	Flow of filtered air [m³/h]	100	700	800	900	1000	1100
X_4	Relative recirculation airflow rate	0.1	0.2	0.3	0.4	0.5	0.6

boundary of the constraint area, or at least one of the functions $C_j(\vec{x})$ is close to zero, then the value of the function $P(\vec{x})$ and hence the value of the function Z will become very large. Thus, the effect of the function $P(\vec{x})$ is to create a "crest with steep edges" along each boundary of the constraint area. Therefore, if the search starts from an admissible point and the minimum of the function $\varphi(\vec{x},r)$ is searched without any restrictions, then the minimum of the original function (3) will, of course, be reached within the admissible domain for the constrained task. Assuming that r is a sufficiently small value for the effect of the function $P(\vec{x})$ to be small at the minimum point, we can make the minimum point of the function $\varphi(\vec{x},r)$ without constraints coinciding with the minimum point of the function f(x) with constraints.

Optimization of the two-stage dust concentrator design and operating parameters involves finding the maximum of the function (3)

$$\eta_{TSDC} = f(X_1;\ X_2;\ X_3;\ X_4)\ .$$

SUMT, the block diagram of which is shown in Figure 2, assumes minimization of the function $f(\vec{x})$.



2 The block diagram of SUMT

Therefore, as a function f(x) a function

$$f(\vec{x}) = -\eta_{TSDC} = -f(X_1; X_2; X_3; X_4) \dots \quad (7)$$

was adopted, with the factor X_4 being fixed at certain levels (-1...+1).

The penalty function with eight imposed constraints

$$P(x) = r \cdot \Big(\frac{1}{X_1+1} + \frac{1}{1-X_1} + \frac{1}{X_2+1} + \frac{1}{X_2-1} + \frac{1}{X_3+1} + \frac{1}{X_3+1} + \frac{1}{X_3-1} + \frac{1}{\Delta P_{TSDC}-A} + \frac{1}{B-\Delta P_{TSDC}}\Big) \quad (8)$$

where ΔP_{TSDC} – the hydraulic resistance of the two-stage dust concentrator, calculated by the expression (2);

A and B – respectively, the lower and upper levels of the set hydraulic resistance of the machine.

The sum of the expressions (7) and (8) is the initial equation $\varphi(\vec{x},r)$, the solution of the minimization task of which makes it possible to obtain the optimal values of the factors X_1, X_2, X_3 for a given value X_4 and is performed as follows.

Given the initial point $\vec{x}_0$ defined by the values X_1, X_2, X_3, and by checking for its admissibility, we form the function $\varphi(\vec{x},r)$, assuming that $r=r_0=1$. After finding the minimum of the function $\varphi(\vec{x}_0,r_0)$ at the point $\vec{x}_k^*$ using Davidon-Fletcher-Powell method [7], a new function $\varphi(\vec{x},r)$ is formed for which $r=r_0/10$, and $\vec{x}=\vec{x}_k^*$. After that a repeated operation of minimization follows.

Thus, an iterative procedure is performed. At the k step, the function $\varphi(\vec{x},r_k)$ is minimized, the minimum of which is at the point $\vec{x}^*_k$ and is used as a subsequent point of the iterative procedure for minimizing the function $\varphi(\vec{x},r_{k-1})$, where $r_{k+1}=r_k/10$.

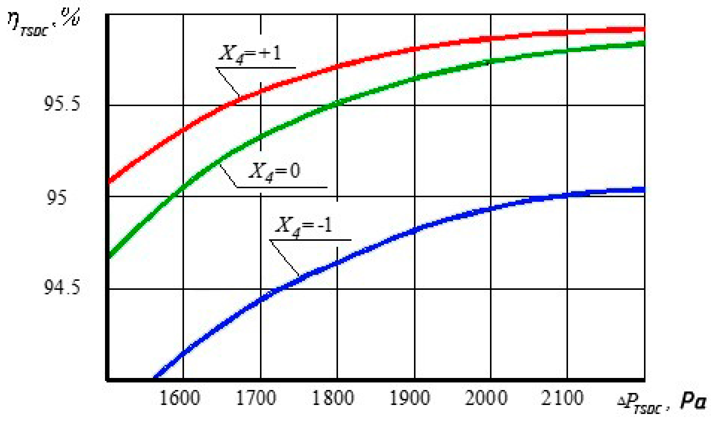
The sequence r_k decreases and tends to zero, hence the sequence of points of minima converges to the solution of the task of minimizing the function (7).

Proceeding from the above, a program was developed for calculating the optimal values of the factors X_1, X_2, X_3 of the regression equation (1) the efficiency of the dust collecting of the two-stage dust concentrator.

The results of calculating the optimal values of the factors X_1, X_2, X_3, for a number of fixed values of the relative recirculation airflow rate (X_4) and various limitations of the maximum possible hydraulic resistance of the two-stage dust concentrator are presented in the Table 2.

Analysis of the presented calculation results shows that for each value of the maximum possible hydraulic resistance of the machine and the level of variation in the relative recirculation airflow rate, there is a well-defined set of optimal values of factors X_1, X_2, X_3. Moreover, the values of these factors vary in a rather wide range.

Consequently, the optimum values of the height of the entrance pit in the second stage (X_1) and the depth of immersion of an exhaust pipe (X_2) of the two-stage dust concentrator will depend on the specified operational parameters of the machine: hydraulic resistance ΔP_{TSDC}, flow of filtered air (X_3) and relative recirculation airflow rate (X_4). This greatly complicates the technique of engineering calculation of the proposed machine. Therefore in the future an attempt will be made to fix these factors at certain levels with the exception of factor X_4, because its value will be equal to the required flow rate in the recirculation line of the aspiration system [9].



3 Dependence of the efficiency of dust collection of the TSDC from the hydraulic resistance at optimal values of X_1, X_2, X_3

4 Implications

Analysis of the dependence of the maximum possible dust collection efficiency of the TSDC on the set level of hydraulic resistance (Figure 3) [10] showed that the optimal value of the hydraulic resistance of the TSDC is 1800...1900 Pa.

Given a level of ΔP_{TSDC} = 1800 Pa, combinations of the optimal values of factors X_1, X_2, X_3 were determined with X_4 varying from -1 to +1 in steps of 0.1 (Figure 4).

Table 2 The results of calculating the optimal values of factors at a given level of the hydraulic resistance of the two-stage dust concentrator

Parameter		Level of the hydraulic resistance of the TSDC [Pa]						Level of X_4
		1600	1700	1800	1900	2000	2200	
Optimal factor values	X_1	0.321	0.289	0.277	0.269	0.267	0.262	-1
	X_2	0.098	0.124	0.147	0.155	0.196	0.266	
	X_3	-0.12	0.05	0.222	0.392	0.552	0.853	
Efficiency of the TSDC [%]		94.23	94.51	94.7	94.83	94.94	95.08	
Optimal factor values	X_1	-0.016	-0.029	-0.037	-0.047	-0.073	-0.08	0
	X_2	0.084	0.109	0.131	0.146	0.154	0.223	
	X_3	0.022	0.156	0.328	0.492	0.649	0.943	
Efficiency of the TSDC [%]		95.24	95.33	95.49	95.61	95.70	95.81	
Optimal factor values	X_1	-0.23	-0.249	-0.26	-0.268	-0.292	-0.33	+1
	X_2	0.063	0.083	0.099	0.124	0.145	0.176	
	X_3	0.08	0.253	0.419	0.579	0.73	0.999	
Efficiency of the TSDC [%]		95.39	95.56	96.69	95.80	95.87	95.69	

Table 3 Operational characteristics of the TSDC under optimal and accepted combinations of factor values X_1, X_2, X_3

Factors X_1, X_2, X_3		Optimal	Accepted	Optimal	Accepted
Operational characteristics of the TSDC		Efficiency of dust collection [%]		Hydraulic resistance [Pa]	
Level of variation of the relative recirculation airflow rate (X_4)	-1	94.7	95.26	1800	1901
	0	95.49	95.46	1800	1830
	+1	95.69	95.4	1800	1759

Table 4 The ratio of the basic geometric dimensions (in fractions of D_K) of the TSDC

#	Name	Designation	Value
1	Body diameter	D_k	1
2	Diameter of the cylindrical insert	D_i	0.63
3	Diameter of an exhaust pipe	D_{out}	0.31
4	Internal diameter of annular pit	D_r	0.85
5	Diameter of dust ventage	d_n	0.2
6	Height of body	h_k	1.9
7	Height of the entrance pit in the II stage	h_s	0.33
8	Height of the cylindrical part of II stage	h_c	0.5
9	Depth of immersion of an exhaust pipe	h_{out}	0.27
10	Height of the hopper	h_h	0.6…0.7
11	Length of body	l_c	1.4

After a joint analysis of the obtained graphical dependencies with the regression equations of the dust collection efficiency (1) and hydraulic resistance (2) of the TSDC, the following combination of factor values was adopted: $X_1 = 0.15$; $X_2 = 0.25$; $X_3 = 0.4$.

The regression equations (1) and (2) in this case take the following form:

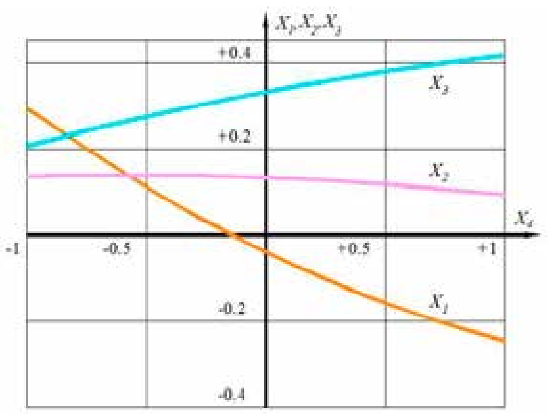
$$[eta]_{TSDC} = 95.46 + 0.07 \cdot X_4 - 0.13 \cdot X_4^2 \qquad (9)$$

$$\Delta P_{TSDC} = 1830 - 71 \cdot X_4 \qquad (10)$$

5 Conclusions

The data presented in Table 3 show that the decision made allows a significantly increase in the efficiency of dust collection in the area of low recirculation airflow rate, in addition, the efficiency of the TSDC becomes more stable and depends less on X_4, which is confirmed by the obtained dependence (9). The increase in hydraulic resistance is insignificant (5.5 %), and in the area of high values of the relative recirculation airflow rate there is even a drop in the hydraulic resistance of the machine, which explains a small decrease in the overall efficiency of dust collection.

Taking into account the step and the variation levels (Table 1), the optimal values of the factors after decoding were: the height of the entrance pit in the second cleaning stage (X_1) – h_s = 133 mm, the depth of immersion of an exhaust pipe (X_2) – h_{out} = 108 mm, the airflow rate for cleaning (X_3) - Q_a = 940 m³/hours.



4 Dependence of the optimal values of the factors X_1, X_2, X_3 from the factor X_4 at the level of $\Delta P_{TSDC} \leq 1800$ Pa

The ratio of the basic geometric dimensions of the optimized design of a two-stage cyclone-type dust concentrator with a body diameter D_k is shown in Table 4. The optimal air velocity in the section of the TSDC was determined by the formula:

$$V_{opt} = \frac{(2-q) \cdot Q_a}{0.785 \cdot D_k^2} \qquad (11)$$

where q – relative recirculation airflow rate.

Considering the insignificant effect of the relative recirculation airflow rate on the cleaning efficiency of the two-stage dust concentrator, the optimal fictitious gas velocity in the section of the machine was calculated for q = 0.4 and amounted to 3.33 m/s [4].

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