The air separator design improving

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Abstract. The article addresses the issue of grinding cement clinker in ball mills. The world various activities increasing the efficiency of the ball mills with low efficiency are presented and offered in the article. An effective way to increase the efficiency of ball mills is to transfer them to a closed circuit of work with air separators. To improve the air separator efficiency, the article proposes a modified aerodynamic design of the air separator. The parameters of the components included in the aerodynamic scheme, such as cyclones, dampers, a fan, a rotary valve and so on, are determined. A mathematical model of the modified separator operation recorded for the circulation circuit and the main direction of the path are proposed. According to the proposed method, an industrial air separator was calculated to obtain the fine powders. It is shown that by controlling the proposed aerodynamic scheme gas material tract air separator parameters, the separation process can be controlled.

1. Introduction
In modern conditions around the world, according to the U.S. Geological Survey, since 2013 more than 4 billion tons of cement has been produced annually. Cement production is the basic construction industry of any country [1]. The main technological redistribution in cement production is its fine grinding clinker with additives in various types of mills. At the same time, grinding consumes up to 40% of all electricity consumed in cement production [2]. Grinding cement clinker is carried out in various types of grinding plants [3, 4]. However, ball mills are still the main grinding apparatus for the cement production grinding products [5]. They cover up to 60% of all cement production needs for reliable grinding equipment [6]. A significant drawback of traditional ball mills are significant energy losses due to heating of grinding media (up to 80%), mill vibration, noise, wear of the inside mill equipment and balls, etc. [7]. This leads to a significant decrease in the ball mill output and the overspending of the energy consumed by the ball mill. One of the effective ways to increase the ball mills efficiency is to transfer them to a closed circuit of work with air separators [1, 8, 9]. On the other hand, the use of separators does not fully solve the issues of increasing the cement grinding efficiency. Since its appearance, the design of air separators went through 3 stages [10], increasing the efficiency of their work from 30 ... 35 % to modern 65...80 % [6, 11]. However, these separator performance indicators cannot be called acceptable. With this air separator operation, a large number of coarsens appears. That increases the size of the transport devices, increases their energy consumption and metal expenditure [12, 13].

2. Theoretical
To improve the air separator efficiency, we propose to change the aerodynamic configuration of the air separator (Figure 1). The changes that we offer are: a rotary valve 5, to block the air flow into the air separator, a pipe for fresh air intake 6, a branch pipe for discharge of separation air and a separation filter, for cleaning the separation air. The main parts of the gas path of the separator are: air separator 1, cyclone 2, fan 3, separation filter 4, rotary valve 5, pipe for fresh air inlet 6, flues including bends 7 and tees 8 and 9.

Due to this, the aerodynamic resistance of the separator is only about 1700 Pa, which corresponds to coefficient of local resistance (CLR), referred to the full cross section of the separator $F_s = 11.93 \, \text{m}^2$ under the normal operating conditions $Q = 18 \, \text{m}^3/\text{s}$, $t = 62{}^\circ\text{C}$, $\rho = 0.9 \, \text{kg/m}^3$, $\zeta_s = 50$. This is exactly the value of the CLR recommended in the reference book [14] for direct-flow cyclones.

The dynamic separator considered as an example of a separator is equipped with two $TsN$-15 cyclones with a diameter of 2 m each. The coefficient of the cyclones' local resistance $TsN$-15 is:

$$\zeta = 155 \cdot 0.86 + 35 = 168.3$$  \hspace{1cm} (1)

Figure 1. The proposed aerodynamic scheme of the separator gas tract

A centrifugal fan with a sufficiently large capacity is used as a stimulator of the movement of the gas flow in the gas path of the separators. $Q = (40 \ldots 80) \, 000 \, \text{m}^3/\text{h}$, $p = 10.4 \ldots 6.6 \, \text{kPa}$ [15]. The aerodynamic characteristic of the fan in its working area can be approximated by the following quadratic dependence:

$$\Delta p_f = 15.124Q^2 + 163.495Q + 10477.385 = -10.5G^2 + 136.2G + 104477.36$$  \hspace{1cm} (2)

where $Q = G/\rho$, $\rho = \rho(t = 20{}^\circ\text{C}) = 1.2 \, \text{kg/m}^3$.

As a dust collector can be used fabric (bag) filters of various types. Below, for the calculations, we take the average value of the filter resistance $\Delta p_{fi} = 1450 \, \text{Pa}$.

The modification of centrifugal air separators proposed in this work involves the installation of a rotary single-leaf butterfly valve (rotary valve) in the gas duct after the filter (Figure 2).
The coefficient of the rotary valve local resistance, referred to the velocity of the undisturbed flow of separation air $w_0$, is determined by the ratio [16]:

$$
\zeta_v = \frac{\Delta P}{\rho w_0^2} \frac{1+0,5(1+\sin \alpha)}{(1-\sin \alpha)^2} + \left(1 - \frac{50}{Re}\right) C,
$$

(3)

where $\alpha$ is the angle of inclination of the rotary valve, deg; $Re = w_0D_d/\mu$ – is the Reynolds number; $D_d$ is the hydraulic diameter of the duct. The empirical constant $C$ depends on the angle of the rotary valve $\alpha$ inclination.

This dependence can be approximated by a quadratic function $C = 0.084\alpha^2 - 3.15\alpha + 0.04$.

Dynamic air viscosity $\mu$ included in the Reynolds number expression depends on temperature [17]:

$$
\mu = \frac{0.0066}{384 + \frac{t}{273}} ^{1.5}.
$$

(4)

For the air separator operation normal conditions $Re \gg 1$, therefore the rotary valve local resistance coefficient dependence on the angle of rotation $\alpha$ can be represented as:

$$
\zeta_v = 0.084\alpha^2 - 3.15\alpha + 0.04.
$$

(5)

From the equation (3) it follows that with a fully open rotary valve ($\alpha = 0$), $\zeta_v = 0.04$, and with an almost closed ($\alpha = 70^\circ$), $\zeta_v = 170$.

The gas tract of the air separator is an aerodynamic network containing two nodes - exhaust and supply tees, a recirculation circuit and the main direction, which can also be considered as an external circuit that closes through the atmosphere. When the rotary valve is completely closed, only the main direction works, when the circuit is open, the circulating circuit basically works (only part of the separation air is sent to the filter, equal to the supply and intake air flow through leaks).

With a partially closed rotary valve, the air separator operates in a mixed scheme. At this time, both the circulation circuit and the main direction function simultaneously. The mathematical model of the modified separator includes ratios for the density of gas flows, equations of material and heat balances, ratios for the local resistance coefficients of a rotary valve (3) and tees, a characteristic of a fan (2), the first Kirchhoff law (the law of conservation of mass of air flows for tees) and the second Kirchhoff law (the sum of the pressure losses equal to the pressure difference created by the fan. This model is written for the circulation circuit and the main direction of the air tract [18, 19]. When the recording pressure losses, the velocities of gas flows will be expressed through their mass flow rates, air densities, and cross-sectional areas. Then, based on the second Kirchhoff law, we obtain the following equations:

– for the main direction of the air tract:
\[
\frac{\zeta_{en}}{2\rho F_{en}^2} + \frac{G^2}{2\rho_{cm} F_{ar}^2} + \frac{\zeta_s}{2\rho F_{s}^2} + \frac{G^2 \rho_{ar}}{2\rho^2 F_{ar}^2} + \frac{\zeta_r}{8\rho^2 F_{r}^2} + \frac{G^2 \rho_{r}}{2\rho^2 F_{r}^2} + \frac{2\zeta_k}{2\rho^2 F_{ar}^2} + \frac{\zeta_{bf}}{2\rho^2 F_{bf}^2} + \Delta p_{f} + \zeta_{as} \frac{G_i^2}{2\rho^2 F_{as}^2} = \Delta p_f(G);
\]

(6)

– for the circulation circuit:

\[
\frac{\zeta_{en}}{2\rho F_{en}^2} + \frac{G^2 \rho_{ar}}{2\rho^2 F_{ar}^2} + \frac{\zeta_s}{2\rho F_{s}^2} + \frac{2\zeta_k}{2\rho^2 F_{ar}^2} + \frac{\zeta_{bf}}{2\rho^2 F_{bf}^2} + \frac{G^2}{2\rho_{cm} F_{ar}^2} + \frac{(G-G_i)^2 \rho_{ar}}{2\rho^2 F_{ar}^2} + \zeta_{bs} \frac{G^2}{2\rho_{cm} F_{ar}^2} = \Delta p_f(G).
\]

(7)

In the equations (6, 7), \(F_{en}\) is the cross-sectional area of the pipe for the inlet of fresh air; \(F_{ar}\) is the cross-sectional area of the duct pipe; \(F_s\) is the cross-sectional area of the separator pipe; \(F_c\) is the cross-sectional area of the cyclone pipe and \(F_{as}\) is the cross-sectional area of the exhaust pipe; \(\Delta p_f(G)\) – defines the equation of the fan characteristics recorded through the mass flow rate of separation air (2).

3. The discussion of the results

Let us consider the graph-analytical method for the approximate engineering calculation of the aerodynamic characteristics of a separator operating according to a mixed flow-circulation scheme. As noted above, the primary objective of the proposed method for controlling the aerodynamic properties of the separator gas tract is to reduce the temperature of the separation process and the finished product to 90...105°C and achieve a certain vacuum in the separator itself [20].

Let us consider as an example the calculation of the air separator operation mixed mode, which can be realized as a result of the reconstruction proposed in this work.

At a temperature of separation air \(t = 105^\circ C\) \(p = -52\) \(Pa = -5.3\) mm of water column, i.e. the zero point is in the exhaust tee in front of the separator, and the separator itself operates under vacuum.

The calculations also show that with a constant operation of the fan, an increase in the resistance of the rotary valve and the transition to a mixed separation mode leads to a decrease in the separation air consumption to 7%. This also leads to a change in its composition, i.e. mass fraction of fresh air \(K\).

In Figure 3 shows the relationship between the angle of the rotary valve and the fraction of fresh air entering the air separator. It can be seen that with increasing angle of the rotary valve, the proportion of fresh air entering the separator increases.

\[\text{Figure 3. The dependence of the fresh air proportion in the separation air from the rotary valve angle}\]

It was also established that the relationship between the rotary valve rotation angle and the performance indicators of the separator is very strong. With an increase in the rotation angle by only a
few degrees, the fresh air influx sharply increases, the temperature of the separation process and the finished product decrease (Figure 4). And after $\alpha = 70^\circ$, the parameter $K$ is close to 1.

![Figure 4](image)

**Figure 4.** The finished product temperature dependence from the rotary valve installation angle

Figure 5 shows the dependence of the vacuum in the separator chamber on the rotary valve angle. It can be seen here that with an increase in the parameter $\alpha$, the vacuum in front of the air separator increases.

![Figure 5](image)

**Figure 5.** The dependence of the separation air pressure at the separator inlet from the rotary valve angle: 1 - calculated data; 2 – the data obtained as a result of the experiment.

4. **Summary**

At a rotation angle of $\alpha = 85^\circ$, a direct-flow mode of operation of the air separator is established, in which its entire path operates under vacuum (the vacuum in front of the separator reaches its maximum value and amounts to -142 Pa) and the temperature of the separation air decreases to 90°C.

In the direct-flow mode of the air separator operation due to the residual cement dust in the separation air, the separation efficiency is increased. But maintaining this mode requires large additional energy costs for cleaning the spent separation air before it is released into the atmosphere and for heating the fresh air entering the workshop during the cold season. The calculations showed that the maximum deviation from the data obtained at the experimental setup does not exceed 8.4%.

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