Estimation of Rectangular Separator Efficiency

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Abstract. Gas cleaning systems are used in many industries and in everyday life. For example, trapping particles and droplets from process gases; air cleaning in spray booths; separation of particles in pneumatic transport systems; cleaning of air supplied to power plants. Typically, the main element of this system is a filter or a cyclone. Cyclones create great hydraulic resistance and cannot catch small particles. Filters, after a while they clog, they cannot be restored and they need to be changed. Therefore, the authors have developed a device capable of catching small particles with little hydraulic resistance. It has a simple construction. It lacks small parts and small channels. The device can be used instead of cyclones. Alternatively, it can be used to pre-purify gas flows in front of the filters. This will significantly increase the period of their replacement. The procedure of solid particles and droplets capture efficiency calculation in rectangular separators is presented. It is shown that high values of process efficiency are obtained in case of small particles separation. Recommendations on the selection of optimal technological and design parameters are suggested. If these separators are installed before the filters, they can significantly extend service life of filters.

1. Introduction

Separators are used for solid particles and droplets capturing from gas flow by means of gravity, inertia of centrifugal force. They can be used in industrial vacuum cleaners and can allow increasing the cleaning efficiency.

Underway vehicle bodies machining painting chambers are used. Great number of costly filters is installed in these chambers for cleaning air by removing spray overage and dust, entered from outer space [1-5]. Using proposed separators allows enhancing a purification system as well as extending a service life of filters.

Last years the purpose of non-waste processing technology development becomes actual due to large amount of hydrocarbon wastes. The most preferred way of solving this problem is gasification of wastes which allows to receive gas similar to natural. Nonetheless, solid fuel gasification goes along with emission of great number of solid particles. Obviously, such gas can’t be used directly because of deposits formation on the cell surfaces which gas passes through. Using of separators allows solving this problem [6-9].

Similar problem appears during the natural gas transport. Water vapor availability in natural gas decreases its calorific power and contributes to hydrate forming. Also at low temperature the liquid, ice and hydrate plugs are appeared. Therefore, the main purpose of gas refining is in removal of...
moister and foreign matter from gas. Using of throttle devices is possible for gas purification, but thereby gas total pressure drop begins that is not favorably in thermodynamical aspect [10-17].

In paper [18] the construction of rectangular separator and results of solid particles and droplets capturing process study with support of software package are presented. The authors propose the estimating method of efficiency calculation based on solution of relatively simply equations.

2. Calculation procedure

The purpose of this research is to investigate geometric size and operating mode depending on stage efficiency of rectangular separator. Calculation scheme of device stage is depicted in figure 1.

Equations of particle motion in cylindrical coordinates are the following [19,20]:

\[
\frac{dU_r}{d\tau} = \frac{U_0^2}{r} + \frac{3}{4} \frac{\rho_G}{\rho_L} c_a \frac{U_0}{a} (U_r - U_r),
\]

\[
\frac{dU_\phi}{d\tau} = -\frac{U_\phi U_0}{r} + \frac{3}{4} \frac{\rho_G}{\rho_L} c_a \frac{U_0}{a} (U_\phi - U_\phi),
\]

\[
\frac{dU_z}{d\tau} = -g + \frac{3}{4} \frac{\rho_G}{\rho_L} c_a \frac{U_0}{a} (U_z - U_z),
\]

\[
\frac{dr}{d\tau} = U_r, \quad \frac{d\phi}{d\tau} = \frac{U_\phi}{r}, \quad \frac{dz}{d\tau} = U_z,
\]

where \( U_0 \) – relative, \( U_r \) – radial, \( U_\phi \) – tangential and \( U_z \) – axial velocity of particle components, m/sec; \( \rho_G \) – density of gas, kg/m³; \( \rho_L \) – density of liquid, kg/m³; \( c_a \) – aerodynamic drag coefficient; \( a \) – particle diameter, m; \( g \) – acceleration of gravity, m/sec²; \( W_\phi, W_r, \) and \( W_z \) are the tangential, radial, and axial velocities of air, m/sec; \( \phi, r, \) and \( z \), coordinates of particle in a cylindrical coordinate system; \( \tau \) – flight time, sec.

The initial conditions for set of equations are:

\[
\left(U_r(0) = U_{r0}, \quad U_\phi(0) = U_{\phi0}, \quad U_z(0) = U_{z0}, \quad r(0) = R_d, \quad z(0) = z_0, \quad \phi(0) = \phi_0, \right)
\]

where \( z_0 \) – distance from pattern origin, m; \( r \) – duration of particle flight, sec; \( r \) – current radius in device workspace, m.

As supposed, the only small particles will be captured in separator and therefore their motion by means of gravity can be neglected. This allows using the two-dimensional model:

\[
\frac{dU_r}{d\tau} = \frac{U_0^2}{r} + \frac{3}{4} \frac{\rho_G}{\rho_L} c_a \frac{U_r}{a} (-U_r)
\]
The following assumptions are allowed: gas axial velocity and dependence of particles on gas flow structure are neglected due to low concentration of particles.

To calculate the tangential velocity such relation is usually used:

\[ W_\varphi = W_{cp} \left( \frac{r}{r_{cp}} \right)^n, \]

where \( r_{cp} = \frac{(b_1 + b_2)}{2} \) – the mean radius, m; \( b_1 \) – the bead width, m; \( b_2 \) – the air passage distance, m; \( W_{cp} \) – average air velocity, m/sec; \( n \) – index.

The initial conditions which are used for equations solving are: \( U_\varphi(0) = 0 \); \( U_r(0) = 0 \); \( \varphi(0) = -\pi/2 \); \( r = r_0 \), where \( r_0 \) – flight start coordinate, m. Initial radius of particle location is selected from the condition of particle deposition on upper device edge (in C point, figure 1).

The aerodynamic resistance coefficient \( c_a \) is calculated with equation:

\[ c_a = \frac{24}{Re} + \frac{4}{\sqrt{Re}}, \]

where \( Re = \frac{U_0 a}{\nu_G} \) – Reynolds number for particle; \( a \) – particle diameter, m; \( \nu_G \) – kinematic viscosity index, m²/sec.

C point (figure 1) coincides with lower edge of rectangular separator element and complies with the track end of particle, which blows out from A point. Particle separation efficiency is determined from the assumption that particles, which blow out below initial radius, are captured in the separator stage, but other particles fly into the next stage. Based upon this assumption particle separation efficiency in single stage can be determined in the following way:

\[ \eta = \frac{G_1}{G_0}, \]

where \( G_0 \) – flow rate of gas steam through one side of separator stage, m³/sec; \( G_1 \) – flow rate of gas in which particles are captured, m³/sec.

Flow rate of gas steam through one side of separator stage can be obtained as:

\[ G_0 = x \int_{h/2}^{b_1/2 + b_2} W_\varphi(z) dz. \]

Based on equation (1):

\[ G_0 = x \int_{h/2}^{b_1/2 + b_2} W_{cp} \left( \frac{r}{r_{cp}} \right)^n dz. \]

Then

\[ G_0 = \frac{x W_{cp}}{r_{cp}^{n+1}} \left( \frac{b_1}{2} + b_2 \right)^{n+1} - \left( \frac{b_1}{2} \right)^{n+1}, \]

where \( x \) – separator height, m.

Similarly, the flow rate of gas in which particles are captured is the following:
\[
G_1 = \frac{xW_{cp}}{r_{cp}^n(n+1)} \left( \left( \frac{b_1}{2} + b_2 \right)^{n+1} - r_{\text{cur}}^{n+1} \right),
\]

where \( r_{\text{cur}} \) – current radius, m.

Then efficiency can be determined by the following equation

\[
\eta = \frac{\left( \left( \frac{b_1}{2} + b_2 \right)^{n+1} - r_{\text{cur}}^{n+1} \right)}{\left( b_1^2 + b_2^2 \right)^{n+1} - \left( \frac{b_1}{2} \right)^{n+1}}.
\]

For estimating calculations, we can accept that \( n = 1 \) according to previously conducted accounting through application programs. Consequently, it can be written:

\[
\eta = \frac{b_1^2 + 4b_1b_2 + 4b_2^2 - 4r^2}{4b_2(b_1 + b_2)}.
\]

3. Results and discussion

As a result of calculation the efficiency dependence on geometrical size of device workspace are received.

\[\text{Figure 2. Separator efficiency dependence at } W_{cp} = 10 \text{ m/sec, } b_1, \text{ mm: 1 –3; 2 –5, 3 – 7; (a) } a = 10 \mu m; \text{ (b) } b = 20 \text{ mm.}\]

In case of small size \( b_1 \) values efficiency decreases in all range of stage width values. Such significant reduction is explained by flow rate increasing of those part of gas stream in which particles are losing to settle. Centrifugal force increases but trajectory length of moving particle increases too. With increasing of \( b_1 \) a local maximum appears in efficiency dependence. Moreover, this maximum is observed at nearly constant value of stage width (figure 2a).

As in all similar devices particle capturing efficiency increases at particle diameter increment (figure 2b). When particles of 6 \( \mu m \) diameter are captured the process efficiency doesn’t practically on size \( b_1 \) value. During capturing larger particles separators with \( b_1 = 3 \) mm have the highest efficiency.

Proposed separators can be used instead of cyclone in pneumatic conveying systems. Therefore, constructions with high values of cell width have been studied (figure 3a). It was identified that
particles of 50 μm diameter are captured with efficiency of more than 0.75. Increasing of velocity up to 15 m/sec leads to efficiency raise up to 0.92 minimally. It is discovered that efficiency value of 1 can be reached after selecting the optimal values of velocity and some geometrical sizes.

The marked dependence of efficiency on technological and design parameters can’t be established, so a graph with dimensionless coordinates was drawn (figure 3b). In this case it was found that at \( b_1/b < 0.23 \) efficiency doesn’t depend on mean gas velocity. In range of \( 0.15 < b_1/b < 0.23 \) efficiency equals to 1. At values of \( b_1/b < 0.15 \) efficiency increases virtually as a linear reliance.

![Figure 3](image-url)

**Figure 3.** Separator efficiency dependence at \( a = 50 \mu m \): (a) 1, 2, 3 – \( W_{cp} = 15 \) m/sec, 4, 5, 6 – \( W_{cp} = 10 \) m/sec, \( b_1, \) mm: 1, 4 – 3; 2, 5 – 5, 3, 6 – 7; (b) \( W_{cp}, \) m/sec: 7 – 15, 8 – 10.

In conclusion, it should be noted that the proposed methodology can be used for estimating efficiency calculations when selecting the optimal values for the geometric dimensions of rectangular separators.

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