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Separation of dust particles in the low-pressure pneumatic conveying system

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Abstract. This paper focuses on the possibility of separation of dust particle created as a by-product of technological processing of composite materials. The aim was to design and verify technology for the separation of dust particles from polydisperse granular mixtures, which are created by physical-mechanical processes of materials processing (crushing, sorting, machining or surface treatment of products such as grinding or polishing the surface). Under experimental conditions, a low-pressure pneumatic conveying system was designed and tested in operation, supplemented by a powerful electrostatic dust particles separation system. The entry requirement was to design a system that would be able to work with high separation efficiency using low-pressure suction. The designed separation conveying device consists of three parts: the conveyance section for the grain material suction and conveying, the coarse grain share cyclone separator and the electrostatic precipitator of the dust particles released from the air flow. Operational capacity of the proposed technology was verified by evaluating the separation efficiency of processing the polydisperse granular mixture resulting from the crushing of laser printer toner cartridges. These contain toner powder residues, which are the source of composite dust particles. The separation efficiency of the system was monitored according to the set pressure of the air in front of the electrostatic separator. Evaluation of the results thus obtained confirmed the operational reliability of the system at low-pressure operation and the high separation efficiency of the electrostatic separator under the set operation conditions.

Key words: dust particles, electrostatic separation, low-pressure pneumatic conveying system.

INTRODUCTION

This paper focuses on the possibility of separation of dust particles created by physical-mechanical processes of materials processing. The dust particles are separated from the air flow used for dust suction and transport. The aim was to design and verify technology for the separation of dust particles from polydisperse granular mixtures with a large dispersion of size and density of particles created by the physical-mechanical process of crushing the material. The technology is designed to achieve a high dust particle separability at low volume air flow and low operating pressure throughout the system (low-pressure suction, pneumatic conveying and separation). Achieving high separability at low pressure is a prerequisite for low-energy operation of the whole technology. In the thesis, the construction solution, verification of the operational function and evaluation of dust particle separation efficiency of the proposed separation conveying device are elaborated.

Experience from various manufacturing operations shows that the presence of fine dust particles (dispersed in the air in the production environment) is a significant factor affecting the safety of operation, product quality, production economy, as well as the health and safety of workers (Tönshoff et al., 1997; Heederik et al., 2012; Kažimírová & Opáth, 2016). Emissions of dust particles are monitored as an air pollutant. These emissions are monitored at national and international levels and their permissible content is regulated in the form of emission limits for each source of the polluting dust particles (EP and Council, 2010). Industrial technologies using physical-mechanical materials processing techniques are not among the dominant sources of air pollution. On the other hand, it is necessary to address the problem of the impact of dust particles created by physical-mechanical processing of materials, as a technological, safety and hygienic risk factor of the production environment (Balout et al., 2007; Kalliny et al., 2008). Concentration of dust particles in the production environment is monitored in accordance with valid legislation (health and safety of workers) (Council of the European Communities, 1998).

Among the physicochemical properties of dust particles, important are those that affect the hygiene and safety of operation and the efficiency of separation from the environment. Significant physicochemical properties of dust particles are size distribution and particle shape, chemical and mineralogical composition and, potentially, particle resistivity (unit electric resistance) (Aksa et al., 2013). Dust particles are generally irregular in shape and their size cannot be precisely defined. Therefore, an equivalent diameter is used to determine the size. The most important physical property of dust particles observed is the so-called aerodynamic equivalent diameter. It corresponds to the size of the spherical particle of density 1,000 kg m^3 that has the same steady velocity due to the gravitational force in the ambient air as the particle observed (Kulkarni et al., 2011). From the health effect point of view, different size fractions of dust particles are defined where the aerodynamic diameter is given in micrometers (Kim et al., 2015). Particles of PM10 (particles smaller than 10 μm) to PM0.1 (particles smaller than 100 nm) are usually determined.

Processes involving crushing, sorting, machining or surface treatment of products such as grinding or polishing the surface are considered the most important sources of dust particles in the production environment (in the workplace) (Tilmatine et al., 2009). These processes result in mixtures of dust particles of submicroscopic to microscopic size of different physical and chemical properties. The released dust particles subsequently make a polydisperse system together with the air (Al-Salem et al., 2009; Malaťák & Passian, 2011). The high polydispersity of the mixture results from the crushing process. Depending on the nature of the material processed, mixtures of substances with large dispersion of size and density are produced (Vaculík et al., 2016). The size and density dispersion of the resulting particles increases the operational demand for conveyance of the mixture and the separability of the dust particles. In operation, this demand is solved by changing the properties of the conveyed material (reduction of particle size and density dispersion by sorting) or by adjusting the operating parameters of the suction system, i.e. by increasing the air flow volume and the operating pressure (Taylor, 1998).

In a manufacturing environment where physical-mechanical processes of material processing are applied, dust particles are removed by suction. Various suction arms or suction filter tables are used. These devices are then combined with powerful separation systems where the dust particles are separated from the air flow (Cao et al., 2018). The separation efficiency of dust particles at the point of their origin, the energy intensity of the suction system, and the subsequent separation of the dust particles from the carrier medium are important operation indicators of the entire suction system (Burgess et al., 2004). The operational disadvantage of the equipment used is its high energy intensity. This is due to the large operating pressures that are required to convey the exhausted material and the correct operation of the dust particle separators (Goodfellow & Tähti, 2001). Reducing the energy intensity of the operating system can be achieved by shortening the convey routes, by using a separation method with low-pressure drop, or by a combination of several separation methods (use of a multi-stage sorting separators).

Methods of sedimentation (use of gravity, centrifugal, inertial forces), filtration, diffusion or separation using particle electric properties are used to separate dust particles from the air flow (Peukert & Wadenpohl, 2001). By setting comparable conditions, i.e. properties of the dispersed particles (size, shape, mass concentration, electric properties), properties of the dispersion (concentration and fractional composition of the solid phase) and the environment (density, viscosity, power and electric field strength), the lowest pressure drop is achieved at the separation using electric properties of particles (electrostatic precipitators), pressure drop is 50–250 Pa. On the contrary, filtration separation systems (e.g. fabric filters) work with the greatest pressure drop, the pressure drop at 500–2,000 Pa (Burgess et al., 2004; Goodfellow & Tähti, 2001).

MATERIALS AND METHODS

Under experimental conditions, the separation conveying device for suction of crushed material, its pneumatic conveyance and subsequent separation of the dust particles from the air flow was designed and tested. This device was designed to work with a high dust separation with a low volume air flow and a low operating pressure throughout the suction system, pneumatic conveyance and separation. This was assured by the construction of the conveyor section of the device and by the use of the separator with a low-pressure drop. The designed separation conveying device consists of three parts: the conveyance section for the grain material suction and conveying, the coarse grain share cyclone separator and the electrostatic precipitator (hereinafter referred to as 'ESP') of the dust particles released from the air flow.

The operational efficiency of the separation conveying device was verified by assessing the dust particle separability when processing the polydisperse granular mixture resulting from the crushing of electrical waste. In particular, used laser toner cartridges were processed. These contain residues of toner powder that is the source of composite dust particles of submicroscopic size. The separability of released dust particles was monitored as a function of the change of the pressure in the conveying pipeline in front of the ESP.

Design and function of the proposed separation conveying device

Construction of the separation conveying device is shown in Fig. 1. The electrical waste is shredded by knife mill Terier G200/300 (1). From a knife mill, the crushed material is fed into a closed metal conveying pipeline (2) of circular profile diameter of 150 mm and it is conveyed by a combination of pneumatic and mechanical conveyance to a cyclone separator (3) with tangential inlet size of 600 x 1,750 mm. At the bottom, the cyclone separator is closed by a turnstile feeder (4). The cyclone separator separates the crushed material from the air flow. The air from the cyclone separator with dust particle fractions, which are not separated by the cyclone separator, then enters the EPS of the dust particle AEROFOG–E (5). It is a series of (industrially) manufactured EPS of horizontal chamber structure with air flow volume up to 1,800 m^3 hod^{-1}. The interconnection conveying pipeline between the EPS and the cyclone separator and the interconnection conveying pipeline between the EPS and the pressure source is of circular profile diameter of 300 mm. A radial fan URBAN Technik VE–2000 (6) is a pressure source with an air volume flow rate of 1,800 m^3 hod^{-1}, operating pressure of 1,800 Pa and engine speed at 2,800 min^{-1}. During the measurement, a mechanical fabric filter (7) was placed in front of the fan, which prevented any dust particles to be emitted at high operating pressures and thus prevented reduction of the EPS separability. Operating parameters of the separation conveying device were designed based on the calculation of air–conditioning variables (volume flow rates, air flow velocity, operating pressures, pipe dimensions).

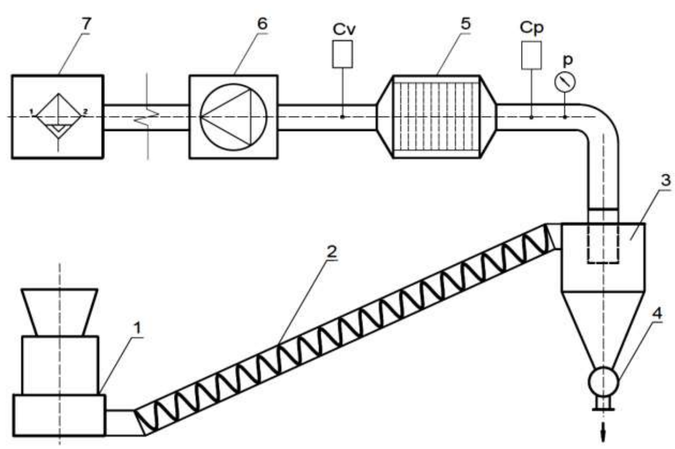

Figure 1. Separation conveying device construction: 1 – knife mill, 2 – combined (pneumatic and mechanical) conveyance, 3 – cyclone separator, 4 – turnstile feeder, 5 – electrostatic precipitator, 6 – fan, 7 – fabric filter, p – pressure sensor, C_p, C_v – dust analyser probes.

The use of low pressure in the entire system of the designed device allows the construction of combined (pneumatic and mechanical) conveyance (2), shown in Fig. 1. The essence of the construction is a low–pressure pneumatic conveying pipeline in combination with a mechanical towing part (Jehlička & Sander, 2015). The combination of both types of conveying is designed in such a way that the towing part in the form of an axis–less helix is inserted into the inner space of the conveying pipeline. In such a defined environment, the material is conveyed due to the dynamic effects of the flowing media and is simultaneously carried by the mechanical movement of the rotating axis–

less helix. Such technical solution allows carrying out both pneumatic and mechanical conveying of particles in a single conveying space (conveying pipeline).

With this construction of the pneumatic conveying pipeline, it is possible to convey the material of a wide spectrum of specific weight of individual particles. Particles with lower density and greater aerodynamic resistance are carried by the air flow mainly through the centre of the pipeline. Particles of larger density are moved by the mechanical energy of the axis–less helix. The described pneumatic pipeline construction can be utilized to handle short distances in the horizontal and oblique plane.

Method of measurement of dust particles separability

Dust particle separability was monitored as a function of the change of the operating air pressure. The operating pressure was set by the frequency control of the fan revs. The fan revs were set by the Movitrac LTE–B + frequency converter within the range of 1,400 min^{-1} to 2,600 min^{-1}, always by 200 min^{-1}. The operating pressure and the mass concentration of the dust particles in the pipeline were measured at each set of the fan revs. The location of the probes is in Fig. 1. A Testo 521–1 device monitored the operating pressure with a pressure sensor located in the conveying pipeline at a distance of 0.7 m from the EPS entrance. The mass concentration of the dust particles was monitored by the optical real–time measurement method using the Testo 380 dust particle analyser. There were two dust analyser probes (C_p and C_v). The first was located in the pipeline about 0.5 m before the entrance to the EPS (C_p) and the other was in the outlet pipeline about 0.6 m behind the EPS (C_v).

The Testo 380 analyser is available on the market in the original user interface, which is optimized to evaluate the dust particle mass concentrations in the flue gas mixture. In order to measure dust particle mass concentrations of pre–defined physicochemical properties in the air flow, it was necessary to recalibrate the supply setting. The recalibrating of the analyser was performed in cooperation with the Testo service representative. Accuracy of dust particle mass concentration measurements after analyser recalibration is burdened with an error corresponding to inaccuracy in the specification of the physicochemical properties of the dust particles into the analyser software application. In order to monitor the changes in the dust particle mass concentrations in relation to the set operating parameters of the separation conveying device and graphically illustrate these changes, the accuracy of the operational measurement is sufficient and within the range of measured values it is above 95%.

The dust particle separability O_c was calculated from the general relationship:

$$O_c = \frac{C_p - C_v}{C_p} \cdot 100\% \qquad (1)$$

where C_p – particle mass concentration on input (mg m^{-3}); C_v – particle mass concentration on output (mg m^{-3}).

With each set of the fan revs, the measurement of the pressure and mass concentrations of the dust particles was repeated five times, always in 5 minute intervals. Mean values were calculated from the values thus measured.

RESULTS AND DISCUSSION

The proposed separation conveying device has three construction parts that are not common in similar dust removal devices in common operation practice. It involves the use of combined (pneumatic and mechanical) conveyance between the dust particle source and the coarse grit separator, the use of a low-pressure drop dust separator and in addition, the inclusion of this separator in front of the fan on the suction line, see Fig. 1. The described construction modification allows energy efficient operation at a low operating pressure of up to 1,000 Pa.

In order to verify the assumption of operational reliability and high dust separability in low-pressure operation (suction of the crushed material, its pneumatic conveyance and subsequent separation of the dust particles from the air flow), dust particle separation was monitored in dependence on changes in operating pressure. Table 1 shows the set fan revs, the mean values of the measured operating pressures and the mean mass concentrations of the measured dust particles on the inlet and outlet of the EPS, which correspond to the set fan revs. Further, in Table 1, the calculated values of dust particle separation of the EPS are given.

Table 1. Operation pressure and concentration of dust particles

Fan revs [min^{-1}]	Pressure [pa]	Particle mass concentration on outlet c_v [$mg\ m^{-3}$]	Particle mass concentration on inlet c_p [$mg\ m^{-3}$]	Dust particle separability o_c [%]
1,400	450	1.16	58	98
1,600	587	1.5	60	97.5
1,800	743	1.83	61	97
2,000	918	2.27	65	96.5
2,200	1,111	4.87	65	92.5
2,400	1,322	11.22	66	83
2,600	1,552	19.5	65	70

The dependence of the observed factors, i.e. the mass concentration of the dust particles on the outlet of the EPS and the operating pressure, is shown in Fig. 2. The measured values are intersected by the trend line. To illustrate the variation of the mass concentration of the dust particles at the operating pressure, the exponential trend of the trend line is used. It corresponds the most to the actual operational changes of the monitored factors. Correlation reliability is 0.99.

From the measured mass concentrations of dust particles on the outlet of the EPS follows the dependence on the change in the operating pressure in the system. This dependence is exponential. The graphic presentation in Fig. 2 shows, that the increase in mass concentrations up to the pressure of 1,000 Pa is very gradual and does not exceed the mass concentration of 5 $mg\ m^{-3}$. For pressures above 1,000 Pa, there is a characteristic steep increase in the mass concentration of dust particles. The increase of the dust particle mass concentration at the operating pressure above 1,000 Pa is related to the changes in other operating factors. The velocities and volumes of the air flow vary in the system and, as shown in Fig. 3, overall separation decreases. The course allows a conclusion that the designed separation conveying device reliably separates the dust particles during low-pressure operation up to 1,000 Pa. Outlet mass concentrations of dust particles at low values below 5 mg m^{-3} comply with the legal regulations in force in the EU Member States. This applies to both dust emission limits as well as health and safety of workers (EP and Council, 2010; Council of the European Communities, 1998).

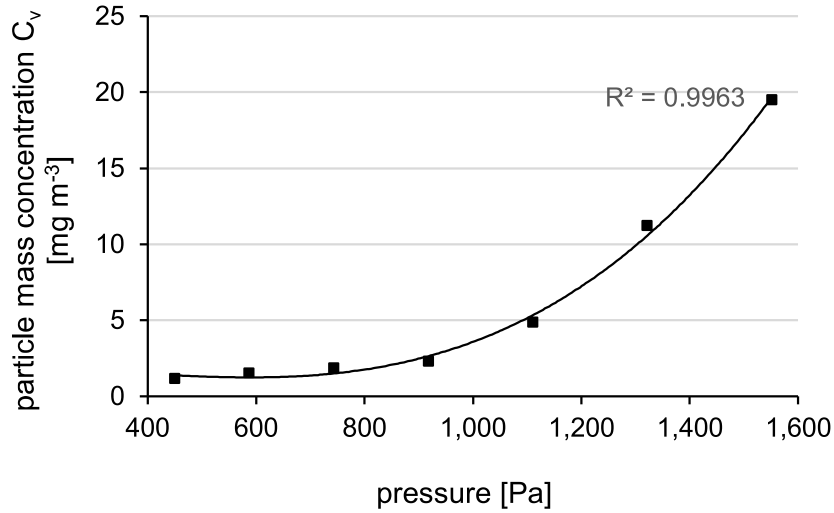

Figure 2. Dependence of mass concentration of dust particles on the outlet of the separator and operating pressure.

The values of the inlet mass concentrations dust particles (C_p) have a balanced value over the entire measuring range. This is given by the uniform properties of the processed material at all measurements. Small changes (in mg m^{-3} units) may be due to sedimentation of particles in the conveying pipeline due to a drop in operating pressure or due to physicochemical reactions that cause the dust particles to bind to the coarse fraction of the grit with which they are subsequently separated in the cyclone separator.

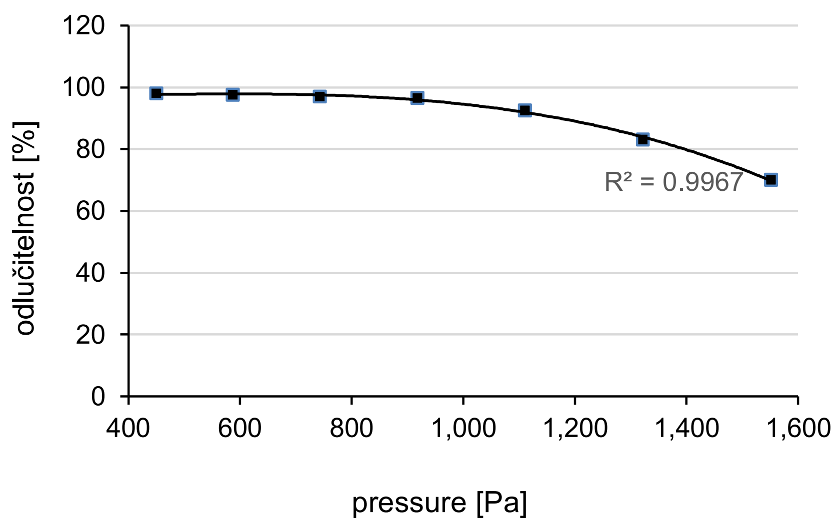

Figure 3. Separability of dust particles in dependence on operating pressure.

The dependence of the outlet mass concentration of the dust particles at the operating pressure and other operating values that are related to the set pressure (volume flow and flow velocity) is affected by the physical properties of the crushed material. When using the EPS, it is primarily particle resistivity and less particle size and shape (Goodfellow & Tähti, 2001).

An objective assessment of dust particle separability in the proposed separation conveying device would be to compare the measured values of the separability of dust particles released during the processing of the toner cartridges with the separability of the dust particles resulting from the processing of materials of different properties, i.e. other pre-sorted electrical waste. The grit from the printer toner cartridge is a mixture of plastic particles (a cassette case) and submicroscopic carbon particles and metal oxides (toner powder) (Pirela et al., 2015). The resulting grit from toner cartridges has optimal resistivity (Mazumder et al., 2006) and hence high separability on the EPS (Matsusaka & Masuda, 2003). On the other hand, the material resulting from the crushing of other pre-sorted electrical waste will show a much wider range of physicochemical properties.

From the operation energy point of view, it would be interesting to compare the method of mechanical separation by air filtration and the method of electrostatic separation with the same total dust particle separability. When using filtration, the overall separation is affected by the size and shape of the particles. Filtration separates the solid particles from the air flow and holds them on the filter element. From the energy point of view, the pressure drop that occurs on the filter element is a problem. Industrial filters can work with a final pressure drop of up to 2,000 Pa (Burgess et al., 2004). By comparing the electrostatic separation method and the mechanical separation method based on air filtration, the energy saving of electrostatic separation would be clearly proved with the proposed mechanical equipment.

CONCLUSIONS

The result of the experiment is the design of a technology for the separation of dust particles, which are created by physical-mechanical processes of materials processing. The proposed technology and its operational verification are focused on the separation of dust particles from polydispersion granular mixtures with large scattering of particle size and density, which are created by the physical-mechanical process of crushing composite materials. The separation conveying device was designed to achieve a high degree of separation with minimal energy consumption for the whole technology operation, which allows conveyance, separation of the grit from the air flow and separation of the dust particles using low operating pressure. The measurements were made by processing a material, which was assumed to have a high content of dust particles of submicroscopic size. The material used were toner cartridges for laser printers containing toner powder residues. The operational efficiency of the separation conveying device at low-pressure operation was verified by assessing the dust particles separability in dependence on the change in air pressure in the conveying pipeline in front of the ESP.

Experimental measurements showed that on the EPS outlet the growth of mass concentrations of dust particles up to a pressure of 1,000 Pa (low-pressure operation) is very gradual and does not exceed 5 mg m^{-3}. For pressures above 1,000 Pa, a steep increase in the mass concentration of unseparated dust particles is characteristic, which corresponds to the exponential course. It can be concluded from the course that the designed separation conveying device reliably separates the dust particles during low pressure operation up to 1,000 Pa. Outlet mass concentrations of dust particles in low values below 5 mg m^{-3}, comply with the legislation in force in the EU Member States.

According to the proven results, the dust separation technology in low-pressure operation can generally be considered as operationally efficient. The technical design of the proposed technology is structurally simple and demonstrates high technical and technological reliability.

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