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Separation Science and Technology

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

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Online publication date: 08 November 2003

To cite this Article Bryczkowski, Andrzej and Smołka, Wojciech(2003) 'A High-Duty Horizontal Dust-Collector with a Rotary Baffle', Separation Science and Technology, 38: 14, 3493 — 3511

To link to this Article: DOI: 10.1081/SS-120023413

URL: http://dx.doi.org/10.1081/SS-120023413

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SEPARATION SCIENCE AND TECHNOLOGY
Vol. 38, No. 14, pp. 3493–3511, 2003

A High-Duty Horizontal Dust-Collector with a Rotary Baffle

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ABSTRACT

The article deals with the design and the experimentally verified description of the horizontal dust-collector with a rotating baffle. The device is characterized by its compact structure, high efficiency, and low pressure drop. The principle of operation of the apparatus is based on putting the dusted gas into swirling motion with a rotational velocity equal to rotational speed in the flow channel. The value of centrifugal force reacting on particles is, in this case, limited only by strength of material and power necessary to force the rotational velocity of the gas stream. The separated dust is collected by slots situated crosswise to the gas flow on the outer wall of the flow channel. Research was done on the apparatus with an inner diameter of 100 mm, outer diameter of 216 mm,

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DOI: 10.1081/SS-120023413 0149-6395 (Print); 1520-5754 (Online)
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and channel length of 298 mm, at a rotational velocity from 2000 to 3700 rpm for rate of flow from 300 to 660 m^3/h.

Key Words: Deduster; Rotary buffle.

INTRODUCTION

The growing awareness of ecological requirements and economical considerations increased interest in highly efficient methods of cleaning the emitted gases out of dust, particularly dry dedusting methods. In industry, high-duty dust-extraction devices are applied, such as electrofilters, bag filters, and ceramic filters, the latter being the most effective ones. The installation of these apparatuses is, however, connected with the high capital and operating costs,[1–3] because of costly material and energy. Additionally, filters and electrofilters are very sensitive to changes of the gases and dedusted particles.[4]

With respect to the achieved effectiveness of dust extraction, an economic alternative are dust-collectors with rotating separator baffles. Until recently, the application of rotating elements was restricted mainly to classifiers of fine-grained materials. Now, however, the results of investigations have been published concerning the application of dust-collectors with rotating elements for the purpose of separating dust from gas.[5–7] Investigations on the design of these devices have been taken up also at the Institute of Chemical Processing of Coal, aiming at the dedusting of post-pyrolytic gases from a circulating fluzidized bed reactor. There are prerequisites for two of the investigated designs to be further developed, viz. the cyclone-type dust-collector with a rotating baffle and the take-off of the dedusted gas at the bottom,[8,9],[a] and the dust-collector with a horizontal baffler.[10],[b] The description of the process and the experimental verification of this latter variant are subject of the present article.

THEORETICAL SECTION

Principle of the Operation and Design of the Dust-Collector

The principle of the dust-collector operation is the introduction of the dedusted aerosol in such a way that it flows along the channels inside the rotor,

[a]Patent PL 5185871.
[b]Patent PL 174241B1. Medaille D'OR 42nd World exhibition of invention, research, and industrial innovation Brussels Eureka, 1993.

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reaching a velocity equal to the rotational speed of the rotor. By adjusting the rotational speed of the rotor, the centrifugal forces affecting the aerosol particles can be influenced. The only restricting factors are the strength of the material the rotor is made from and economic reasons. Thanks to the tangential inlet and outlet of the gas stream, the erosion is reduced and part of the energy used to provide rotational speed to the aerosol can be recovered. Thus, for each flow rate, a rotational speed may be achieved at which the pressure drop of the gas passing through the dust-collector is equal to zero.

Due to the design and operation of the deduster, it is advantageous to remove the separated dust together with a gas stream, which is rather small compared with that of the inlet. In such a case, the apparatus operates as a dust concentrator, resulting in an outlet stream of pure gas and a small stream of gas with a high dust concentration that is dedusted on a proportionally smaller filtration surface. In this way, the costs of operation and investments can be reduced considerably.

Such a dust-collector with a separating baffle is shown in Fig. 1. It is a flow-type apparatus with a horizontal rotating baffle. The fundamental

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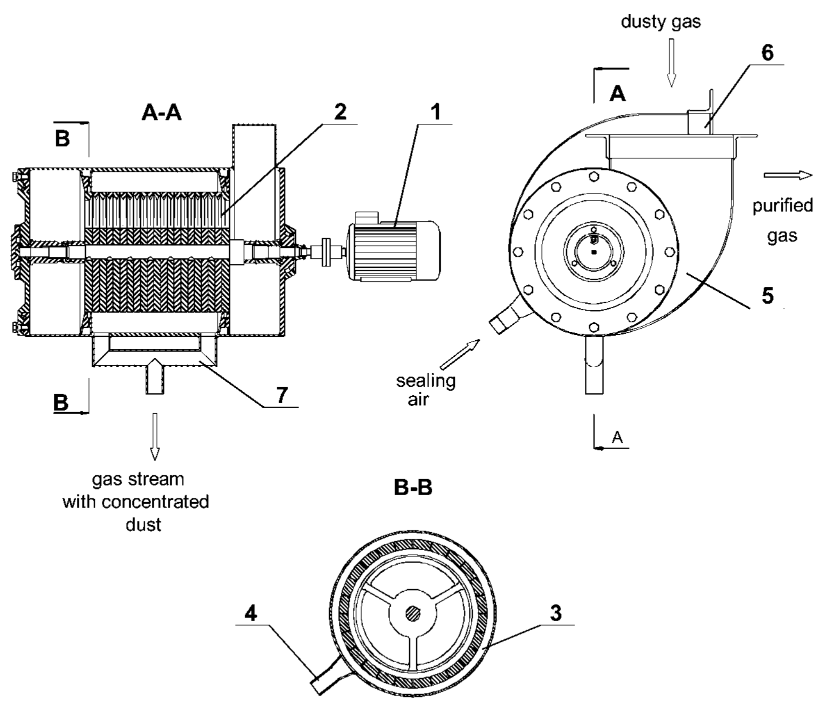

Figure 1. Dust collector with a rotating separating baffle.

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part of this deduster is the rotor (2) with an inner radius $r_{in} = 0.05\,m$ and external radius $r_{ex} = 0.108\,m$, driven by a motor (1) and consisting of adequately shaped rings mounted on a shaft (Fig. 2). In this way, a rotating element was obtained with an internal space through which the dusty gas flows and circumferential clearances through which the concentrated dust is carried away with a small amount of gas. The dust-catching space is sealed pneumatically on the out-most rings of the rotor. The concentration of dust in the gas collected with separated dust increased 8 to 30 times in comparison with inlet concentration at rotational velocity varying from 2000 to 3700 rpm.

The gas containing the solid phase is fed into the apparatus tangentially through the inlet channel (5), then flows through the internal channel of the rotating rotor and having been purified, leaves the apparatus tangentially through the discharge channel (6). Due to centrifugal forces, the particles of dust are shifted inside the rotor toward its external surface and leave the rotor through the clearances between the rings. From the outer space, the dust, concentrated in a small amount of gas, can be passed through the discharge channel (7) to either a bag or a ceramic filter and separated from the gas. The ratio of the flow rate of collected gas with dust to the inlet flow rate varied in the range of 0.03 to 0.1.

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Dedusting Efficiency

Three variants of the process with different degrees of detailed description have been verified experimentally. In the case of the first variant, it was assumed that the velocity distribution of the gas in the channel was

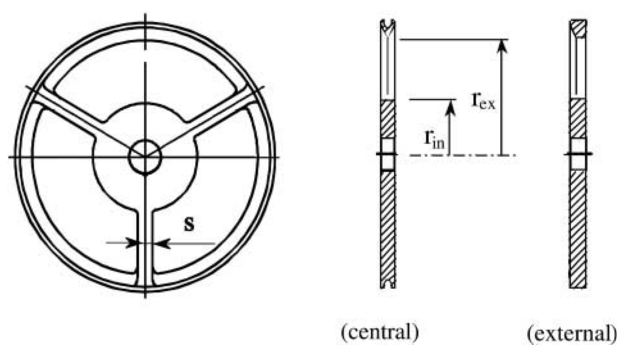

Figure 2. Ring of the rotor of the separating baffle.

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known, determined by the generalized velocity distribution,[11] adjusting the tangential stress for the given volumetric flowrate of the gas. In such a case, the fractional efficiency of dust extraction can be determined as the ratio of the mass rate of flow of the gas through the surface between the curve, which determines the boundary radius and the contour of the channel in the radial direction in relation to the mass flow rate at the inlet to the channel.

The limiting radius is defined in polar coordinates as the position of the particle in the cross-section of the inlet, whereas in the cross-section of the outlet, it will appear on the surface of the rotating channel.

The other two variants assume the gas velocity to be constant in relation to the radius. In one of these cases a radial change of the gas density was taken into account considering three ranges of particle settling, i.e., that of Stokes, Allen, and Newton.[12] The second case concerned the settling of the particle in the range of laminar region for a constant gas density. The experimental verification of the aforesaid models showed that the adjustments, expressed by correlation coefficient differed only slightly.

Therefore, taking into account the fact that only the latter variant leads to an analytical solution describing the efficiency of dust extraction, the following assumptions were made.

- The dust particles are spherical.
- There is no interaction between the dust particles.
- The velocity of the particle in the tangential direction of the flow of gas equals the velocity of the gas.
- In the cross-section the gas velocity is constant.
- Along the path of flow, the discharge of a small amount of gas is uniform.
- At the inlet to the rotor, the concentration distribution is uniform.
- The gas density is constant.
- The particle moves within the laminar range.
- The gravity force is small if compared with the centrifugal force and is neglected.

Fig. 3 presents a diagram denoting the fundamental quantities needed to deduce the relation expressing the efficiency of dust extraction.

The time needed for the dust particle to cover the distance dl in direction l and the distance dr in the direction r can be determined according to the relation:

$$\frac{dr}{u_r} = \frac{dl}{u_l} \tag{1}$$

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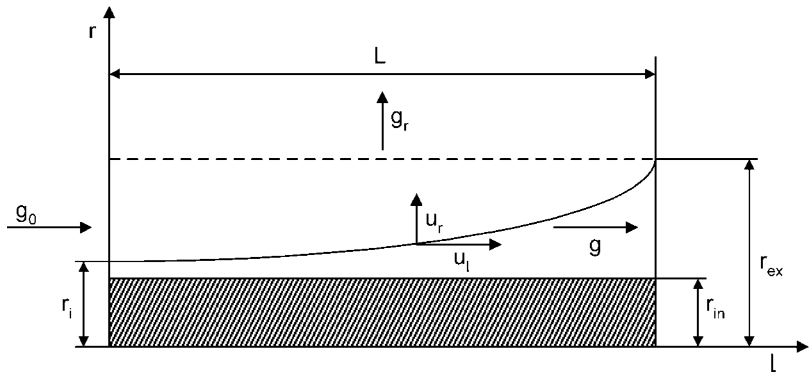

Figure 3. Simplified diagram of the channel including the basic quantities.

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Balance of forces reacting on the particle in the field of centrifugal forces, considering buoyancy, leads to the following relationship:

$$m_p \frac{du_r}{dt} = (m_p - m_g)\frac{u_\theta}{r} - 3\pi\mu d(u_r - v_r) \tag{2}$$

Where m_p is the particle mass, m_g is the gas mass contained in particle volume, u_θ is the tangential velocity of solid particle, u_r is the radial velocity of a solid particle, and v_r is the radial velocity of gas flow.

Considering the simplifying assumptions, and taking into account that channels rotate with constant angular velocity ω, Eq. (2) takes the form:

$$u_r = \frac{d^2(\rho_s - \rho)\omega^2 r}{18\mu} + v_r \tag{3}$$

The first expression on the right side of Eq. (3) is the particle velocity drop in laminar range in the field of centrifugal forces. Applying Cunningham correction, the radial velocity of a solid particle will be expressed as:

$$u_r = \frac{d^2(\rho_s - \rho)\omega^2 rCu}{18\mu} + v_r \tag{4}$$

The particle velocity due to the radial flow of the gas is

$$v_r = \frac{g_r}{2\pi rL\rho} \tag{5}$$

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Assuming that gas is taken off along the path of its flow uniformly, the air flow rate along the axis l in the dust-collector is expressed by the relation:

$$g = g_o - \frac{g_r}{L} l \qquad (6)$$

Thus the velocity along the axis u_l can be expressed as:

$$u_l = \frac{g_o - g_r \frac{l}{L}}{f\rho} \qquad (7)$$

Substituting Eqs. (4), (5), and (7) into relation (1) leads to the differential equation:

$$\frac{dr}{\frac{g_r}{2\pi L\rho r} + \frac{d^2(\rho_s - \rho)\omega^2 Cu}{18\mu} r} = \frac{f\rho dl}{g_0 - g_r \frac{l}{L}} \qquad (8)$$

After introducing the expressions

$$k = \frac{g_r}{g_0} \qquad (9)$$

$$c_1 = \frac{kg_o}{2\pi L} \qquad (10)$$

$$c_2 = \frac{d^2\rho(\rho_s - \rho)\omega^2 Cu}{18\mu} \qquad (11)$$

Integrating the right-hand side of Eq. (8) within the limits 0 to L, Eq. (7) leads to the form:

$$\int_{r_i}^{r_{ex}} \frac{dr}{\frac{c_1}{r} + c_2 r} = \frac{1}{2c_2} \int_{r_i}^{r_{ex}} \frac{2c_2 r dr}{c_1 + c_2 r^2} = \frac{1}{2c_2} \ln(c_1 + c_2 r^2)|_{r_i}^{r_{ex}} = c \qquad (12)$$

where

$$c = \frac{fL}{kg_0} \ln \frac{1}{1-k} \qquad (13)$$

After substitution of integration limits and transformation the relation for

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the square of the limiting radius is obtained:

$$r_i^2 = \left(\frac{c_1}{c_2} + r_{ex}^2\right)e^{-2c_2c} - \frac{c_1}{c_2} \tag{14}$$

Substituting the Eqs. (10) and (11), the expression c_1/c_2 takes the form:

$$\frac{c_1}{c_2} = \frac{9kg_0\mu}{\pi Ld^2\rho(\rho_s - \rho)\omega^2 Cu} \tag{15}$$

After introduction of the dimensionless quantity,

$$L_i = \frac{d^2(\rho_s - \rho)\omega^2 LCu}{9\mu u_0} \tag{16}$$

and

$$g_0 = u_0 f \rho \tag{17}$$

relation (15) may also be written in the form:

$$\frac{c_1}{c_2} = \frac{f}{\pi}\frac{k}{L_i} \tag{18}$$

Taking into account Eqs. (11), (13), and (17), the expression $2c_2c$ takes the form:

$$2c_2c = L_i\frac{1}{k}\ln\frac{1}{1-k} \tag{19}$$

Ultimately, the relation for the square of the limiting radius can be expressed by the following formula:

$$r_i^2 = \frac{f}{\pi}F_i^2 \tag{20}$$

where

$$F_i^2 = \left(\frac{k}{L_i} + C_1\right)e^{-L_i\frac{1}{k}\ln\frac{1}{1-k}} - \frac{k}{L_i} \tag{21}$$

$$C_1 = \frac{\pi}{f}r_{ex}^2 \tag{22}$$

For the assumed uniform dust concentration in the cross-section of the inlet,

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the fractional efficiency of dust extraction is expressed by the equation

$$\eta_i = \frac{f_i}{f} \tag{23}$$

The surface areas can be calculated from the following equations with negligible errors.

$$f_i = \pi(r_{ex}^2 - r_i^2) - ns(r_{ex} - r_i) \tag{24}$$

$$f = \pi(r_{ex}^2 - r_{in}^2) - ns(r_{ex} - r_{in}) \tag{25}$$

Allowing for Eqs. (23) and (24)

$$\eta_i = C_2 - F_i^2 + C_3 F_i \tag{26}$$

where

$$C_2 = \frac{\pi r_{ex}^2 - nsr_{ex}}{f} \tag{27}$$

$$C_3 = \frac{ns}{\sqrt{\pi f}} \tag{28}$$

$$\lim_{L_i \to 0} \eta_i = 0 \tag{29}$$

For $\eta_i = 1$, limiting values F_i are calculated from the relation

$$F_{i,m}^2 - C_3 F_{i,m} + 1 - C_2 = 0 \tag{30}$$

and so

$$F_{i,m} = \frac{C_3 + \sqrt{C_3^2 + 4(C_2 - 1)}}{2} \tag{31}$$

From Eq. (21), the limiting value of dimensionless quantity $L_{i,m}$ can be calculated as follows:

$$L_{i,m} = \frac{\ln \dfrac{C_1 + \frac{k}{L_{i,m}}}{F_{i,m}^2 + \frac{k}{L_{i,m}}}}{\frac{1}{k} \ln \frac{1}{1-k}} \tag{32}$$

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Because $\lim_{k \to 0} \frac{1}{k} \ln \frac{1}{1-k} = 1$, for $k = 0$

$$F_i^2 = C_1 e^{-L_i} \tag{33}$$

$$L_{i,m} = \ln \frac{C_1}{F_{i,m}^2} \tag{34}$$

In Fig. 4, the relationships between fractional efficiency in applied variation range of k and dimensionless number L_i are presented. Characteristics of fractional efficiency for $k = 0.03$ and $n = 3700$ rpm is presented in Fig. 5.

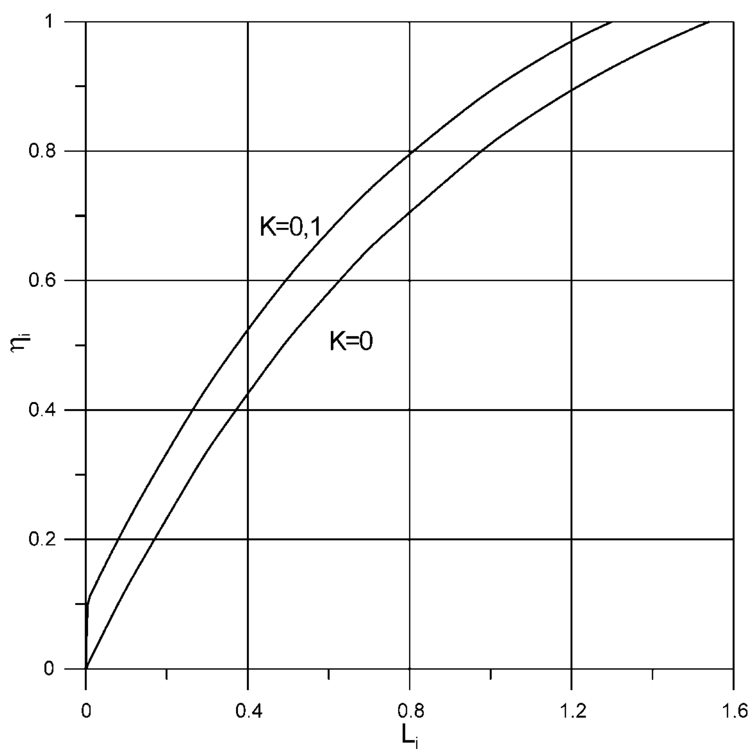

Figure 4. Fractional efficiency in dependence on dimensionless number L_i in applied range of k.

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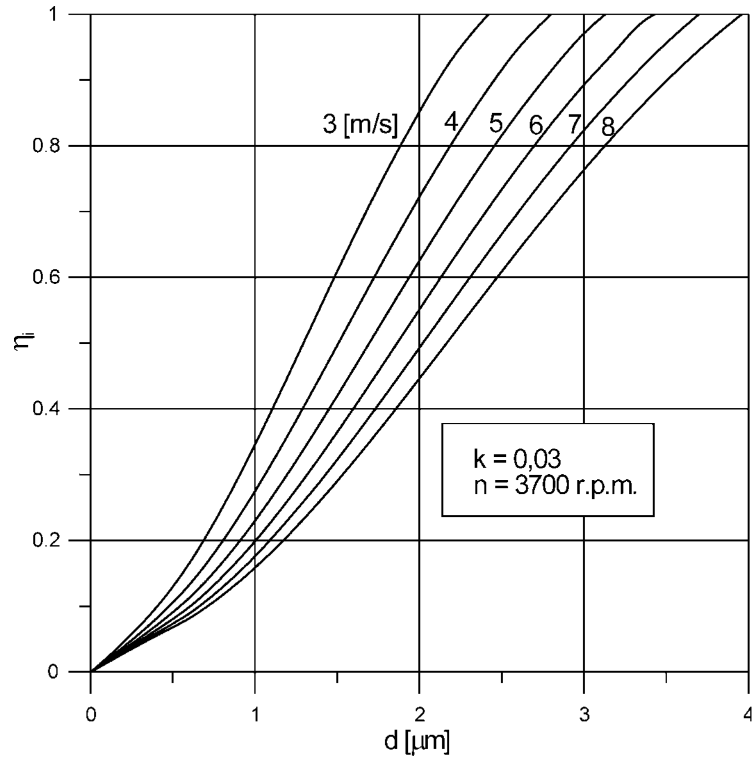

Figure 5. Characteristics of fractional efficiency for $k = 0.03$ and $n = 3700$ rpm.

Pressure Drop

In the case of the dust-collector with a rotating baffle, in addition to partial pressure drops due to local resistances and a pressure drop caused by the gas flow through the channels of the rotor, there is an increase of pressure due to the rotary motion of the baffle.

To determine the form of the relation describing the pressure differences due to the rotary motion of the baffle, we compared the power imparted to the rotating gas stream with the power expressed by the difference of pressures.

$$M_k = u_0 f \Delta p_w \tag{35}$$

where M_k is the power imparted to the rotating flux of gas.

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The power imparted to the elementary layer of gas amounts to

$$dM_k = \frac{w^2}{2} d\dot{g} \tag{36}$$

where $d\dot{g}$ is the mass rate of gas through the elementary surface (kg/s), and w is the peripheral speed (m/s).

Taking into account that

$$w = r\omega \tag{37}$$

and

$$d\dot{g} = 2\pi u_0 \rho r dr \tag{38}$$

we get the relation

$$dM_k = \pi\rho\omega^2 u_0 r^3 dr \tag{39}$$

After the integration of this equation within the limits r_{in} to r_{ex}, assuming constant density, we get

$$M_k = \frac{\pi}{4}\rho\omega^2 u_0 (r_{ex}^4 - r_{in}^4) \tag{40}$$

From Eqs. (35) and (40), the relation concerning the difference of pressures can be expressed as follows:

$$\Delta p_w = \frac{\rho\omega^2}{4}(r_{ex}^2 + r_{in}^2) \tag{41}$$

The pressure drop of the gas through the rotating channel is rather small, (within 0.3 to 0.4% of the pressure drop caused by local resistance) and can be neglected. The total pressure drop can be expressed by the following relation

$$\Delta p = \xi \frac{\rho}{2} u_{in}^2 - \frac{\rho\omega^2}{4}(r_{ex}^2 + r_{in}^2) \tag{42}$$

In the investigated range of flow parameters, the maximum relative difference of the gas densities at the inlet and the discharge from the deduster amounted to 0.9%, whereas the analogical difference of densities for the radii r_{z} and r_{w} was 0.8%. The ratio of compression to pressure drop caused by local resistance ratio ranges from 0 to 12.8.

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EXPERIMENTAL SECTION

The dust extraction efficiency was determined by samples taken beyond the separator for a known amount of dust dosed at the inlet to the dust-catcher. The sample was taken observing the isokinetic condition on the level $H =$ 0.94 to 1.1, where

$$H = \frac{velocity\ of\ the\ gas\ at\ the\ inlet\ to\ the\ end\ of\ the\ aspirating\ probe}{velocity\ of\ the\ gas\ in\ the\ conduit\ at\ the\ point\ of\ sampling}$$

The dust contained in the gas sample sucked in by the probe was separated on a measuring cartridge. The experimental effectiveness of dust extraction of the apparatus was calculated based on the increase of the dry mass of the cartridge, which was measured in compliance with the principles of the standard concerning the measurement of dust concentrations in waste gases making use of the gravimetric method.[13]

The total experimental efficiency of dust extraction was determined by means of the relation

$$\eta_{\mathrm{exp}} = 1 - \frac{m_{out}}{m_{dos}} \tag{43}$$

where m_{out} is the mass of dust discharged from the deduster together with the waste gas

$$m_{out} = m_g \frac{\dot{V}_{out}}{\dot{V}_g} \tag{44}$$

where m_{g} is the mass of emitted dust, m_{dos} is the mass of dosed dust, $\dot{V}_{\mathrm{out}}$ is the volumetric flow rate at the outlet of the dust collector (Nm^3/h), and $\dot{V}_{\mathrm{g}}$ is the volumetric flow rate through the measuring cartridge (Nm^3/h).

In these investigations, dolomite dust with a density of 2600 kg/m^3 was used, prepared in a classifier of the type Alpine Turboplex 50 ATP (Alpine Aktiengesellschaft, Augsburg, Denmark). The grain-size distribution was measured by means of a laser analyzer from Malvern Instruments M6.10 (Malvern Instruments Ltd., Wercestershire, UK), measuring the suspension of dry particles in air. The range of measurements of the analyzer was 0 to 118 μm with an accuracy of 4% in relation to the median. The grain-size distribution is shown in Table 1. The grain size of the applied dust indicates that the isokinetic condition need not be satisfied in this case.[3,14]

The grain-size distribution was stable throughout the investigations. In the whole range of investigations, the concentration of dust was contained within the values 1.07 and 7.38 g/m^3. This justifies the assumption that in

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Table 1. Grain-size distribution.

Medium grain-size in the class (μm)	Fraction (mass %)
21.70	0.3
18.75	0.3
16.20	2.1
13.95	6.1
12.00	10.2
10.35	11.3
8.95	11.2
7.75	9.3
6.70	7.6
5.75	6.5
4.95	5.0
4.30	3.6
3.70	3.0
3.20	2.8
2.80	2.6
2.40	2.2
2.05	1.5
1.75	1.2
1.50	1.3
1.30	1.3
0.60	10.6
Median	7.3 μm

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the case of experimental conditions, the dust concentration does not affect the efficiency of dust extraction.[15–19]

RESULTS AND DISCUSSION

Overall efficiency was calculated from the equation

$$\eta_{cal} = \sum_{i=1}^{N} x_i \eta_i \tag{45}$$

Figure 6 provides a comparison of efficiencies calculated in compliance with the relations presented in this analysis with the efficiencies obtained

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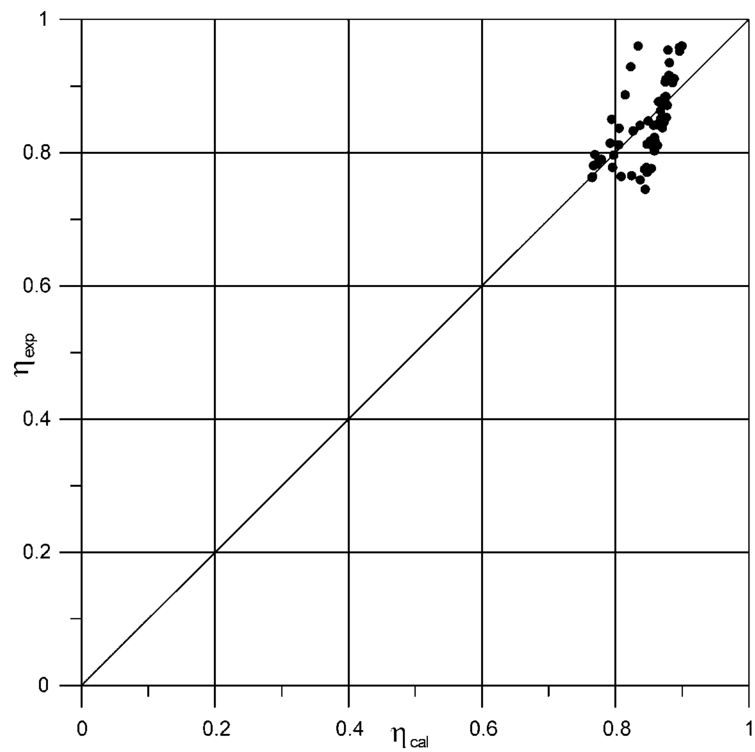

Figure 6. Comparison of experimental efficiency of dust extraction with theoretically calculated efficiency.

experimentally. Correlation of experimental data by theoretically derived formulae gives a standard deviation $\sigma = 0.048$, mean error 3.8%, and maximum error 12%. Considering the above-mentioned results, empirical corrections have not been applied.

The theoretical relation for resistance of flow was correlated with the experimental results, introducing the correction factors at the expression representing the difference of pressures caused by the rotation of the baffle. After correction, the relationship describing pressure drop can be expressed as:

$$\Delta p = 0.945 \frac{\rho}{2} u_{in}^2 - 0.566 \frac{\rho \varpi^{2.22}}{4} (r_{ex}^2 + r_{in}^2) \qquad (46)$$

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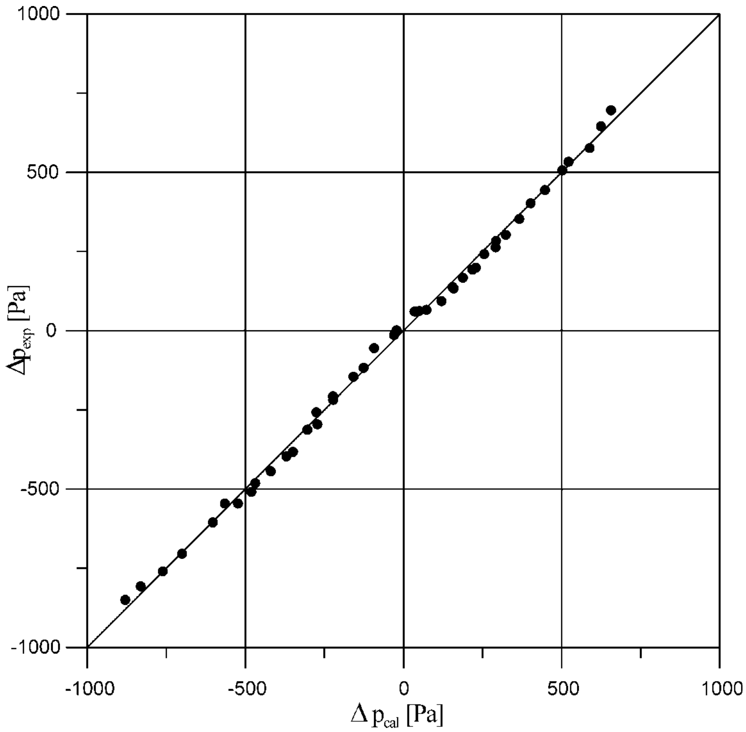

Figure 7. Comparison of the experimental pressure drop with the calculated pressure drop.

Standard deviation for pressure drop calculated from Eq. (46) equals 21. A comparison of experimental values with calculated ones is found in Fig. 7.

CONCLUSION

Gas flow in the channels of the apparatus is turbulent, in the range of Reynolds numbers from 17,800 to 38,800. Additional sources of turbulence are inlet effects and the edges of dust off take rings situated crosswise to the gas flow.

Turbulence generated in the zone of rings is probably partly reduced due to the radial flow of small amount of gas with dust. Turbulence of flow

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suggests simplifying the assumption of constant rate of flow of the gas. The constant gas swirling velocity in the apparatus under consideration, equal to the flow channel angular velocity, ensures high centrifugal accelerations (from 639 g to 1653 g on the outer radius), which is crucial to the separation quality.

Experimental results indicate that the dust-collector is characterized by high efficiency compared with its dimensions. Taking into account the fact that a very fine-grained dust was applied in the investigations. The efficiency of dust extraction observed in the range from 75 to 96% justifies the statement that this dust-catcher is a high-duty device. Its efficiency may be easily augmented by increasing the rotational speed of the baffle. From the point of view of its mechanical resistance, much higher rotational speeds are possible.

This deduster is characterized by very small pressure drop, and above some values of rotational speed, the baffles may even act as pumping device. This latter property may be particularly attractive when dust-extraction systems are to be modernized.

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NOMENCLATURE

c_1, c_2, c	constants defined by Eqs. (10), (11), and (13)
C_1, C_2, C_3	constants defined by Eqs. (22), (27), and (28)
Cu	Cunningham number
d	particle diameter
f	surface of the cross-section of the gas flow through the deduster
F_i	dimensionless quantity defined by Eq. (21)
g_0	mass rate of the gas flow at the inlet to the rotor
g_r	mass flow rate of the radial flow of the gas
k	ratio of the mass rate of flow of the gas discharged together with the dust to the mass of the inlet stream
l	axial coordinate
L	length of the rotor
L_i	dimensionless coefficient for the i-th fraction
n	number of rotor arms
N	number of fractions
Δp_{cal}	calculated pressure difference
Δp_{exp}	experimental pressure difference
Δp_w	pressure difference due to the rotary motion of the separating baffle
r	radial coordinate
r_i	limiting radius

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r_{in}	inner radius of the rotor
r_{ex}	external radius of the rotor
s	width of rotor arm
u_i	settling velocity of the particle
u_{in}	velocity of the gas at the inlet to the apparatus
v_r	velocity of the radial gas flow
u_0	flow rate of the gas at the inlet to the rotor
x_i	mass fraction

Greek Letters

ρ	gas density
ρ_s	particle density
ω	angular velocity
μ	dynamic viscosity
η_{exp}	experimental efficiency of dust extraction
η_i	fractional efficiency of dust extraction
η_{cal}	calculated efficiency of dust extraction
ξ	local friction factor

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Received August 2002
Revised March 2003

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