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ROTATING DUST SEPARATOR OF HIGH EFFICIENCY

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ODPYLACZ WIRNIKOWY WYSOKIEJ SKUTECZNOŚCI

W pracy określono główne parametry ruchu swobodnego cząstek pod wpływem sił grawitacji oraz w warunkach przeciążenia. W części teoretycznej podano podstawy fizyczne ruchu cząstek w kanałach wirujących oraz uproszczoną metodę do określenia skuteczności odpylania. W części eksperymentalnej omówiono stanowisko badawcze oraz budowę i zasadę działania odpylacza wirnikowego. W zakończeniu pracy sformułowano wnioski oraz sugestie dotyczące aplikacji technicznych.

Summary

Paper brings a description of free motion of particles suspended in the atmospheric air and being under action of the gravitational field together with additional accelerations caused by their relative motion. Theoretical part of the paper presents physical background of the particles motion within rotating channels together with the simplified method allowing to determine efficiency of the dust separator. Experimental part of the paper describes the test stand layout together with details of the dust separator design and its principles of action. In the closing part final conclusions and suggested practical applications of the devices under investigation are presented.

INTRODUCTION

Air pollution becomes a result of human technical activities related to a sufficiently high level of human civilisation what on the other hand results in growing a health hazard. From the point of view presented in this paper we concentrate our attention on the air pollution caused by the dust. Main factors affecting a health risk in this case are: chemical components of the dust, its concentration, and its sizes distribution. It must be mentioned as well that the dust is danger not only for the human being (and the biosphere in general) — it also affects so called the third world (here we have in mind terminology of Karl

R. Popper) – of the human products and machines of all kinds. Pollutant reduces their life time, increases the costs of their maintenance. Pollution of the environment becomes in a high degree related to the gas emission of factories and industrial enterprises. Most often there is not enough financial means to build simultaneously appropriate systems of filtering which would prevent the contamination of the atmospheric air or water resources. Quite often such devices are very expensive at the stage of their initial investment, and also their service job becomes expensive.

This paper brings a short description of a newly designed dust separator together with its theoretical background [11, 13]. Under the same name were known products such as, for instance, the Roto-Clone made by the American Air Filter Company or the Econdust made by Bronswerk (see [9]) which could not withstand practical requirements. The main difference between them and the devices under attention lies in the design of the rotor which in this case allows to produce high accelerations acting for sufficiently long time what opens the way to achieve a sufficiently high efficiency of the dust separation. Earlier known such devices were able to imply also a high acceleration upon dust particles but their efficiency became comparatively low due to a short time of acting of such a high acceleration on a dust particle.

References [2, 6, 8 and 17] offer the description of motion of the particles, forces acting upon them, and how properties of the gas and its motion affect the motion of the particles suspended in the gas. References [4 and 7] describe in a detail the motion of the systems of particles, analysing effects of their concentration and their physical and chemical properties upon the resulting motion of the particles. References [1, 3, 5, 9, 10, 16 and 18] present the design of the dust separators and theoretical background for their functioning.

TWO PHASE MEDIA AND THEIR FLOWS

MAIN FACTORS OF THE FLOW

Motion of two phase media usually incorporates a variety of separated volumes with a single phase component – surrounded by the boundaries which permanently fluctuate and evolve in time and space. The special attention was payed regarding two phase flows represented by a gas and highly dispersed solid particles within it. The level of the dispersion and the concentration of the particles allows to neglect their inner chaotic motion by assuming that their velocity corresponds to the mean speed of the flow.

INERTIAL MOTION OF THE DUST PARTICLES

Studying the motion of a single dust particle under the gravitational forces becomes the simplest case of the dust motion which, on the other hand, supplies the investigator with important features of the general case of such phenomenon. Ref. [14] presents properties of the particles moving inside of the motionless gas medium under the presence of the gravitational field accompanied by the forced motion which involves accelerations being 1000 times greater than those imposed by the gravitation. Numerical results presented there allow to propose the following conclusions:

- considering particles with diameters $d < 10$ μm and densities $\rho_c = 2000$ kg/m^3 if the gravity multiplier reaches the value $k = 1000$ then the velocity of the particle comparing to its initial value may increase hundreds times; in particular for particles of diameter $d = 1$ μm it increases 820 times of the initial value, while for $d = 10$ μm it increases 103 times;
- for the particles which diameter satisfies condition $d < 10$ μm unsteady motion of such particles can be neglected at all.

TWO PHASE FLOWS IN ROTATING CHANNELS

EQUATIONS OF MOTION OF THE PARTICLES IN ROTATING CHANNELS

The dust particle motion in a rotating channel becomes much more difficult mathematical problem than its free falling under gravitational forces. One of the reasons lies in unknown *a priori* velocity field in a cross section of the channel perpendicular to the axis of rotation. The geometry of such a cross section is formed to satisfy stress analysis requirements and the requirements of the mass flow through-out them. In the foregoing analysis to simplify the complexity of this picture the following have been assumed:

- velocity field of the gas mass flow is known and the same for different concentrations of the dust particles and their distribution along the channel;
- mass flow of the gases through-out the channel corresponds to the steady flow conditions;
- angular velocity of the rotor is constant;
- rotation of the particle around its own axis has been neglected as well as the gradient of the velocity and related to it flow carrying forces acting on a particle;
- gradient of the pressure and its implications regarding the axial and radial particle motion also have been neglected.

Polar coordinates were chosen to write equations of motion (see Fig. 1).

Following basic laws of Newtonian mechanics and including the above listed simplifications the equations of motion were derived in the form:

- axial direction – coordinate x:

$$\frac{\mathrm{d}W_{cx}}{\mathrm{d}t} = B \cdot C_x \cdot (W_x - W_{cx}) \cdot \sqrt{(W_x - W_{cx})^2 + (\omega_w \cdot r)^2}; \tag{1}$$

- radial direction – coordinate r:

$$\frac{\mathrm{d}W_r}{\mathrm{d}t} = r \cdot \omega^2 - g \cdot \cos\varphi - B \cdot C_x \cdot W_t \cdot \sqrt{(W_x - W_{cx})^2 + W_r^2 + (\omega_w \cdot r)^2}; \tag{2}$$

- tangential direction – coordinate φ:

$$\frac{\mathrm{d}\omega_w}{\mathrm{d}t} = 2 \cdot \frac{\omega}{r} \cdot W_r - \frac{g}{r} \cos\varphi - C_x B \cdot \omega_w \cdot \sqrt{(W_x - W_{xc})^2 + (\omega_w \cdot r)^2}. \tag{3}$$

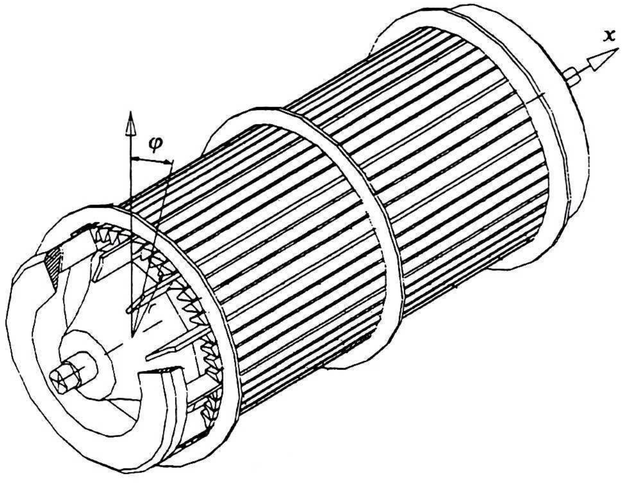

Fig. 1. Perspective view of the rotor showing polar coordinates

Abbreviations (see also Fig. 2):

$W_{cx} = \dfrac{dx}{dt}$ – axial component of the velocity of a dust particle,

W_x – axial component of the gas at the considered point,

$B = \dfrac{3}{4} \cdot \dfrac{\rho}{\rho_m} \cdot \dfrac{1}{d}$ – a constant,

ρ – density of the gas,

ρ_m – density of the particle,

d – particle diameter,

C_x – drag coefficient of the dust particle,

$a_c = 2 \cdot \omega \cdot \dfrac{dr}{dt}$ – Coriolis's acceleration,

$\omega = \dfrac{d\varphi}{dt}$ – angular velocity of the dust particle relative to the rotor,

φ_w – angular velocity of the dust particle relative to the channel wall,

$\omega_w = \dfrac{d\varphi_w}{dt}$ – angular position of the dust particle regarding the channel wall.

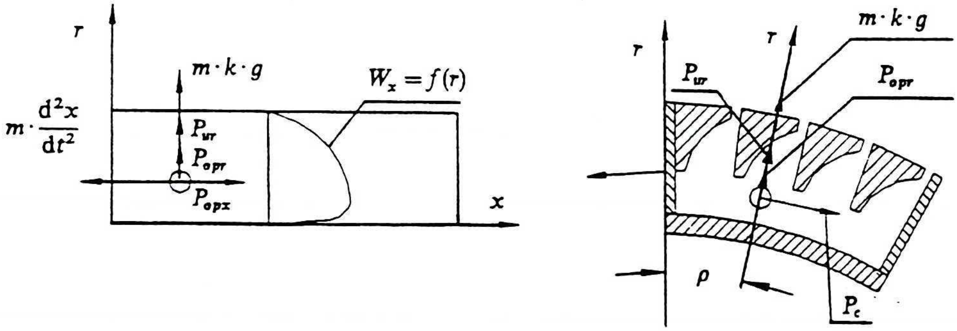

Fig. 2. Details of the forces acting on a dust particle within rotating channel of the rotor

Neglected terms in the above written equations of motion can be justified as below.

Rotation of the particle around its own axis was neglected as well as the flow carrying forces acting on a particle due to this effect (see Ref. [12]). This can be explained commencing from the equation of motion of the rotating rigid body:

$$I \cdot \frac{\mathrm{d}\omega}{\mathrm{d}t} = M_t. \tag{4}$$

The moment developed by the friction acting on a sphere of radius R which rotates with angular velocity ω inside of the viscous liquid due to Ref. [15] is given by

$$M_t = \pi \cdot \mu \cdot d^3 \cdot \omega. \tag{5}$$

Substituting formula (5) into equation (4) together with the required moment of inertia and integrating obtained equation leads to a particular solution:

$$\omega = \omega_0 \cdot e^{\frac{60 \cdot \mu}{\rho_m \cdot d^2} \cdot t}. \tag{6}$$

This analytical result was used to derive particular numerical results for the paper. However, the final conclusion derived from them states that the quartz dust particles of diameters less than 10 μm practically after at least $8.5 \cdot 10^{-3}$ sec may possess angular velocity equal to the surrounding them gas. Having in mind that for the dust particle considered dimensions – the length of the rotor channels will be tenth times greater than distances of the acting flow carrying forces – this allows to neglect these force terms.

Gradient of the pressure in fact implies forces acting on a particle in the radial direction. Within rotating channels of the dust separator ODP-225 the mean value of this gradient is equal to:

$$\frac{\mathrm{d}p}{\mathrm{d}r} = 10\,800 \text{ Pa/m}. \tag{7}$$

It was assumed that the force exerted on a particle having cubic shape with a side d is given by the formula:

$$\Delta P_c = \frac{\mathrm{d}p}{\mathrm{d}r} \cdot d^3. \tag{8}$$

On the other hand, the centrifugal force acting on a spheric particle of diameter d can be expressed by:

$$\Delta P = \frac{\pi}{6} \cdot d^3 \cdot \rho_c \cdot r \cdot \omega^2. \tag{9}$$

To compare numerically those forces it was additionally supposed that $\rho_c = 2000$ kg/m^3, $r = 0.1$ m, $n = 2985$ rpm. In these circumstances from (9) was found that $\Delta P_{od} \cong 9\,327\,000$ d^3 N and from the formula (8) that $\Delta P_c \cong 10\,800 \cdot d^3$ N. It means that centrifugal forces are 860 times greater that corresponding gradient pressure forces. For this reason they can be neglected in such considerations.

Gradient of the pressure acting in the axial direction in the same conditions becomes about 50 times smaller than the radial gradient of the pressure. This means that it is also reasonable to neglect this term in such considerations as presented in this paper.

Equations (1) through (3) describe the particle motion within channels directed parallelly to the direction of the angular velocity. Solving this system of equations leads to the derivation of the particle trajectories – what becomes the essential factor regarding the efficiency of the dust separation.

SIMPLIFIED EQUATIONS OF MOTION DESCRIBING BEHAVIOUR OF THE PARTICLES IN ROTATING CHANNELS

Numerical experience based upon solutions of the general case suggests that for the dust particles whose dimension is less than 10 μm there is a possibility to neglect factors and terms which do not contribute to the foregoing motion of such small particles. This simplification does not affect significantly the resulting trajectory of the dust particles but leads to the significant reduction of the computer time necessary to complete numerical analyses of such cases and offers much simpler picture of the dust particle motion.

With this in mind the further analysis was conducted based upon assumptions:

- velocity of the particle in the rotating channel is equal to the velocity of the gas at the same point;
- gravity acceleration term due to the condition $r \cdot \omega^2 \gg g$ was been neglected;
- the dust particles radiuses are less than 10 μm.

To justify the above assumptions the following reasoning was applied:

- for the dust particles of diameter $d < 10$ μm and $\rho_c = 2000$ kg/m^3 the particle velocity satisfies condition $W_{cx} < 6 \cdot 10^{-3}$ m/s. Therefore, having in mind that W_x the mean flow velocity becomes of order 10–25 m/s – it leads to $\left(W_x - \frac{\mathrm{d}x}{\mathrm{d}t}\right) = 0$;
- for the dust particles $r \cdot \omega^2 \gg g$. Remaining parameters are: $r = r_{\min} = 0.09$ m, $r = r_{\max} = 0.1125$ m, $n = 2985$ rpm. It leads to the condition 8794 m/s^2 < $< r \cdot \omega^2 <$ 10992 m/s^2, which allows to neglect the second term in the expression $(r \cdot \omega^2 - g \cdot \cos\varphi)$.

Eventually the equations of motion will take the shape:

$$\frac{\mathrm{d}W_r}{\mathrm{d}t} = r\cdot\omega^2 - B\cdot C_x\cdot W_r\cdot\sqrt{W_r^2+(\omega_w\cdot r)^2}; \tag{10}$$

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = 2\cdot\frac{\omega}{r}\cdot W_r + B\cdot r\cdot\omega_w^2. \tag{11}$$

Equations (10) and (11) were solved numerically. In Fig. 3 are shown trajectories of the dust particles within rotating channel by assuming a constant speed of the axial air flow for every radial coordinate. In Fig. 4 the axial flow velocity was varying (with the radial coordinate) preserving the mean value equal to $\bar{W}_x = 10$ m/s.

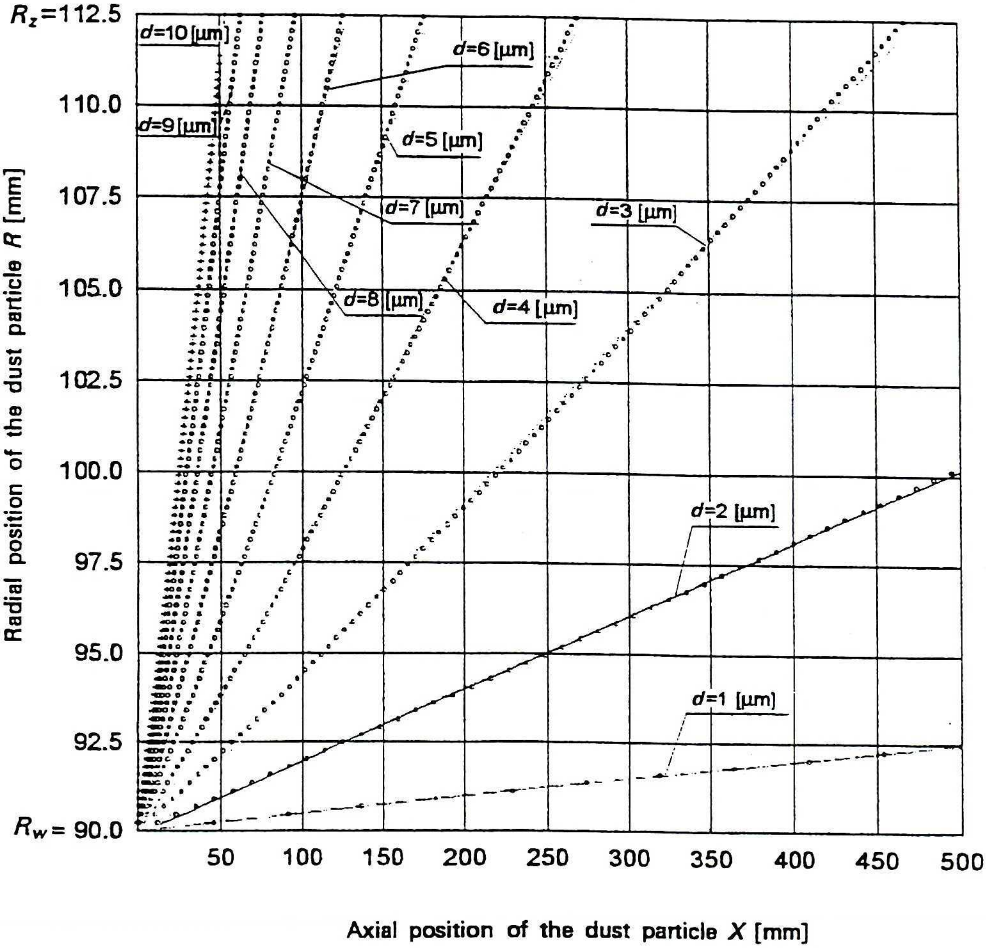

Fig. 3. Trajectories of the spherical dust particles for a constant axial speed

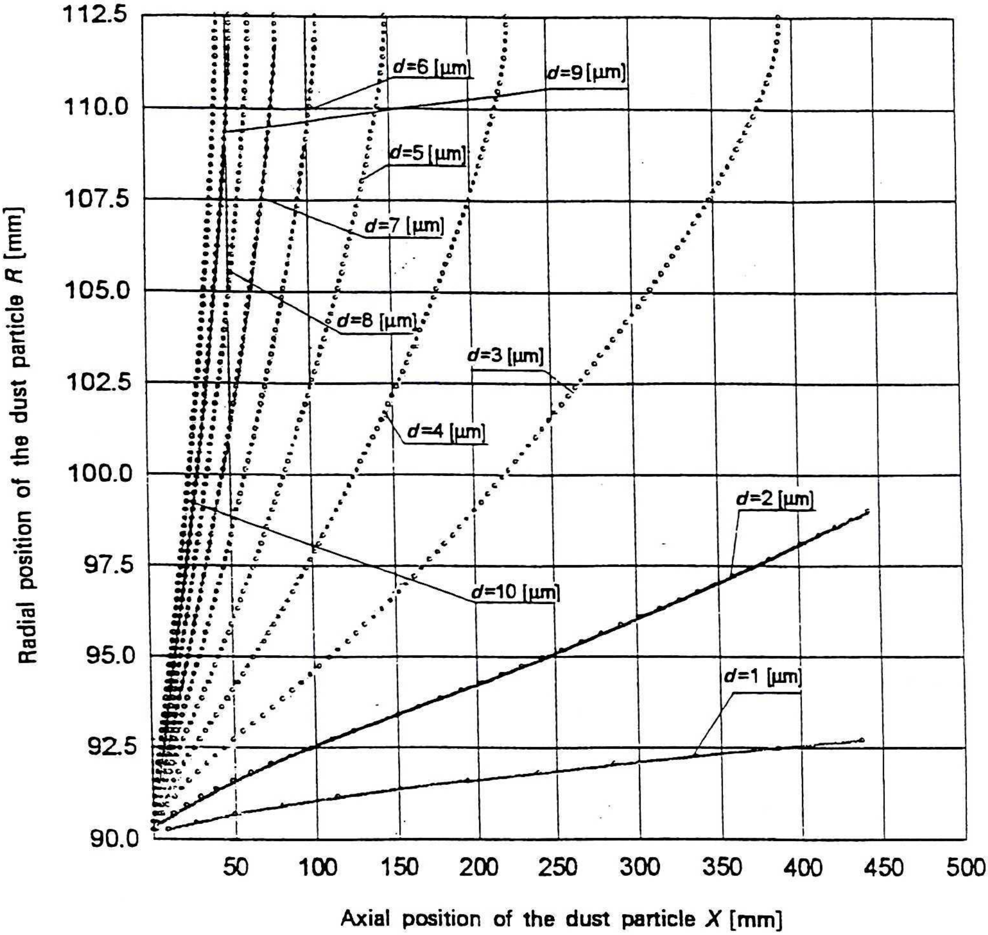

Fig. 4. Trajectories of the spherical dust particles for the axial speed varying in radial direction

Presented in Fig. 3 and Fig. 4 examples were solved assuming, moreover, some particular numerical values listed below:

1) dust particle diameters $d = 1, \ldots, 10$ µm,
2) dust particle density $\rho_c = 2000$ kg/m^3,
3) initial radial position of the particle regarding the axis of rotation $r_p = 90$ mm,
4) angular velocity of the rotor $n = 2850$ rpm,
5) gas flow speed within the channel constant for the entire cross section $W_x = 10$ m/s,
6) channel axis was parallel to the axis of rotation, corresponding radiuses of the channel were inner radius $R_w = 90$ mm, outer radius $R_z = 112.5$ mm, accordingly.

Examining results shown in Fig. 3 and Fig. 4 one may find how the dust particle trajectories evolve due to the changes in their axial velocity. It is seen that reducing axial speed results in greater radial deflection which in turn increases the efficiency of the separation.

THE EFFICIENCY OF THE DUST SEPARATION PROCESSES

However, the efficiency of the dust separation processes becomes the function of the dust particle concentration – the assessment of the efficiency becomes one of the essential issues in practicing dust separators. Therefore, the simplified procedure leading to the rough account of this quantity is given.

Basic simplifications and assumptions:

- dust particle sizes probability distribution and dust particle material are known;
- known are working parameters of the dust separator such as diameter and length of the rotor channels, angular velocity of the rotor, flow intensity, input temperature of the medium (to be separated);
- geometry of the dust separator channels satisfies the geometrical similarity conditions regarding the standard dust separator ODP-225.

Related conditions, definitions and assumptions:

- limiting diameter d_g is referring to the case that the particle trajectory begins at the radial distance R_w and reaching the exit of the rotor channel, i.e. travelling the total axial distance L_k will be radially located at the distance R_z. In this circumstances a particle leaves the separator, i.e. the corresponding efficiency for the particles of the greater diameter than d_g becomes 100%;
- limiting radius $R_g(d)$ for the particle of a given diameter d assesses that the path trajectory of the particle under attention, which at the inlet begins at this distance and ends at the exit at the radial distance R_z, will leave the dust separator while travelling the total distance L_k. Particles with diameters d less than d_g may also reach the maximum efficiency 100% under additional condition that their initial radial distance is equal to the corresponding limiting radius $R_g(d)$;
- concentration of the dust particles at the inlet is directly proportional to the intensity of the gas flow;
- dust particle which has left the channel cannot return again to the channel;
- radial velocity distribution of the dust particles corresponds to the results known from the standard dust separator ODP-225.

With the above in mind it can be seen that the efficiency of the dust separator under consideration can be estimated by the amount of the dust particles whose trajectories ended before reaching in radial direction the value of the external radius of the rotor. In this way the formula (12) was obtained:

$$\eta = 100 - \frac{1}{Q_c} \sum_{i=1}^{T} [0.5 \cdot \Delta M_1(i) + M_1(i)] \cdot \Delta Q(i), \tag{12}$$

here:

$M_1(i)$ – mass fraction of the particles with diameter $d(i) < d_{gr}$, at radius $R(i) > R_w$,

$\Delta M_1(i) = M_1(i+1) - M_1(i)$ – mass fraction of the particles from the strata $R(i+1)$ and $R(i)$,

$\Delta Q(i)$ – mass flow associated with the strata $R(i+1)$ and $R(i)$,

Q_c – total mass flow.

To illustrate the above result numerical calculations related to the dust separator ODP-225 were performed. This procedure used the data known for the experimental investigations listed below:

1. Quartz dust particles designated as 10 W with the probabilistic characteristics of its sizes in Fig. 5.

2. Velocity distribution for the radial direction of the channel corresponds to the standardised velocity profile registered for the dust separator ODP-225 – as shown in Fig. 6.

3. Limiting dust particle diameter derived numerically $d_g = 2.75$ μm.

4. Limiting radiuses R_g for the particles $d < d_g = 2.75$ μm – below the sizes of the limiting diameter given numerically in Tab. 1 and shown in Fig. 7.

5. Cross sections of the channel in axial direction.

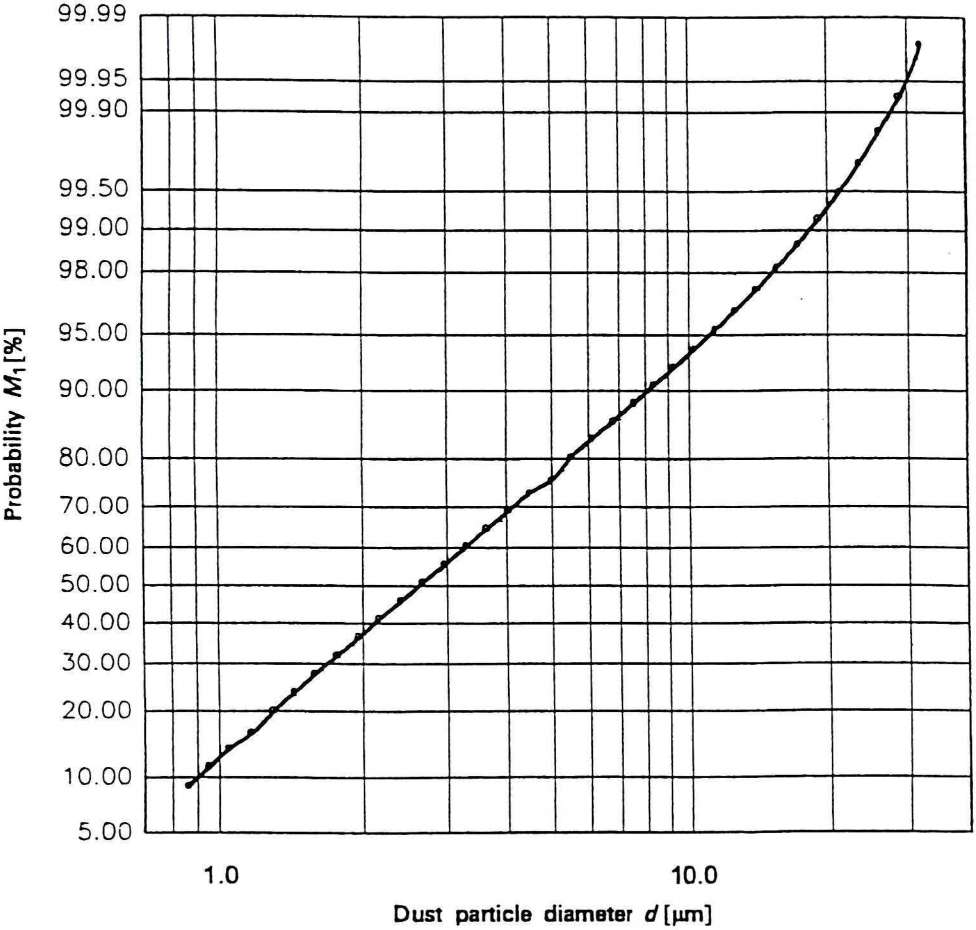

Fig. 5. Probability density of the dust particle sizes

Results shown in Fig. 5 were derived by using the Laser-Particle-Sizer made by the Fritsch and named analysette 22. Its principle of action uses the process of interferences which occurs while monochromatic laser light strikes analysed particles. The further process uses the theory named after Fraunhofer and strictly speaking is applied down to about the size of the wavelength of the

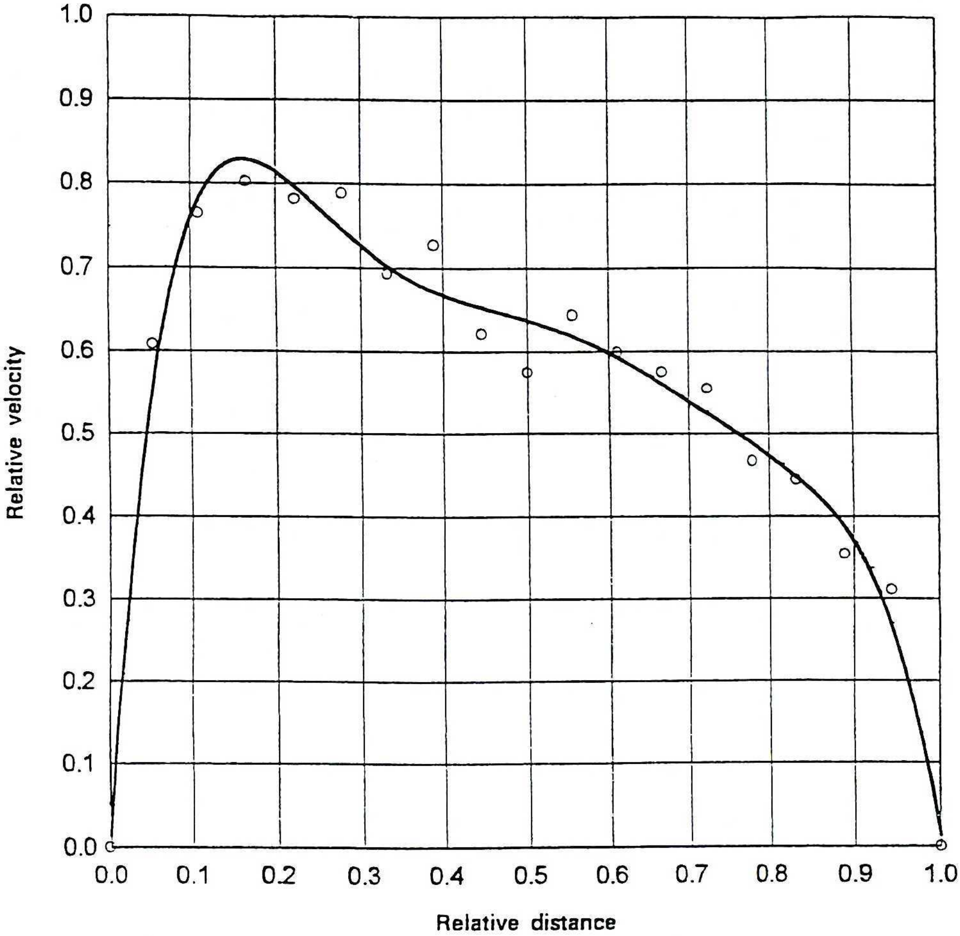

Fig. 6. Distribution of the relative velocity as a function of the relative position

Table 1. Limiting radiuses for different dust particle sizes below limiting diameter $R_g = 3$ μm

Particle diameter d [μm]	Limiting radius R_g [mm]	Particle diameter d [μm]	Limiting radius R_g [mm]
0.5	111.6	1.75	102.82
0.75	110.7	2.0	99.9
1.0	109.12	2.25	96.97
1.25	107.32	2.5	93.6
1.5	105.3	2.75	90.22

incident light which in this case has a length of about 0.6328 μm. They can be displayed either as the probability density function or as a probability distribution function (as shown in Fig. 5).

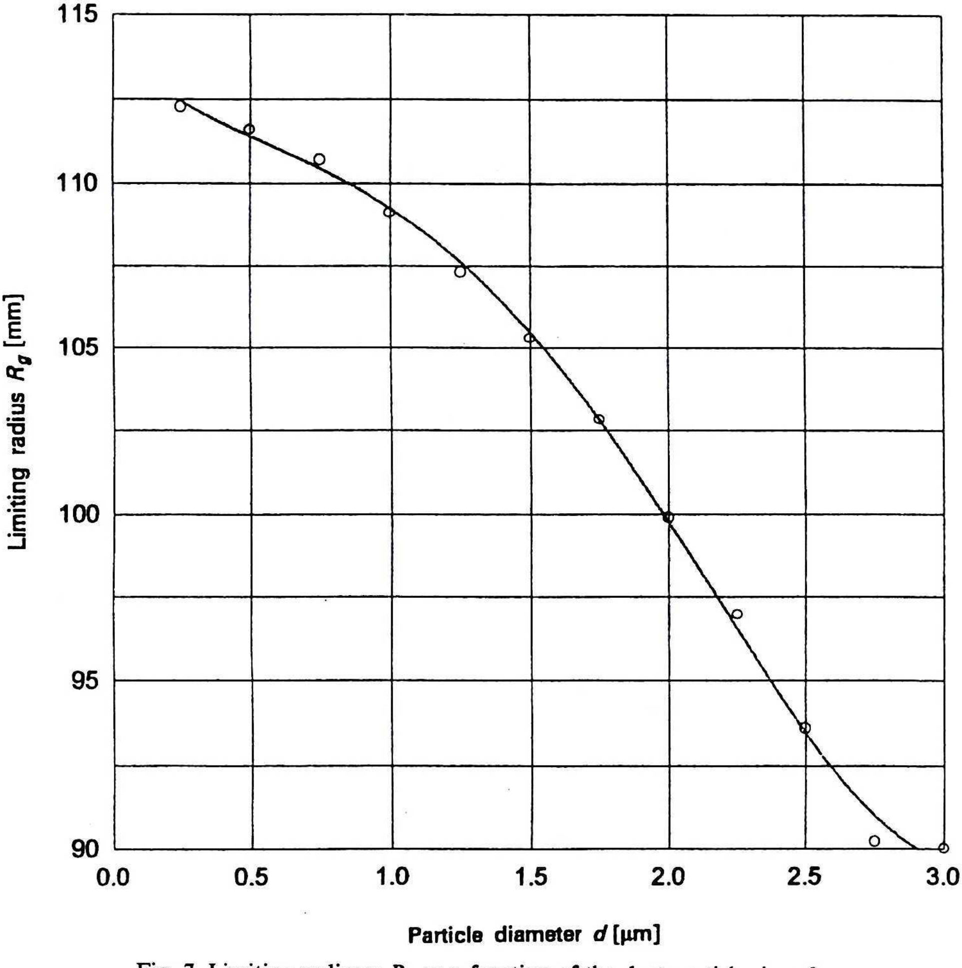

Fig. 7. Limiting radiuses R_g as a function of the dust particle sizes d

A COMPARISON BETWEEN EXPERIMENTAL RESULTS AND THEORETICAL PREDICTIONS

To enable a comparison between theoretical predictions and experimental results regarding the efficiency of the dust separation it was assumed identically for both – the experiments and the theory – that:

- angular speed – $n = 2850$ rpm,
- mass flow – $Q = 608.6\ m^3/h$,
- dust material – quartz,
- sizes probability distributions as shown in Fig. 5.

In these circumstances the efficiency derived theoretically and experimentally quite ideally coincided – as shown below:

$$\eta_{\text{theory}} = 96.5\%, \qquad \eta_{\text{exper}} = 97.5\%.$$

EXPERIMENTAL STAND TO TEST THE DUST SEPARATOR

TESTING STAND LAYOUT

Important components of the experimental stand are shown in Fig. 8. From the left to right one may see supplying dust devices (container, generator of vibrations and a pipeline), leading to the main devices – the dust separator – connected with a pipeline which is functioning as a controlling and measuring devices from which the gas enters the radial fun closing the experimental line.

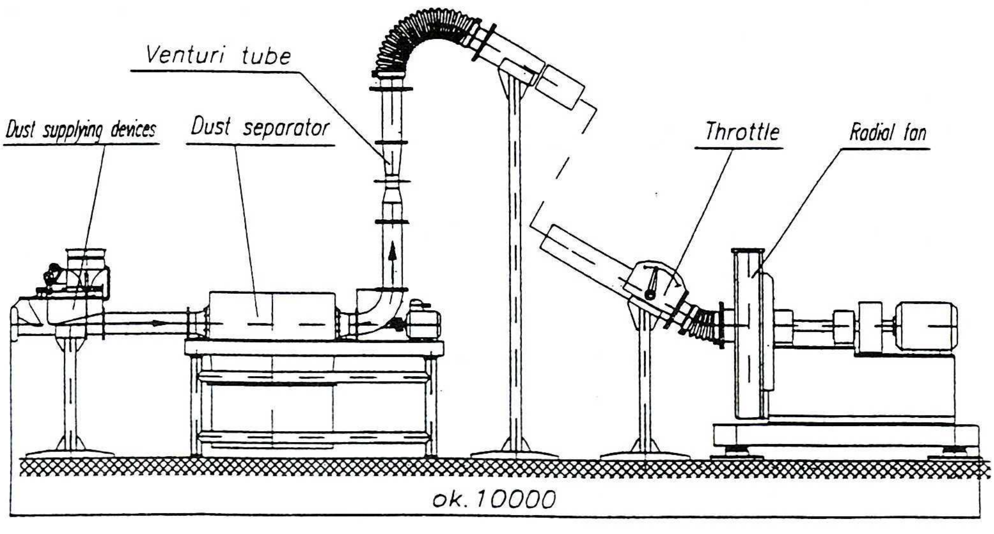

Fig. 8. Outlook of the experimental stand

To control the gas flow and measure its parameters there is a sequence of instruments which begins with a Venturi tube to determine the mass flow; afterwards, it was settled the sounding part which supplies the samples of the gas, and then – a throttle. The rotor is driven by the asynchronous electric motor coupled with the frequency modulator.

THE DESIGN AND WORKING PROCEDURE OF THE DUST SEPARATOR

The design of the rotating dust separator is shown in Fig. 9. The dimensions indicated there are given in millimetres. The major part of the separator becomes the rotor 1 which is supported by bearings 2 and 3 at the both ends.

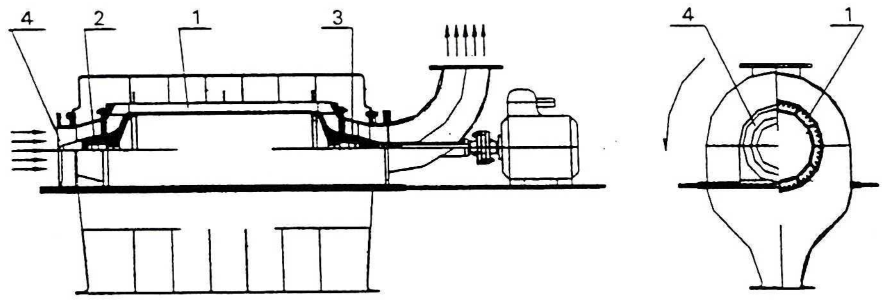

Fig. 9. Radial cross-section of the dust separator

The inlet 4 has a collar designed to connect the separator with the pipe line conducting dust material. The input and the output of the dust separator are similar each to another although the mouth of the devices is designed with a connector leading to the electric engine which runs the separator. The inlet of the dust separator is followed by the parallel channels separated by the slats through-out the entire cylindrical part of the rotor. The profile-like slats have a special holes to enable separated dust particle to leave the devices.

The dust separator is fed from the natural sources of the gas which is going to be cleaned. The flow is directed towards the rotor. The flow transfers the gas in the axial direction, while the angular speed of the rotor implies radial inertial forces which cause an intensive radial transgression of the heavy dust particles to the outer edges of the rotor. From there through-out the special holes the dust particles leave eventually the rotating channels and then fall onto a special container at the bottom part of the dust separator. The exit of the dust separator is also formed into a collar which on its part is designed for coupling with the collar of the pipe line conveying free of the dust particles gas to the atmosphere.

It has to be mentioned that the investigated dust material was quartz due to its satisfactory recurrent structure which in repeated experiments assesses their high similarity. The same does concern the physical source supplying the dusty gas to the experimental stand.

SOME INVESTIGATIONS REGARDING THE EFFICIENCY OF THE DUST SEPARATOR

INTENSITY OF THE DUST FRACTION AT THE INLET

For the entire accessible range of the intensity with which the fraction of the dust particles occurs within the gas there were no visible effects implying the efficiency of the dust separator under investigation. The results of the investigations are collected in Tab. 2 and Fig. 10. The series of three measurements was done during the testing procedure. There are some differences in obtained results but they are placed within expected boundaries of the experimental errors and some imperfections in assessing the uniform density of the dust particles, and the procedure to catch precisely the timing of the investigated separation.

Table 2. Intensity of the contaminants versus efficiency

Number	Dust concentration C_1 [g/m^3]	Angular velocity of the rotor [rpm]	Flow intensity Q [m^3/h]	Efficiency η [%]
1	11.12	2850	640	95.0
2	28.75	2850	640	95.6
3	90.93	2850	640	95.3

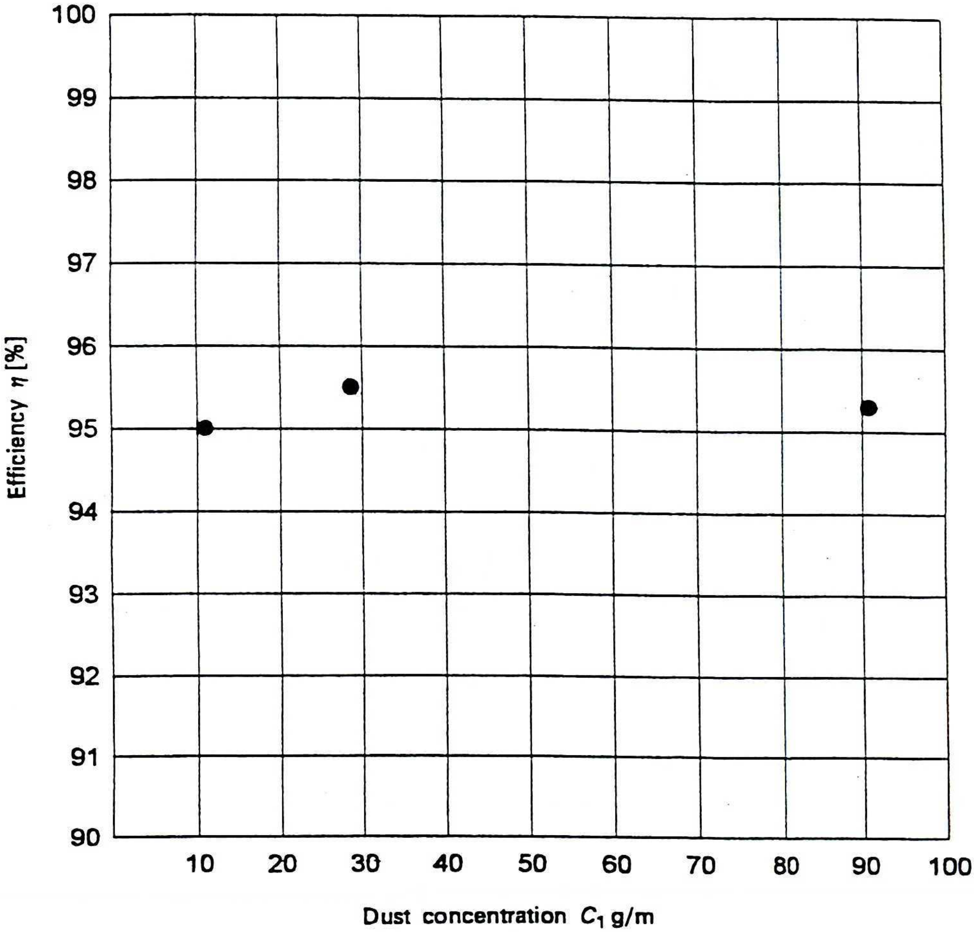

Fig. 10. Intensity of the dust fraction vs. dust separation efficiency

FLOW RATE VARIATIONS

From the rational point of view, changing the flow rate should change the efficiency of the dust separator. Increasing the flow rate implies an increase in required time of passing through the separator. This suggestion reflects apparently another simple implication: the shorter time of acting the gravitational field the poorer results in dust separation. In fact, experimental results do not prove this suggestion – changing the flow rate more than twice practically did not cause observed essential changes in the efficiency of the dust separation as it is shown in Tab. 3 and Fig. 11. To explain this apparent paradox we propose to take into account another factor which may play important role in changing the effects of the separation. We suppose that an increase in the flow rate affects the flow direction at the inlet, which in turn increases accelerations acting on dust particles. To watch more carefully those changes were conducted five experiments, their results are presented in Tab. 3 and Fig. 11.

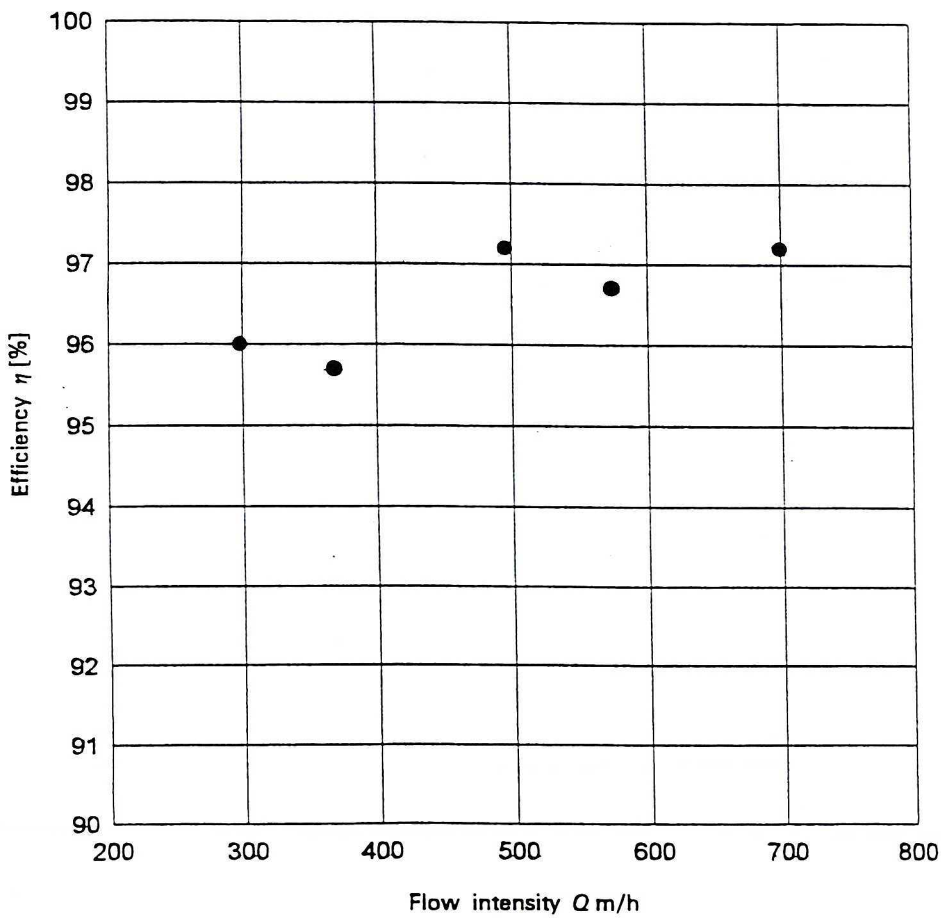

Fig. 11. Flow rate variations versus the dust separation efficiency

Table 3. Flow rate variations versus the dust separation efficiency

Number	Flow intensity Q [m³/h]	Angular velocity of the rotor [rpm]	Efficiency η [%]
1	299.1	2850	96.0
2	369.6	2850	96.0
3	495.9	2850	96.0
4	575.0	2850	96.0
5	700.4	2850	96.0

SUMMARY AND CONCLUSIONS

Presented and analysed in this paper procedure of the separation of the dust particles shows new and quite encouraging possibilities in this respect. Existing devices, such as cyclonic dust separators, precipitation chambers, and/or gravitational dust separators, although use the inertial separation but the accelerations implied upon dust particles within such devices are lower by an order in comparison with the accelerations developed by the proposed devices. This fact plays a decisive role in the observed increase of the efficiency regarding proposed design. In this newly designed dust separator many parameters can be fixed due to the actual needs. The total time of acting accelerations upon a dust particle, mean velocity of the particle moving along the channels, their cross section, flow intensity, and angular velocity of the rotor can be adjusted regarding the desire and current needs of the user. By fixing the dust material properties, shapes and density their foregoing motion can be numerically predicted.

Some general conclusions can be now reiterated:

1. Processes and motion of the two phase flow (as well multi phase flows) described here and taking place within rotating channels are in favour of the separation different phases, especially the solid phase (as well liquid phase) which posses a high degree of dispersion.

2. Efficiency of the phase separation becomes a function of the accelerations developed during rotation (the angular velocity), the shape of the cross sections of the rotating channel, the axial length of the channel, flow parameters, and the dispersion of the dust particles and their density.

3. Solutions of the simplified equations of motion gives rise to determine with a satisfying accuracy the efficiency of the dust separation if the probabilistic characteristics of their sizes, together with the radial geometry of the channels and parameters describing the flow motion are known. These relations give chance for the proper choice of the all mentioned parameters at the designing stage of the dust separator under attention.

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