Industrial separators for gas cleaning

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INDUSTRIAL SEPARATORS FOR GAS CLEANING

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ELSEVIER SCIENTIFIC PUBLISHING COMPANY
Amsterdam — Oxford — New York — 1979

Published in co-edition with
SNTL Publishers of Technical Literature, Prague

Distribution of this book is being handled by the following publishers

for the U.S.A and Canada
Elsevier North-Holland, Inc.
52 Vanderbilt Avenue
New York, N. Y. 10017

for East European Countries, China, Northern Korea, Cuba, Vietnam and Mongolia
SNTL Publishers of Technical Literature, Prague

for all remaining areas
Elsevier Scientific Publishing Company
335 Jan van Galenstraat
P.O. Box 211, 1000 AE Amsterdam, The Netherlands

Library of Congress Cataloging in Publication Data

Štorch, Otakar.
Industrial separators for gas cleaning.
(Chemical engineering monographs; v. 6)
Translation of Čištění průmyslových plynů a exhalací odlučovači.

Bibliography: p.
Includes index.
1. Separators (Machines) 2. Gases—Cleaning—Equipment and supplies. 3. Dust—Removal—Equipment and supplies.
TP 159. S4S7513 628.5'3'2 78-10916
ISBN 0-444-99808-X

ISBN 0-444-41295-6 (series)

Translation by Julius Freundlich

Printed in Czechoslovakia

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Foreword

In these times of constant progress in technology, of rapidly expanding industries and ever new processing techniques in so many of them, industrial gas cleaning is rapidly gaining in scope and importance. Gas cleaning facilities are nowadays indispensable ancillaries of every plant where, for economic or environmental reasons or both, solid or liquid particles have to be separated out from a gas stream. Moreover, the equipment used for this purpose up to now is increasingly falling short of the ever more stringent requirements imposed by public health regulations, so that much of it is growing ripe for replacement by new, more efficient and more dependable installations. In most countries, the introduction of new and replacement of existing gas cleaning facilities is being hastened by legislation which reflects our growing awareness of the enormity of the damage caused by industrial air pollution.

All too often, however, any rational selection of gas cleaning equipment is hampered by the sheer diversity of types now on the market. The prospective buyer is confronted by a wide range of units based on entirely different physical principles, and with a huge variety of others which, although identical in their basic principles, differ substantially in detail design.

This book therefore sets out to review the existing types of gas cleaning equipment; to outline their underlying principles and principal design features; to list their chief technical data, their relative advantages and drawbacks; and to facilitate the choice by making a few recommendations about the kinds of equipment which are most suitable for some of the major industries. Most of these recommendations are based on long-term experience, but some have of necessity had to be founded on theory rather than on accumulated know-how.

Apart from this survey of the presently available gas cleaning equipment, the book also deals in brief outline with the fundamentals of the dust handling techniques involved in the operation of this equipment. This aspect is all too often underrated; yet it is a fact, borne out by dearly paid experience, that no one can design, install or operate gas cleaning facilities properly unless he is fully familiar with the problems specific to the field of dust handling.

Symbols and terminology

a	(microns), (m)	Particle diameter
a	$(\mathrm{m\,s^{-2}})$	Acceleration
a_{mean}	(m)	Mean particle diameter
a_1	(microns)	Reduced equivalent diameter of a fictitious spherical particle
b_v	$(\mathrm{m\,s^{-2}})$	Acceleration by centrifugal field
f	$(\mathrm{s\,m^{-1}})$	Specific area of collecting surface
g	$(\mathrm{m\,s^{-2}})$	Acceleration by gravity
h	(hours)	Annual utilization of separator
i	$(\mathrm{A\,m^{-1}})$	Specific current intensity
i	$(\mathrm{kJ\,kg^{-1}})$, $(\mathrm{kcal\,kg^{-1}})$	Enthalpy per kg of matter
k	$(\mathrm{kg\,m^{-3}})$	Concentration of solid or liquid particles in gas
k_0	$(\mathrm{g\,m^{-3}})$, $(\mathrm{kg\,m^{-3}})$	The part of k_p trapped in the separator, $k_0 = k_p - k_v$
k_p	$(\mathrm{g\,m^{-3}})$, $(\mathrm{kg\,m^{-3}})$	Particle concentration in gas at separator inlet
k_v	$(\mathrm{g\,m^{-3}})$, $(\mathrm{kg\,m^{-3}})$	Particle concentration in gas at separator outlet
l	(m)	Thickness of dust layer at time of resistance measurement
m_m	(kg)	Mass of solid particle
—	$(\mathrm{m_n^3})$	1 $\mathrm{m^3}$ at +20 °C and 1 atmosphere
m_v	(kg)	Mass of macroparticle of gas
n	$(\mathrm{kg^{-1}})$	Number of particles in 1 kg of dust
p	(Pa)	Gas pressure
p_0	(Pa)	Reference gas pressure
p_p	(Pa)	Partial pressure of saturated water vapour
q_p	$(\mathrm{C\,kg^{-1}})$	Electrical charge of 1 kg of dust
r	$(\mathrm{J\,kg^{-1}\,{}^{\circ}K^{-1}})$	Specific gas constant
r	(m)	Half diameter of cyclone outlet
r	(m)	Half diameter of wire electrode
r	(m)	Radius of curvature
r_m	(m)	Radius of solid particle trajectory
r_v	(m)	Radius of gas flow line

t	(°C)	Temperature
u'	–	Amortization factor of separating equipment
u''	–	Amortization factor of enclosed space in buildings
u'''	–	Amortization factor of floor space occupied by separators
v_i	($m\ s^{-1}$)	Average ion velocity in electric field
v_m	($m\ s^{-1}$), ($cm\ s^{-1}$)	Particle velocity
v_k	($m\ s^{-1}$), ($cm\ s^{-1}$)	Terminal particle velocity
v_p	($m\ s^{-1}$), ($cm\ s^{-1}$)	Free falling velocity of particle
v_r	($m\ s^{-1}$)	Centripetal velocity component
v_u	($m\ s^{-1}$)	Circumferential velocity component
v_v	($m\ s^{-1}$), ($cm\ s^{-1}$)	Gas flow velocity
v_v	($m\ s^{-1}$)	Absolute velocity of gas macroparticle
v_z	($m\ s^{-1}$)	Axial velocity component
v_D	($m\ s^{-1}$)	Velocity related to cross section of cyclone of diameter D
v_F	($cm\ s^{-1}$)	Flow speed of filtered gas
w	($cm\ s^{-1}$)	Mean (effective) separating brisk velocity in electrostatic precipitator
x	($kg\ kg^{-1}$)	Specific moisture content
A	($m^3\ hour^{-1}$)	Make-up water needed for separator
A	($m^3\ kg^{-1}$)	Constant for permittivity calculations, dependent on gas or particle material
C	($N\ m^{-1}$)	Surface tension
C_a	(crowns m^{-3})	Water costs
C_e	(crowns kWh^{-1})	Electricity costs
C_n	(crowns)	Annual costs of spares and replacement parts
C_{oz}	(crowns)	Cost price of separating equipment
C_p	(crowns m^{-3})	Cost of enclosed space in buildings
C_u	(crowns m^{-2})	Cost of floor space
C_{12}	($N\ m^{-1}$)	Surface tension at interface of solid and liquid
C_{13}	($N\ m^{-1}$)	Surface tension at interface of solid and gas
C_{23}	($N\ m^{-1}$)	Surface tension at interface of liquid and gas
D	($m^2\ s^{-1}$), ($cm^2\ s^{-1}$)	Diffusion coefficient
E	(kW)	Power input for fan drive
E'	(kW)	Total power input for separator and all its ancillaries
F	($V\ m^{-1}$)	Electric field intensity
F_0	($V\ m^{-1}$)	Initial critical intensity of electric field
G	($kg\ s^{-1}$), ($kg\ hour^{-1}$)	Mass flow through separator

G_c	(N)	Gravitational force of particle
G_m	(kg)	Weight of solid particles
G_o	(kg)	The part of G_p trapped in the separator, $G_0 = G_p - G_v$
G_p	(kg)	Weight of solid or liquid particles entering the separator
G_v	(kg)	Weight of solid or liquid particles leaving the separator untrapped
H_d	(hours)	Annual shutdown time for replacing components
H_u	(hours)	Annual shutdown time for maintenance
I	(A)	Electric current intensity
K_m	(%)	Cost coefficient for erection and installation work
K_p	(%)	Cost coefficient for design work
M_d	(crowns hour^{-1})	Wage rate of equipment operator, including overheads allowance
M_u	(crowns hour^{-1})	Wage rate of maintenance worker, including overheads allowance
MO	(microns), (m s^{-1})	Separation limit
N		Number of molecules per mol (*Loschmidt number*)
N_1	(crowns per 1000 m^3)*	Cost of project and design work
N_2	(crowns per 1000 m^3)*	Cost price of separating equipment
N_3	(crowns per 1000 m^3)*	Cost of erection/installation work
N_4	(crowns per 1000 m^3)*	Costs of buildings to house separating equipment
N_4'	(crowns per 1000 m^3)*	Cost of site for separating equipment
N_5	(crowns per 1000 m^3)*	Electricity costs for fan drive
N_6	(crowns per 1000 m^3)*	Total electricity costs for separator operation
N_7	(crowns per 1000 m^3)*	Water costs
N_8	(crowns per 1000 m^3)*	Costs of spares and replacements
N_9	(crowns per 1000 m^3)*	Wage bill for operation and routine maintenance
N_{10}	(crowns per 1000 m^3)*	Wage bill for installation of replacements
O_c	(%)	Overall collecting efficiency
O_d	(%)	Partial collecting efficiency
O_f	(%)	Fractional collecting efficiency
P	(N)	Force, electrical forces

*Note: Costs N_1 to N_{10} are referred to 1000 m^3 of cleaned gas.

P_m	(m^2)	Particle surface area
P_n	(N), (kp)	Force perpendicular to the gas flow
P_t	(N), (kp)	Force opposing the motion of a macroparticle of gas
P'_m	($m^2\ kg^{-1}$)	Specific surface area of particles
PMO	(microns), ($m\ s^{-1}$)	Approximate separation limit
$\bar{P}$	(Pa)	Vector of pressure gradient
$\bar{P}_n$	(Pa)	Pressure gradient component perpendicular to gas flow lines
$\bar{P}_t$	(Pa)	Pressure gradient component tangential to gas flow lines
Q	($m^3\ s^{-1}$), ($m^3\ h^{-1}$)	Volumetric flow rate
Q_c	(C)	Electric charge of particles
Q_{c1}	(C)	Electric charge of one particle
Q_h	($m^3\ s^{-1}$), ($m^3\ h^{-1}$)	Throughflow capacity of separator
Q_n	(C)	Saturated particle charge
Q_τ	(C)	Parcicle charge in time τ
R	($J\ mol^{-1}\ {}^\circ K^{-1}$)	Molar gas constant
R	(N)	Aerodynamic drag
R	(ohms)	Resistance of dust layer
R	(m)	Half diameter of centrifugal chamber in a cyclone
R	(m)	Half diameter of tubular electrode
R	(m)	Gap between wire and plate electrodes
S	(m^2)	Surface area of dust layer at time of resistance measurement
T	(K)	Thermodynamic temperature of gas
T_0	(K)	Reference absolute temperature of gas
U	(V)	Feed voltage
U_0	(V)	Initial critical voltage
U_p	(V)	Arc-over voltage
V	(m^3)	Enclosed space needed for separator operation and maintenance
V'	(m^2)	Floor space needed for separator operation and maintenance
V_m	(m^3)	Volume of solid particles
V_s	(m^3)	Apparent bulk volume
Z	(%)	Proportion of retained particles
$Z(a)$	–	Retained fractions curve related to a
$Z(v_p)$	–	Retained fractions curve related to v_p
$-\frac{dZ}{da}$	–	Particle frequency related to a

$-\frac{dZ}{dv_p}$	–	Particle frequency related to v_p
$-\frac{dZ(a)}{da}$	–	Particle size distribution curve related to a
$-\frac{dZ(v_p)}{dv_p}$	–	Particle size distribution curve related to v_p
α	(degrees)	Angle of impact
β	–	Damping coefficient
β	–	Relative charging coefficient (ratio of real to saturated particle charge)
β_{mean}	–	Mean relative charging coefficient
δ	–	Relative weight of gas in given reference state
ε	($F\ m^{-1}$)	Permittivity
ε_0	($F\ m^{-1}$)	Permittivity of vacuum ($8.855 \cdot 10^{-12}$)
ε_r	–	Relative permittivity
η	(Pa s)	Dynamic viscosity of gas
ϑ	(degrees)	Angle between liquid/solid interface and tangent to liquid surface at point of contact between solid, liquid and gas (contact angle)
$\varkappa$	–	Charging coefficient
λ	–	Excess air ratio in combustion process
ν	($m^2\ s^{-1}$)	Kinematic viscosity of gas
ξ	–	Drag coefficient of particle
ξ_D	–	Aerodynamic resistance coefficient of separator
ϱ	($kg\ m^{-3}$)	Specific gravity
ϱ_i	($C\ m^{-3}$)	Space charge of gas ions
ϱ_{im}	($C\ m^{-3}$)	Maximum space charge of gas ions
ϱ_k	($kg\ m^{-3}$)	Specific gravity of fluid
ϱ_m	($kg\ m^{-3}$)	Specific gravity of a solid particle
ϱ_p	($C\ m^{-3}$)	Space charge of dust
ϱ_{pn}	($C\ m^{-3}$)	Saturated space charge of dust
ϱ_s	($kg\ m^{-3}$)	Bulk density
ϱ_{st}	($kg\ m^{-3}$)	Tapped density
ϱ_v	(ohmmetres)	Specific resistance of dust layer
τ	(s)	Time; time elapsed since start of charging
ω	(s^{-1})	Angular velocity
Δh	(Pa)	Pressure drop across the separator at $\varrho = 1\ kg\ m^{-3}$
Δp	(Pa)	Pressure drop across the separator
Δp_F	(Pa)	Pressure gradient across filter cloth

Explanations of some of the terms

Particle diameter a (microns or m)

This measure of solid or liquid particle sizes is either the diameter of a spherical particle which will just pass through a screen with a mesh size of *a*, or else the diameter of a fictitious spherical particle with the same free falling velocity and same specific gravity as the real particle under consideration (i.e the equivalent particle diameter).

Free falling velocity v_p (m s^{-1})

This is the speed at which the particle will descend, under the effect of gravity alone, in a stationary volume of carrier gas. For Reynolds' numbers up to and including unity, it can with sufficient accuracy be established from *Stokes's expression*

$$v_p = \frac{1}{18} a^2 \frac{\varrho_2 - \varrho_1}{\eta} g \qquad (1)$$

Terminal velocity v_k (m s^{-1})

This is the ultimate speed which the particle will attain, relative to the carrier gas, under the effects of the equilibrium of forces acting upon it in the separator.

Proportion of retained particles Z (%)

This is the numerical proportion, or proportion by weight, of particles which exceed a specified value of the parameter which characterizes the particle size; in other words, which exceed a given mesh size, equivalent diameter, free falling velocity, or actual particle size, in terms of *a* or v_p.

Retained fractions curve $Z(a)$ *or* $Z(v_p)$

This curve (Fig. 1) shows how the magnitude of *Z* varies with the value of the characteristic parameter *a* or v_p.

Particle incidence $-\dfrac{dZ}{da}$ *or* $-\dfrac{dZ}{dv_p}$

This quantity, related either to the number of particles or to their weight, is the negative value of the figure obtained by differentiation of the retained particle proportion *Z* by the size-governing parameter (*a* or v_p).

Particle size distribution curve $-\frac{dZ(a)}{da}$ *or* $-\frac{dZ(v_p)}{dv_p}$

This curve (Fig. 1) indicates how the frequency of incidence of any given particle size varies with the value of the size-governing parameter (such as a or v_p).

Overall collecting efficiency O_c (%)

This is the ratio (multiplied by 100) between the weight of solid or liquid particles trapped in the separator (G_0) and the weight of these particles (G_p) entering that separator in the carrier gas within a certain span of time, at a certain flow rate and physical state of the carrier gas, and given a certain concentration and a certain set of physical properties of the particles,

$$O_c = \frac{G_o}{G_p} 100 \tag{2}$$

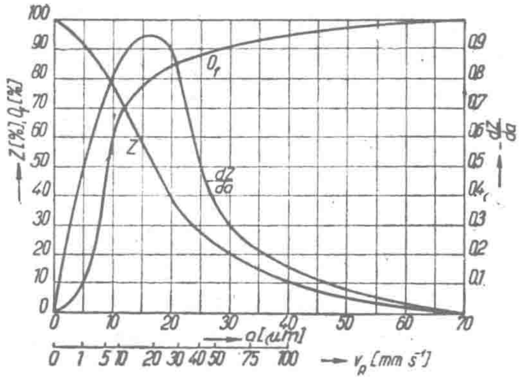

Fig. 1 How the proportion of retained particles Z, the particle frequency $-\frac{dZ}{da}$, and the fractional collecting efficiency O_f vary with the equivalent particle size a.

Since the weight of solid or liquid particles entering the separator equals the sum of the weight of particles trapped (G_0) and the weight of particles leaving the separator untrapped (G_v), i.e. $G_p = G_0 + G_v$, we can also define O_c as

$$O_c = \frac{G_o}{G_o + G_v} 100 = \frac{G_p - G_v}{G_p} 100 \tag{3}$$

Fractional collecting efficiency O_f (%)

This is the ratio (multiplied by 100) between the weight of solid or liquid particles with a certain magnitude of the size-governing parameter which are trapped in the separator, and the weight of particles with the same magnitude of that parameter which enter the separator in the carrier gas, again at a certain flow rate and physical