INDUSTRIAL GAS CLEANING

(2nd Edition – S I Units)

International Series in Chemical Engineering Volume 8

W. STRAUSS

INDUSTRIAL GAS CLEANING

SECOND EDITION

The principles and practice of the control of gaseous and particulate emissions

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PERGAMON PRESS

OXFORD · NEW YORK · TORONTO
SYDNEY · PARIS · BRAUNSCHWEIG

U.K.	Pergamon Press Ltd., Headington Hill Hall, Oxford OX3 0BW, England
U.S.A.	Pergamon Press Inc., Maxwell House, Fairview Park, Elmsford, New York 10523, U.S.A.
CANADA	Pergamon of Canada, Ltd., 207 Queen's Quay West, Toronto 1, Canada
AUSTRALIA	Pergamon Press (Aust.) Pty. Ltd., 19a Boundary Street, Rushcutters Bay, N.S.W. 2011, Australia
FRANCE	Pergamon Press SARL, 24 rue des Ecoles, 75240 Paris, Cedex 05, France
WEST GERMANY	Pergamon Press GmbH, 3300 Braunschweig, Postfach 2923, Burgplatz 1, West Germany

First edition 1966
Second edition 1975

Library of Congress Cataloging in Publication Data

Strauss, Werner.
Industrial gas cleaning.

(International series of monographs in chemical engineering, v. 8)

Bibliography: p.

1. Gases—Cleaning. 2. Fume control. I. Title.

TP242. S75 1975 628.5'3 74-8066

ISBN 0-08-017004-8

ISBN 0-08-019933 x (f)

Printed in Hungary

PREFACE TO THE SECOND EDITION

As READERS of the first edition are aware, this book attempted to review critically the science, technology and "state of the art" of cleaning industrial process and waste gases, with particular emphasis on the control of atmospheric pollution. During the six-year period since the completion of the manuscript of the first edition, there have been some major developments in the technology of gas cleaning, with lesser, but still significant, theoretical developments.

These technological developments include processes for removing sulphur dioxide from flue gases, improvement in the design of direct-flame incinerators, filter materials suitable for temperatures to 400°C and a reverse-flow cyclone, to name only a few. These developments have made the revision of the book an urgent one. The new edition also gives the writer an opportunity to correct a number of errors found in the first edition. He wishes to express his thanks to all those who have written to him pointing these out.

The first edition has been found suitable by many as a textbook for graduate courses and special courses in air-pollution-control technology. In view of this, a brief section has been appended giving some examination questions which were used by the writer. If teachers and practitioners in the field develop new questions, particularly numerical ones, the author would be pleased to receive these to incorporate in future editions.

A criticism levelled at the first edition was that no cost information was included. At that stage this was deliberate as, with the exception of the work of Stairmand,[804] very little had been done in this area. More recently, however, some attempt has been made to assess costs in the United States, England and Australia, and this will be published elsewhere by Mr. J. R. Alonso.[15] A new chapter, Chapter 12, has been added which will help in assessing cost of plants, although it is not intended as a guide to detailed costing.

The author wishes to acknowledge the help by discussions and friendly criticism he has received in the preparation of this new edition from his colleagues and research students at the University of Melbourne and at the Westinghouse Research Laboratories, in particular Prof. S. R. Siemon and Dr. E. V. Somers. He also wishes to acknowledge gratefully the help he has received in the careful revision of the manuscript from Miss V. Carter and Mrs. D. Muir.

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PREFACE TO THE FIRST EDITION

THE control of air pollution at its major and most varied source, the industrial process, is a task confronting an increasing number of engineers and applied scientists. When starting his postgraduate studies some years ago the author was set the problem of finding a new method of reducing the fumes from steel-making processes, with particular emphasis on the fine orange-brown fumes from the then recently introduced oxygen lancing in the open-hearth and the pneumatic steel-making processes. The new process was to be cheaper than the conventional methods used—electrostatic precipitation or venturi scrubbing—although the efficiency requirements were not quite as rigorous. Subsequently a pebble-bed type filter was developed and found to be over 90 per cent efficient in some circumstances.[332]

At the beginning of the programme of research no details of fume emission at the various stages of open-hearth steel making could be found in the published literature, and even if the fume characteristics had been defined, the possible mechanisms of collection were not set down in a textbook or monograph, together with the relevant equations which could be used to test the applicability of a particular mechanism. The author found further that gas cleaning was treated by its practitioners largely as an art based on practical experience and rule of thumb. Although the basic theory of gas-cleaning mechanisms was published in scattered papers, no integrated account of these was available to engineers who wished to use them in "scale-up" calculations or in predicting the effect of a change in one of the process variables, such as gas velocity through a cleaning system. Even now only two aspects of gas cleaning, absorption and electrostatic precipitation, have received extensive treatment, while the gas-cleaning methods involving particle mechanics generally have not been comprehensively reviewed. The author hopes that this book will go some way towards filling this gap, and that it will prove useful to the engineer designing or specifying gas-cleaning plant as well as to the applied scientist developing new methods of gas cleaning.

The author wishes to acknowledge the assitance and encouragement he received from Prof. M. W. Thring, who first directed his interests towards this field, and from his colleagues, in particular, Mr. R. S. Yost, who is responsible for Appendix I, Mr. C. H. Johnson, who read and made many helpful suggestions with respect to Chapters 4 and 7, and Mr. J. B. Agnew, who similarly assisted with parts of Chapter 3. The author is particularly indebted to the Engineering Librarian, Mr. J. Greig, and his staff, for their help with references and diagrams, and Mrs. F. M. Beissel, for her careful typing of the manuscript.

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LIST OF SYMBOLS

Latin Letters

a	constant
	interfacial or surface area per unit volume
	height of cyclone entrance line
	distance from node
	coefficient of diffuse reflection
A	surface area
	aggregate surface area of particles in unit volume
A_p	external surface area of a porous solid
$\mathcal{A}$	area of plates in electrostatic precipitator
	amplitude of sound vibrations
b	constant
	time fraction wind is in a 45° sector
	entrance width of cyclone
	(ab = cross-sectional area of cyclone entry)
B	breadth of settling chamber
	diameter of opening at cone apex in cyclone
c	constant
	concentration (mass or volume) of particles in gas
c_0	number of particles at zero time
	centre-line particle concentration
C	Cunningham correction factor
C_D	drag coefficient
C_{DA}	drag coefficient for accelerating particles
C_0	function of applied voltage $\mathcal{V}$ and electrode geometry ($\mathcal{V}/\ln R_2/R_1$)
C_p	specific heat, constant pressure
C_v	specific heat, constant volume
C_y	generalized eddy diffusion coefficient—cross wind (Sutton[843])
C_z	generalized eddy diffusion coefficient—vertical (Sutton[843])
$\mathcal{C}$	constant
d	diameter of spherical particle
d'	diameter of sphere of influence
d_A	area diameter (diameter of circle with same projected area as that of particle)

d_c	diameter of cloud
d_e	drag diameter
d_s	surface diameter (diameter of sphere with same surface area as particle)
d_v	volume diameter (diameter of sphere with same volume as particle)
d_{crit}	diameter of smallest particle 100 per cent collected
d_{50}	diameter of particle 50 per cent collected
D	diameter of cyclone
	diameter of collecting body (fibre, droplet, rod or sphere)
	diameter of sampling probe
D_C	diameter of core
D_e	diameter of exit pipe in cyclone
$\mathcal{D}$	diffusivity (Brownian)
e	electronic charge
	charge on an ion
e	turbine efficiency
E	strength of heat source relative to surrounding atmosphere ($J\,s^{-1}$; W)
	field strength of electric field ($V\,m^{-1}$)
E'	strength of charging field
$\mathcal{E}$	energy intensity (sonic) ($J\,m^{-3}$)
E_c	critical field strength for electrical breakdown of gases
f	free falling speed of particles
	Fanning friction factor
F	fluid resistance force on particle
F_h	hydrodynamic attractive force in sonic field
F_r	radiation pressure in a sonic field (N)
F_t	thermal force
F_c	fluid resistance to clouds
F_E	electrostatic force
F_{EI}	electrostatic image force (image of collector induced on particle)
F_{EM}	electrostatic image force (image of particle induced on collector)
F_{EC}	coulombic force
F_{ES}	space charge force
F_W	fluid resistance corrected for wall effects
g	gravity acceleration
g_c	gravity-acceleration constant
G	potential temperature gradient in the atmosphere (°C m^{-1})
	force on a particle
	friction constant (Stairmand) for cyclones
$\mathcal{G}$	gravitational settling parameter
h	height of cylindrical section of cyclone
H	total height of smoke plume (effective stack height)
	height of settling chamber
	height of cyclone (or length, if cyclone body curved)

H	field strength of magnetic field (A-turn m^{-1})
H_S	chimney stack height
H_t	height of a transfer unit (gas absorption)
H_T	buoyancy rise of plume
H_V	momentum rise of plume (velocity rise)
$\mathscr{H}$	Henry's law constant
i	ionic current per unit length of conductor
I	light intensity
	index of agglomeration (sonic)
$\mathscr{I}$	sound intensity
J	variable in Bosanquet buoyancy rise equation
k	orifice coefficient
	extinction coefficient
k	Boltzmann's constant
k_f	mass-transfer coefficient—gas to solid surface
k_G	gas-film mass transfer coefficient
k_L	liquid-film mass transfer coefficient
K	correction factor
K_G	overall mass-transfer coefficient (pressure units)
K_L	overall mass-transfer coefficient (concentration units)
l	distance between two particles
	distance for absorption
$\boldsymbol{l}$	distance between enclosing walls
L	rate of liquid flow
	depth of filter bed
	length of settling chamber
	distance between wire and plate in electrostatic precipitator
	distance moved by particle in sonic field
L_1	ratio of liquid flow to gas flow in scrubber (lm^{-3})
m	mass flow
	mass of particle
	irregularity factor—a function of wire condition
M	molecular weight
M'	weight of a molecule
M	rate of deposition (mg m^{-2}/day)
$\mathscr{M}$	function of weights of particles and ions
n	turbulence index (Sutton)
n	number of times greater than the force of gravity
N	molecules per unit volume
	number of points
N_1	ions per unit volume
N	number of revolutions
$\mathscr{N}$	number of revolutions of gas stream in cyclone

N_A	rate of molecular transfer of species A
p_A	partial pressure of component
p_{AM}	logarithmic mean partial pressure of component A
p_i	partial pressure at interface
P	total gas pressure
P_c	cyclone gas pressure (average)
P_i	cyclone inlet gas pressure
Pe	Peclet number
$\mathcal{P}$	power
$\boldsymbol{P}$	probability of collection
Δp	pressure drop
Δp_{CF}	pressure drop with constant gas flow
q	charge on a particle (subscript I refers to particle I)
Q	gas-flow rate ($m^3 s^{-1}$, $m^3 h^{-1}$)
	charge on a collecting body
Q'	rate of emission of pollutant gas
r	radius of particle
	distance between centre of particle and centre of collector
r	resistivity of dust layer
$\bar{r}$	average pore radius
R	universal gas constant
	radius of a circle
	radius of precipitator wire and tube
	interception parameter (d/D)
R_A	drag on accelerating particles
Re	Reynolds number ($u\varrho D/\mu$—pipes, $ud\varrho/\mu$—particles)
Re_c	Reynolds number—collecting body($v_0 D\varrho/\mu$)
R_h	half distance between sphere centres for hexagonal particle arrangement
S	cross-sectional area of absorption tower
	retentivity of charcoal (Turk's equation 3.60)
	stopping distance
	width of corona layer on discharge electrode
	influence factor (ratio of diameter of sphere of influence of particle and actual particle diameter)
	depth of cyclone exit pipe within cyclone
S_*	dimensionless stopping distance
Sc	Schmidt number ($\mu/\varrho\mathcal{D}$)
$\mathcal{S}$	collection surface in electrostatic precipitator per unit volume gas flow
t	time
T	absolute temperature
T_s	stack exit gas temperature
T_1	absolute temperature at which density of stack gases equals density of atmosphere (K)

u	gas velocity
	wind velocity
	molecular velocity
$\bar{u}$	average velocity
	average velocity of gas molecules
u_g	velocity amplitude of gas
u_H	axial velocity
u_i	inlet velocity
	ionic mobility in a field of unit strength
u_p	velocity amplitude of particle
u_R	radial velocity
u_s	superficial velocity
u_t	terminal velocity
u_T	tangential velocity
u_τ	shear velocity
U	average gas velocity
U_S	velocity of sound
v	velocity
	stack exit velocity
v_0	undisturbed upstream fluid velocity
Δv	relative velocity of two particles
V	rate of gas flow (absorption)
	volume of settling chamber
V_a	swept volume
V_A	volume of species A at normal boiling point
$\mathcal{V}$	voltage, potential difference
V_1	voltage of collecting body
$\mathcal{V}_c$	corona starting voltage
V_d	potential across deposited dust layer
w	thickness of refractory
W	rate of solids emission
	weight of adsorbing solid
	distance between successive wires in electrostatic precipitator
x	downwind distance from stack (plume dispersion)
	mole fraction
	downstream distance in precipitator
	thickness of boundary layer
	thickness of dust layer
	dust content of filter cloth
	exponent in voltage/corona current equation
x_e	equilibrium dust content of filter cloth
X	function in Bosanquet buoyancy equation
X_g	amplitude of gas vibration

X_p	amplitude of particle vibration
y	cross wind distance (plume dispersion)
	mole fraction
Z	function in Bosanquet equation
	height of absorption tower
	diffusion collection parameter
z	particles per m^2 of fibre

Greek Letters

α	constant
	blade angle
	entrance loss coefficient for cyclone
	packing density
β	constant
	loss constant
	volume concentration correction factor
γ	specific heat ratio (C_p/C_v)
$\in$	porosity or voidage of a packed bed or porous solid
ϵ	dielectric constant of an aerosol particle
ϵ_0	specific inductive capacity of space ($8{\cdot}85\times10^{9}$ A^{2}N^{-1})
ε	loss number
ζ	dimensionless pressure-loss factor
η	efficiency
η_C	interception-collection efficiency
η_D	diffusion-collection efficiency
η_I	inertial-impaction collection efficiency
η_0	overall efficiency
η_{ICD}	combined efficiency
η_z	particle collection efficiency on fibre
θ	angle of particle movement
	parameter for cylindrical coordinate
$\varkappa$	permeability coefficient
	thermal conductivity
	coagulation constant
$\varkappa_g$	thermal conductivity of gas
$\varkappa_p$	thermal conductivity of particle
$\varkappa_{gtr}$	translational part of thermal conductivity of gas
λ	mean free path of gas molecules
	wavelength of sound waves
μ	viscosity of gas
μ_d	viscosity of droplet
ν	frequency

ξ	constant for free vortex formula
ϱ	gas density
ϱ_F	fibre bed density
ϱ_L	density of liquid
ϱ_V	density of vapour
ϱ_p	density of particle
σ	molecular diameter
	surface tension
	space charge per unit volume
σ_{AB}	sum of radii of two interacting molecules or ions (distance between centres)
τ	dimensionless time parameter
	time constant
	dimensionless precipitator length $(x/Lf(\mathcal{D}))$
	period of vibration
τ_0	fluid shear stress at wall
T	parameter $(= mu_T^2/3\pi\mu dR_2)$
φ	friction factor for cyclones (Stairmand formula)
Φ	current density ($\mathrm{A\,m^{-2}}$)
	dimensionless drift velocity parameter
χ	internal porosity of solid granules
	circularity of particles
ψ	inertial impaction parameter
Ψ	sphericity
ω	drift velocity
ω'	effective migration velocity

CONTENTS