WIND FLOW AND VAPOR CLOUD DISPERSION AT INDUSTRIAL AND URBAN SITES

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It is sincerely hoped that the information presented in this volume will lead to an even more impressive safety record for the entire industry. However, the American Institute of Chemical Engineers (AIChE), its consultants, the Center for Chemical Process Safety (CCPS) Subcommittee members, their employers, and their employers' officers and directors and Hanna Consultants, Dr. Steven Hanna and Dr. Rex Britter, disclaim making or giving any warranties or representations, express or implied, including with respect to fitness, intended purpose, use or merchantability, and/or correctness or accuracy of the content of the information presented in this document. As between (1) American Institute of Chemical Engineers, its consultants, CCPS Subcommittee members, their employers, and their employers' officers and directors and Hanna Consultants, Dr. Steven Hanna and Dr. Rex Britter, and (2) the user of this document, the user accepts any legal liability or responsibility whatsoever for the consequences of its use or misuse.

This book is available at a special discount when ordered in bulk quantities. For information, contact the Center for Chemical Process Safety at the address shown above.

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Preface

For over 40 years the American Institute of Chemical Engineers (AIChE) has been involved with process safety and loss control in the chemical, petrochemical, hydrocarbon process and related industries and facilities. The AIChE publications are information resources for the chemical engineering and other professions on the causes of process incidents and the means of preventing their occurrences and mitigating their consequences.

The Center for Chemical Process Safety (CCPS), a Directorate of the AIChE, was established in 1985 to develop and disseminate information for use in promoting the safe operation of chemical processes and facilities and the prevention of chemical process incidents. With the support and direction of its advisory and management boards, CCPS established a multifaceted program to address the need for process safety technology and management systems to reduce potential exposures to the public, the environment, personnel and facilities. This program entails the development, publication and dissemination of *Guidelines* relating to specific areas of process safety; organizing, convening and conducting seminars, symposia, training programs, and meetings on process safety-related matters; and cooperating with other organizations and institutions, internationally and domestically to promote process safety. Within the past several years CCPS extended its publication program to include a "Concept Series" of books. These books are focused on more specific topics than the longer, more comprehensive *Guidelines* series and are intended to complement them. With the issuance of this book, CCPS has published almost 80 books.

CCPS activities are supported by the funding and technical expertise of over 80 corporations. Several government agencies and nonprofit and academic institutions participate in CCPS endeavors.

In 1989 CCPS published the landmark *Guidelines for the Technical Management of Chemical Process Safety*. This book presents a model for process safety management built on twelve distinct, essential and interrelated elements. The Foreword to that book states:

> For the first time all the essential elements and components of a model of a technical management program have been assembled in one document. We believe the *Guidelines* provide the umbrella under which all other CCPS Technical Guidelines will be promulgated.

This Concept Series Book supports several of the twelve elements of process safety enunciated in the landmark *Guidelines for the Technical Management of Chemical Process Safety* including process risk management, incident investigation, process knowledge and documentation, and enhancement of process safety knowledge. The purpose of this book is to assist designers and operators of chemical facilities to more realistically estimate the effects of on-site and nearby plant structures, process equipment, buildings and other "obstacles" on the transport and dispersion of releases of hazardous materials.

This book should also be useful for emergence response and homeland safety and security personnel who must deal not only with accidental episodic releases but also with deliberate acts.

Acknowledgments

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Dr. Ronald J. Lantzy of Rohm and Haas Corporation initially chaired the Vapor Cloud Modeling Subcommittee. Mr. David Fontaine of Chevron Corporation assumed the chairmanship in June 2000. The other subcommittee members were: Gene K. Lee, Air Products & Chemicals Corporation; Donald J. Connolley, AKZO Nobel Chemicals, Incorporated; William J. Hague, Honeywell International Incorporated; Manny Vazquez, Honeywell International Incorporated, John T. Marshall, Dow Chemical Company; Wilfred K. Whitcraft, DuPont Company; Kenneth W. Steinberg, ExxonMobil R & E; Jeff Robertson, Numerical Applications, Incorporated; Malcolm L. Preston, Eutech; Martin Tasker, Eutech; Mr. Joseph R. Natale, ExxonMobil R & E; Daniel C. Baker, Equilon Enterprises LLC; Albert G. Dietz, Jr.,United States Department of Energy, Jawad Touma, United States Environmental Protection Agency; Breeda Reilly, United States Environmental Protection Agency; Jerry M. Schroy, Solutia, Incorporated; David McCready, Union Carbide Corporation;

Rashid Hamsayeh, Formosa Plastics Corporation, and Richard D. Siegel, Roy F. Weston, Incorporated. The contributions of Sanford G. Bloom, and Doug N. Blewitt are also acknowledged. Martin E. Gluckstein was the CCPS Staff Liaison and was responsible for the overall administration and coordination of the project.

Before publication, all CCPS books are subjected to a thorough peer review process. CCPS also acknowledges the thoughtful comments and suggestions of the peer reviewers John Woodward of Baker Engineering and Risk Consultants, Craig Matthiessen of the United States Environmental Protection Agency, and Jan Windhorst of Nova Chemicals.

Dr. Steven Hanna and Dr. Rex Britter acknowledge the contributions of Dr. Pasquale Franzese, who prepared many of the tables and figures in this book, as well as the read-me files for the CD-ROM. They further acknowledge Linda Hanna of Hanna Consultants, who has been responsible for publication and distribution of the drafts sent to the AIChE Vapor Cloud Modeling subcommittee for review.

List of Symbols

A, B, C, D, E, F	The Pasquill stability class scheme, with A very unstable, B moderately unstable, C slightly unstable, D neutral, E slightly stable, and F very stable.
A	Constant in dispersion Eqs. (56) and (58)
A'	Constant in dispersion Eqs. (66) and (67)
A_f (m^2)	Vertical cross-section or frontal area of obstacle facing the wind.
A_p (m^2)	Horizontal or plan area of obstacle
A_T (m^2)	Total lot area of each obstacle
B and C_g	Often experimentally determined functions of the shape and geometric arrangement of the roughness elements (Schlichting, 1968, and Raupach et al., 1991).
$c_p = 1005$ J $kg^{-1}K^{-1}$	Specific heat of air at constant pressure
C (kg/m^3 or ppmv)	Concentration of pollutant
C/Q (s/m^3)	Normalized concentration
$C(z)$ (kg/m^3 or ppmv)	Height-variable concentration of pollutant in the cloud
C_y (kg/m^2 or ppmv-m)	Crosswind integrated concentration

d (m)	Displacement length
D	Constant in Eq. (14)
f (1/s)	Coriolis force or parameter
$g = 9.8$ m/s^2	Acceleration of gravity
G (m/s)	Free stream or geostrophic wind speed at the top of the boundary layer
h_e (m)	Effective height of plume above ground
H_r (m)	Height of obstacles
HS	Horizontal solidity or lack of porosity of an obstacle, ranges from 0.0 to 1.0
H_s (J/sm^2)	Surface heat flux $H_s = c_p \rho u^* \theta^*$
I	Flow interference constant in Eq. (21)
K (m^2/s)	Eddy diffusivity coefficient
L (m)	Monin–Obukhov length $L = -(u^{*3}/\kappa)/(gH_s/c_p \rho T)$
L (m)	Along-wind length of obstacle
ppmv	Concentration unit of parts per million volume
Q (kg/s)	Continuous source emission rate
Q_t (kg)	Instantaneous source emission
Ri	Richardson number
S_x (m)	Along-wind separation between obstacles
S_y (m)	Crosswind separation between obstacles
T (K)	Temperature
T' (K)	Fluctuation in temperature
T_I (s)	Integral time scale of turbulence
T_{Ix} (s)	Integral time scale of along-wind turbulence
T_{Iy} (s)	Integral time scale of lateral turbulence
T_{Iz} (s)	Integral time scale of vertical turbulence
u (m/s)	Wind speed
$u(z)$ (m/s)	height-variable wind speed
u_{avg} (m/s)	Average cloud speed over time of travel, t
u_c (m/s)	Characteristic wind speed in urban/industrial obstacles
u_e (m/s)	Effective cloud speed, u_e (m/s) $\int u(z)C(z)\,dz / \int C(z)\,dz$
u_{ref} (m/s)	Mean reference wind speed
u^* (m/s)	Friction velocity

u^*_{local} (m/s)	Local friction velocity observed at height z
u_o^* (m/s)	Friction velocity appropriate for flat area in between buildings but with buildings removed
u' (m/s)	Longitudinal wind speed fluctuation
VS	Vertical solidity or lack of porosity of an obstacle, ranges from 0.0 to 1.0
w^* (m/s)	Convective scaling velocity
w' (m/s)	Vertical wind speed fluctuation
W (m)	Crosswind width of obstacle
WD	Wind direction
x (m)	Downwind distance
x_o (m)	Along-wind position of center of puff
x_v (m)	Virtual source distance
y (m)	Crosswind distance from the plume centerline
y_o (m)	Lateral position of center line of plume or puff
z (m)	Height above ground
z_i (m)	Mixing depth
z_{ibl} (m)	Height of internal boundary layer
z_m (m)	Height of instrument above ground
z_o (m)	Surface roughness length
z_{ref} (m)	Reference height (typically between about 2 m and 10 m).
θ (K)	Potential temperature
θ^* (K)	Scaling potential temperature, about –0.1 K at night and 1.0 K in the day
κ	Von Karman constant (assumed to equal 0.4)
$\lambda_p = A_p/A_T$	Ratio of obstacle plan area to lot area
$\lambda_f = A_f/A_T$	Ratio of obstacle frontal area to lot area
ν	Kinematic molecular viscosity $\nu = 1.5 \times 10^{-5}$ m^2/s for air
ρ (kg/m^3)	Air density, equal to 1.2 kg/m^3 at sea level at a temperature of 293 K
σ_u (m/s)	Turbulent velocity fluctuations in the along-wind (x) direction
σ_v (m/s)	Turbulent velocity fluctuations in the lateral (y) horizontal direction

σ_w (m/s)	Turbulent velocity fluctuations in the vertical (z) direction
σ_x (m)	Along-wind dispersion component
σ_y (m)	Lateral dispersion component
σ_z (m)	Vertical dispersion component
τ_o (kg/m/s^2)	Surface stress

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Introduction

1.1. Background

U.S. regulations require that the potential concentrations of toxic or flammable substances in the atmosphere must be calculated as part of health, environmental and safety assessments at and near industrial facilities. For example, these calculations may be part of planning studies, may be used in real-time hazard assessments, or may be part of submittals to regulatory agencies. Similar requirements are often set in other countries. The calculations are needed for routine emissions, such as combustion emissions from stacks, as well as for accidental episodic emissions. These issues are addressed using atmospheric transport and dispersion models, which require a variety of meteorological inputs, often including boundary layer scaling parameters such as surface roughness length, z_0, displacement length, d, friction velocity, u^*, and Monin–Obukhov length, L. Most of these models are being applied by technically trained individuals who are aware of but are not necessarily expert in dispersion phenomena. A need exists for a straightforward guidelines document that describes the meteorological variables of importance for calculating vapor and aerosol concentrations at industrial facilities where the buildings and structures influence the calculations. The basis for parameters such as the surface roughness length needs to be described and methods included for how to estimate that parameter from readily available information such as site plans of industrial plants. It is important to account for the site roughness because the maximum ground level concentration for near-ground releases tends to decrease by about a factor of two for each order of magnitude increase in surface roughness length, z_0.

Practically all models currently available for dispersion calculations implicitly assume that the depth of any vapor cloud is considerably greater than the height of nearby buildings and obstacles. For releases near and within an industrial facility, this is unlikely to always be the case. The appropriateness of existing models for application to industrial facilities must be objectively assessed. For many actual scenarios, models do not currently exist. We have developed within this book a number of novel approaches that may be useful to dispersion calculations in real scenarios.

This book is written at a level so that it is useful to persons such as the *on-site engineer*, the *designer,* the *process hazards analysis (PHA) team member*, and *regulatory personnel*, as well as *fluid dynamicists and transport and dispersion modelers*. It is important to clearly define parameters and methods because this is a cross-discipline activity being carried out by engineers, meteorologists, chemists, economists and others. The book is intentionally short and descriptive, similar to the AIChE/CCPS documents by DeVaull et al. (1995) entitled *Understanding Atmospheric Dispersion of Accidental Releases,* or by Hanna et al. (1996) entitled *Guidelines for Use of Vapor Cloud Dispersion Models*. The book is intended to mesh closely with those related AIChE/CCPS documents.

The book concentrates on explaining dispersion enhancement resulting from industrial buildings, tanks, pipe structures, and other facilities. Emphasis is on simplified descriptions of the effects of roughness obstacles on the boundary layer and on dispersion. Differences between the effects of the obstacles on dispersion of pollutant clouds or plumes with depths less than and greater than the average obstacle height, H_r, are described. Methods of estimating surface roughness length are outlined. Several worked examples based on varied industrial scenarios are presented in the book. A comprehensive list of references, a glossary, and an index are included, so that the book can be more easily used by practicing engineers and other readers and so that they will be able to obtain more detailed technical discussions if they are interested.

Although the focus of the book is on industrial sites, the methods are also applicable to urban sites. In both cases, the enhanced roughness effects are due to the presence of obstacles, and the geometric shapes and spacings of the obstacles are similar at both types of sites. The same physical principles apply. Also, many of the concepts used in this book were derived from observations and scientific analyses whose emphasis was on urban sites.

After reading the book, a person should be more conversant with dispersion phenomena near industrial plants and in urban areas and should have acquired the basics to use gas dispersion models, estimate surface roughness lengths for industrial facilities and urban areas and their surrounding areas, better communicate with regulators and the public, and develop more realistic risk management plans. Another outcome would be improved emergency response planning and preparedness.

1.2. Objectives of This Book

The previous subsection discussed the general background for the book, characterized its intended audience, and provided a brief overview of its contents. The current subsection lists five specific objectives of the book.

Objective 1: *To describe how structures (such as buildings, tanks, and pipe racks) at an industrial or urban site affect dispersion and show how these effects can be parametrized in consequence models.* The results are to be applicable to a wide variety of industrial sites, such as a chemical processing plant or oil refinery, a brewery or food processing plant, or a steel mill, to name a few. The results are also to be applicable to urban areas surrounding the industrial site. We start with the general assumption that the concentration downstream from a source is most strongly influenced by wind speed (advection) and turbulence (diffusion). The roughness obstacles at the industrial or urban site affect both of these – *above* the roughness obstacles, *within* the roughness obstacles, and *downstream* of the roughness obstacles. In most cases the effects generally enhance the cloud dilution. It is assumed that these methods have broad applicability to other regions marked by enhanced roughness, such as residential areas, urban areas, warehouse complexes, and vegetative canopies.

Objective 2: *To explain surface roughness length, z_o, and displacement length, d, so the concepts are understandable to scientists and engineers with little or no meteorological background, such as chemical process plant engineers, safety managers, and other users.* Relate the meteorological concepts to the concept of skin friction coefficients, which may be more familiar to engineers.

Objective 3: *To present criteria for when the structures should be considered broadly as roughness elements or when they should be considered from the viewpoint of their wake effects.* If one takes the "broad" view, there is no need to consider the details of the obstacles and they can be treated in a gross manner; this is desirable and simplifies the dispersion calculations. However, if some isolated large obstacles are present and there is a desire to consider the flow and dispersion near to these obstacles, a more detailed specific investigation may be necessary. Even when adopting the "broad" view, the specific approach may be quite different, depending on the ratio of cloud height to the roughness obstacle heights.

Objective 4: *To assure that the suggested formulas are applicable to a wide range of scenarios and give continuous solutions for values of input variables on the boundary between two regimes, such as rural and urban regions.* It is undesirable to have discontinuities between regimes where solutions are nonexistent or uncertain or where alternate formulas give divergent answers.

Objective 5: *To show how the methods for estimating the surface roughness length can provide inputs to transport and dispersion models that apply to a variety of initial cloud or plume buoyancies, including positively buoyant plumes, negatively buoyant (dense) gas plumes, and neutrally buoyant clouds and momentum jets.* However, in the examples of transport and dispersion models given in Section 4, emphasis is on neutrally buoyant plumes with minimal initial momentum. It is not the intent of this book to suggest specific transport and dispersion model algorithms for buoyant or dense plumes and/or momentum jets in congested areas.

1.3. Overview

The book is organized into several chapters, such that the story is told in a sequence beginning with meteorology and definitions, and ending with specific examples and worked scenarios. Detailed references are provided.

In Chapter 2, an overview is given of the basic physics of meteorology and dispersion modeling in general, consistent with other CCPS books. Definitions are given and methods of estimating the effects of surface roughness obstacles are provided. The proposed simplified algorithms are related to concepts familiar to engineers such as the surface skin friction coefficient, and it is shown how z_0 can be written in terms of that coefficient. The relations between plume dispersion coefficients and atmospheric turbulence are summarized, including the effects of ambient atmospheric stability. The current state-of-the-art concerning relevant experiments and available roughness estimation methods is briefly reviewed. In particular, the many fluid model experiments on flow and dispersion around obstacle arrays are discussed and references given so the readers can obtain the data. Methods by which recently developed dispersion models parametrize the roughness length, z_0, are outlined. For example, the U.S. Environmental Protection Agency's (EPA's) model, AERMOD, uses an estimate of z_0 (Cimorelli et al., 1998). The reliability and limitations of models and data are summarized.

The third chapter of the book provides details concerning methods of estimating the surface roughness length, z_0, and the related displacement length, *d*. Several optional methods for estimating these parameters are presented, such as land use category tables, wind profile methods, and obstacle geometry (morphological) methods. The general characteristics of working models for estimating surface roughness length and displacement length are described (e.g., the Petersen, 1997, method and the Macdonald et al., 1998, method). The importance of the friction velocity, u^*, is emphasized and formulas are included for its estimation based on a wind speed observation and a knowledge of z_0. It is shown how the turbulent velocity components are directly related to u^*. Formulas are also suggested for the variation of wind speed below and above the obstacle heights.

Chapter 4 includes a comprehensive set of equations for estimating transport and dispersion of pollutant clouds at industrial and urban sites. Differences between the two situations when most of the cloud is located at heights less than or greater than the roughness element height are described. The types of problems that are covered include a release within the obstacle array (i.e., the group of buildings, tanks and