WIND FLOW AND VAPOR CLOUD DISPERSION AT INDUSTRIAL AND URBAN SITES

Steven R. Hanna
Hanna Consultants

Rex E. Britter
University of Cambridge

Center for Chemical Process Safety of the American Institute of Chemical Engineers
3 Park Ave., New York, NY 10016-5991
Copyright © 2002
American Institute of Chemical Engineers
3 Park Avenue
New York, New York 10016-5991

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise without the prior permission of the copyright owner.

Library of Congress Cataloging-in-Publication Data

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.

PRINTED IN THE UNITED STATES OF AMERICA
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 non-profit 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

The American Institute of Chemical Engineers and the Center for Chemical Process Safety express their gratitude to all the members of the Vapor Cloud Modeling Subcommittee for their generous efforts and technical contributions in the preparation of this Concept Series Book.

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.

Lastly, CCPS is grateful to the American Petroleum Institute for permitting the distribution of its copyrighted computer program, ROUGH, with this book in the interest of improved knowledge and safer facilities in the industry.

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)

$A_f$ (m²)  Vertical cross-section or frontal area of obstacle facing the wind.

$A_p$ (m²)  Horizontal or plan area of obstacle

$A_T$ (m²)  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).

$c_p = 1005 \text{ J kg}^{-1}\text{K}^{-1}$  Specific heat of air at constant pressure

$C$ (kg/m³ or ppmv)  Concentration of pollutant

$C/Q$ (s/m³)  Normalized concentration

$C(z)$ (kg/m³ or ppmv)  Height-variable concentration of pollutant in the cloud

$C_y$ (kg/m² or ppmv-m)  Crosswind integrated concentration
$d$ (m) Displacement length
$D$ Constant in Eq. (14)
$f(1/s)$ Coriolis force or parameter
$g = 9.8 \text{ m/s}^2$ 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, $u_e = \int u(z)C(z) \, dz / \int C(z) \, dz$
$u_{ref}$ (m/s) Mean reference wind speed
$u^*$ (m/s) Friction velocity
List of Symbols

\( u^*_{\text{local}} \) (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
\( z_{\text{ref}} \) (m) Reference height (typically between about 2 m and 10 m).

\( \theta \) (K) Potential temperature
\( \theta^* \) (K) Scaling potential temperature, about –0.1 K at night and 1.0 K in the day
\( \kappa \) 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
\( \nu \) Kinematic molecular viscosity \( \nu = 1.5 \times 10^{-5} \) m²/s for air
\( \rho \) (kg/m³) Air density, equal to 1.2 kg/m³ at sea level at a temperature of 293 K
\( \sigma_u \) (m/s) Turbulent velocity fluctuations in the along-wind (x) direction
\( \sigma_v \) (m/s) Turbulent velocity fluctuations in the lateral (y) horizontal direction
\( \sigma_w \text{ (m/s)} \) Turbulent velocity fluctuations in the vertical (\( z \)) direction
\( \sigma_x \text{ (m)} \) Along-wind dispersion component
\( \sigma_y \text{ (m)} \) Lateral dispersion component
\( \sigma_z \text{ (m)} \) Vertical dispersion component
\( \tau_o \text{ (kg/m/s}^2) \) Surface stress