Chemical Process Safety
Fundamentals with Applications

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Preface

This textbook is designed to teach and apply the fundamentals of chemical process safety. It is appropriate for an industrial reference, a senior level undergraduate course or a graduate course in chemical process safety. It can be used by anyone interested in improving chemical process safety, including chemical and mechanical engineers and chemists. More material is presented than can be accommodated in a 3 credit semester course.

The primary objective of this textbook is to encapsulate the important technical fundamentals of chemical process safety. The emphasis on the fundamentals will hopefully help the student and practicing scientist *understand* the concepts and apply them accordingly. This application requires a significant quantity of fundamental knowledge and technology.

Since a textbook fundamentally oriented on safety has never been undertaken, we experienced several difficulties. First, an outline that presented the material in a logical and expanding fashion was very difficult to develop. Second, since chemical process safety involves a very large quantity of material, the motivation was always present to include more and more. We have tried to limit the material to those items deemed essential for industrial and university practice. Third, the fundamental basis for much of the material was long lost and had to be redeveloped.

We firmly believe that a textbook on safety could only have been possible with both industrial and academic inputs. The industrial input insured that the material was industrially relevant. The academic input insured that the material was presented on a fundamental basis to help professors and students understand the concepts.

When this textbook is completed, few universities will have required courses in chemical process safety. While the need is recognized, little flexibility is presently available to add additional courses to the undergraduate chemical engineering curriculum. Also, faculty have little background in chemical process safety, and, finally, inadequate instructional materials are available to teach such a course. We hope this textbook solves the instructional material problem and that the remaining problems will be solved in time.

This textbook is designed for a dedicated course in chemical process safety. However, we feel that chemical process safety should be part of every undergraduate and graduate course in chemistry and chemical and mechanical engineering, just as it is a part of all the industrial experiences. This text can be used as a reference resource for these courses.

We will inevitably be criticized by some who believe our presentation is not complete or that some details are missing. The purpose of this book is not completeness but to provide a starting point for those who wish to learn about this important area.

We would like to thank Harold Fisher of Union Carbide and Joseph Leung of Fauske and Associates for reviewing the sections on two-phase flow relief and providing a number of important corrections and modifications. Edward J. Kerfoot, Michael Capraro and Jim Strickland of BASF Corporation reviewed specific chapters. Dan Goerke helped with the homework problems and solutions and suggested a number of important changes. Bruce Barna, Dave Leddy, and Nam Kim of Michigan Technological University helped develop a number of instructional modules that contributed towards the initial basis for this text. Michigan Technological University also provided a sabbatical experience to one of us (D.A.C.) which contributed to the initial textbook development. Professor Edward R. Fisher of Michigan Tech is thanked for this opportunity.

We thank our coworkers at BASF Corporation for giving us the knowledge and deep appreciation for the importance of process safety in laboratories, pilot plants and plants. This especially includes M. Capraro, J. Strickland, and K. Kilponen.

We also acknowledge and thank the members of the Curriculum Committee of the Center for Chemical Process Safety (CCPS) and the Safety and Loss Prevention Committee of the American Institute of Chemical Engineers. We are honored to be members of both committees. The members of these committees are the experts in safety; their enthusiasm and knowledge have been truly educational and a key inspiration to the development of this text.

We thank John Davenport of Industrial Risk Insurers for providing information concerning several case histories which he particularly chose because of their significant relevance to process safety. John also reviewed Chapters 6 and 7 and provided very valuable information on sprinkler system design. Walter Howard, presently a Process Safety Consultant, has given us important safety information and facts and continued encouragement to complete this project.

Finally, we acknowledge our families, who provided patience, understanding and encouragement.

We hope that this textbook helps prevent chemical plant and university accidents and contributes to a much safer future.

Detroit, Michigan

Daniel A. Crowl

Joseph F. Louvar

Nomenclature

a	velocity of sound (length/time)
A	area (length^2) or Helmholtz free energy (energy); or process component availability
A_t	tank area (length^2)
ΔA	change in Helmoltz free energy (energy/mole)
C	mass concentration (mass/volume) or capacitance (Farads)
C_0, C_1	discharge coefficients (unitless) or concentration at a specified time (mass/volume)
C_p	heat capacity at constant pressure (energy/mass deg)
C_V	heat capacity at constant volume (energy/mass deg)
C_{ppm}	concentration in parts per million by volume
C_{vent}	deflagration vent constant ($\text{pressure}^{1/2}$)
$\langle C \rangle$	average or mean mass concentration (mass/volume)
d	diameter (length)
d_p	particle diameter (length)
d_f	diameter of flare stack (length)
D	diffusion coefficient (area/time)
D_0	reference diffusion coefficient (area/time)
D_m	molecular diffusivity (area/time)
D_{tid}	total integrated dose due to a passing puff of vapor (mass time/volume)

E_a	activation energy (energy/mole)
f	Fanning friction factor (unitless)
$f(t)$	failure density function
f_v	mass fraction of vapor (unitless)
F	frictional fluid flow loss term (energy/mass)
g	gravitational acceleration (length/time^2)
g_c	gravitational constant
G	Gibbs free energy (energy/mole) or mass flux (mass/area time)
G_T	mass flux during relief (mass/area time)
ΔG	change in Gibbs free energy (energy/mole)
h	specific enthalpy (energy/mass)
h_L	fluid level above leak in tank (length)
h_L^0	initial fluid level in tank (length)
h_s	leak height above ground level (length)
H	enthalpy (energy/mole) or height (length)
H_f	flare height (length)
H_r	effective release height in plume model (length)
ΔH	change in enthalpy (energy/mole)
ΔH_c	heat of combustion (energy/mass)
ΔH_v	enthalpy of vaporization (energy/mass)
I	sound intensity (decibels)
I_0	reference sound intensity (decibels)
I_s	streaming current (amps)
j	number of inerting purge cycles (unitless)
J	electrical work (energy)
k	non-ideal mixing factor for ventilation (unitless)
k_1, k_2	constants in probit equations
K	mass transfer coefficient (length/time)
K_b	backpressure correction for relief sizing (unitless)
K_g	explosion constant for vapors (length pressure/time)
K_j	eddy diffusivity in x, y or z direction (area/time)
K_P	overpressure correction for relief sizing (unitless)
K_{St}	explosion constant for dusts (length pressure/time)
K_V	viscosity correction for relief sizing (unitless)
K_0	reference mass transfer coefficient (length/time)
K^*	constant eddy diffusivity (area/time)
L	length
LEL	lower explosion limit (volume %)
$LFL = LEL$	lower flammability limit (volume %)

m	mass
m_0	total mass contained in reactor vessel (mass)
m_{TNT}	mass of TNT
m_v	mass of vapor
M	molecular weight (mass/mole)
M_0	reference molecular weight (mass/mole)
Ma	Mach number (unitless)
MTBC	mean time between coincidence (time)
MTBF	mean time between failure (time)
n	number of moles
p	partial pressure (force/area)
p_d	number of dangerous process episodes
P	total pressure or probability
P_b	backpressure for relief sizing (psig)
P_g	gauge pressure (force/area)
P_{max}	maximum pressure for relief sizing (psig)
P_s	set pressure for relief sizing (psig)
P^{sat}	saturation vapor pressure
q	heat (energy/mass)
q_f	heat intensity of flare (energy/time area)
q_s	specific energy release rate at set pressure during reactor relief (energy/mass)
Q	heat (energy) or electrical charge (coulombs)
Q_m	mass discharge rate (mass/time)
Q_m^*	instantaneous mass release (mass)
Q_v	ventilation rate (volume/time)
r	radius (length)
R	electrical resistance (ohms) or reliability
RHI	reaction hazard index defined by Equation 13-1
r_f	vessel filling rate (time^{-1})
R_g	ideal gas constant (pressure volume/mole deg)
Re	Reynolds number (unitless)
S	entropy (energy/mole deg)
S_m	material strength (force/area)
t	time
t_e	emptying time
t_p	time to form a puff of vapor
t_v	vessel wall thickness (length)
t_w	worker shift time

Δt_v	venting time for reactor relief
T	temperature (deg)
T_d	material decomposition temperature (deg)
T_i	time interval
T_m	maximum temperature during reactor relief (deg)
T_s	saturation temperature at set pressure during reactor relief (deg)
u	velocity (length/time)
u_d	dropout velocity of a particle (length/time)
$\bar{u}$	average velocity (length/time)
$\langle u \rangle$	mean or average velocity (length/time)
U	internal energy (energy/mole) or overall heat transfer coefficient (energy/area time) or process component unavailability
UEL	upper explosion limit (volume %)
$UFL = UEL$	upper flammability limit (volume %)
v	specific volume (volume/mass)
v_f	specific volume of liquid (volume/mass)
v_g	specific volume of vapor (volume/mass)
v_{fg}	specific volume change with liquid vaporization (volume/mass)
V	total volume or electrical potential (volts)
V_c	container volume
W	width (length)
W_e	expansion work (energy)
W_s	shaft work (energy)
x	mole fraction or Cartesian coordinant (length)
X_f	distance from flare at grade (length)
y	mole fraction of vapor (unitless) or Cartesian coordinate (length)
Y	probit variable (unitless)
z	height above datum (length) or Cartesian coordinate (length) or compressibility (unitless)
z_e	scaled distance for explosions (length/mass$^{1/3}$)

GREEK LETTERS

α	velocity correction factor (unitless)
β	thermal expansion coefficient (deg^{-1})
δ	double layer thickness (length)
ε	pipe roughness (length) or emissivity (unitless)

ε_r	relative dielectric constant (unitless)
ε_0	permittivity constant for free space ($charge^2$/force $length^2$)
Φ	nonideal filling factor (unitless)
γ	heat capacity ratio (unitless)
γ_c	conductivity (mho/cm)
χ	function defined by Equation 9-6
λ	frequency of dangerous episodes
λ_d	average frequency of dangerous episodes
μ	viscosity (mass/length/time) or mean value or failure rate (faults/time)
μ_V	vapor viscosity (mass/length/time)
Ψ	overall discharge coefficient used in Equation 9-14 (unitless)
ρ	density (mass/volume)
ρ_L	liquid density (mass/volume)
ρ_{ref}	reference density for specific gravity (mass/volume)
ρ_V	vapor density (mass/volume)
σ	standard deviation (unitless)
σ_x, σ_y, σ_z	dispersion coefficient (length)
τ	relaxation time
τ_i	inspection period for unrevealed failures
τ_0	operation period for a process component
τ_r	period required to repair a component
τ_u	period of unavailability for unrevealed failures
ζ	zeta potential (volts)

SUBSCRIPTS

c	combustion
f	formation or liquid
g	vapor or gas
m	maximum
s	set pressure
o	initial or reference

SUPERSCRIPTS

°	standard
′	stochastic or random variable

Contents