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ESTIMATING THE FLAMMABLE MASS OF A VAPOR CLOUD
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ESTIMATING THE FLAMMABLE MASS OF A VAPOR CLOUD

A CCPS CONCEPT BOOK

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PREFACE

For nearly 40 years the American Institute of Chemical Engineers (AIChE) has been involved with process safety and loss control issues in the chemical, petrochemical, hydrocarbon process, and related industries and facilities. 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, a Directorate of the AIChE, was established in 1985 to develop and disseminate information for use in promoting the safe operation of chemical process 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 books in the Guidelines series and are intended to complement them. With the issuance of this book, CCPS will have published over 40 books.

CCPS activities are supported by the funding and technical expertise of over 90 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 forward to that book states:
“For the first time, all the essential elements and components of a model of a technical management program in chemical process safety 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 Estimating the Flammable Mass of a Vapor Cloud supports several of the twelve elements of process safety enunciated in Guidelines for the Technical Management of Chemical Process Safety, including Process Knowledge and Documentation, Process Risk Management, Incident Investigation, and Enhancement of Process Safety Knowledge. The purpose of this book is to assist designers and operators of chemical facilities to realistically estimate the fraction of a cloud or plume of accidentally-released flammable material that is capable of igniting.
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The chair of the Task Force on Flammable Mass was Robert L. Moser of ARCO Chemicals. The task force members were John Davenport, Industrial Risk Insurers (Chair, Explosion Subcommittee); Ronald J. Lantzy, Rohm and Haas Company (Chair, Modeling Subcommittee); John V. Birtwisle, Solutia Company; Donald J. Connolley, AKZO Nobel Chemicals; Randy Hawkins, Celanese Corp.; Robert E. Linney, Air Products and Chemicals Company; Robert A. Mancini, Amoco Corporation; John T. Marshall, Dow USA–Texas Operations; Larry J. Moore, Factory Mutual Engineering; and Ephraim Scheier, Occidental Chemicals Corporation. Martin E. Gluckstein was the CCPS Staff Liaison and was responsible for the overall administration and coordination of the project.

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Before publication, all CCPS books are subjected to a thorough peer review process. CCPS also gratefully acknowledges the thoughtful comments and suggestions of the peer reviewers: Daniel A. Crowl, Michigan Technological University; Randy A. Freeman, Solutia, Inc.; Alan Godso, Cigna Insurance Co., David J. Hesse, Battelle Memorial Institute; Georges Melhem, A. D. Little, Inc.; Meso Molag, TNO; Kenneth Mosig, AIU Energy; John A. Noronha, Eastman Kodak Co., Hans Pasman, TNO Defense Research; Jan C. Windhorst, Nova
Accidental Chemical Release: An unintended, or sudden release of chemical(s) from manufacturing, processing, handling, or on-site storage facilities to the air, water, or land.

Adiabatic: A system condition in which no heat is exchanged between the chemical system and its environment.

Adiabatic Lapse Rate (ALR): The negative of the temperature gradient established as dry air ascends in the atmosphere. For air the ALR, $\theta$ is $-0.00995^\circ C/m$ (or $=-0.01 K/m$) for heights below the maximum typical mixing height ($\leq~2000$ m).

Advection: The transport of material by and in the wind.

Aerosol Fraction: The fraction of liquid phase, $1 - x$, which, after flashing to the atmosphere, remains suspended as an aerosol.

Along-Wind Distance, $x$: Distance in the direction the vapor cloud is traveling, i.e. the wind direction. Since the wind direction may change, the along-wind distance may change in direction and time as well.

Atmospheric Dispersion: The low momentum mixing of a vapor/gas or aerosol with air. The mixing is the result of turbulent energy exchange, which is a function of wind (mechanical eddy formation) and atmospheric temperature profile (thermal eddy formation).

Atmospheric Stability: A measure of the degree of atmospheric turbulence, particularly vertical mixing in the atmosphere. In neutral stability, the vertical temperature gradient equals the adiabatic lapse rate (ALR). Stable atmospheric conditions refer to a gradient less than the ALR (ultimately to a temperature inversion), and unstable conditions to a gradient greater than the ALR.

Autoignition Temperature: The minimum temperature of a substance required to cause self-sustained combustion in air, with no other sources of ignition.
**Averaging Time:** The time in atmospheric dispersion testing over which concentration data are averaged to produce a concentration-time series.

**Blast Wave:** The narrow pressure pulse transmitted by an explosion.

**Buoyant Gas:** See Positively Buoyant Gas.

**Buoyant Force:** Mathematically, $(\rho_{\text{cd}} - \rho_{\text{air}})gV_{\text{cd}}$ (in Newtons), the product of the difference in density of a cloud and the surrounding medium (air), the gravitational acceleration, and the volume of the cloud.

**BLEVE (Boiling-Liquid-Expanding-Vapor Explosion):** A type of rapid phase transition in which a liquid contained above its atmospheric boiling point is rapidly depressurized, causing a nearly instantaneous transition from liquid to vapor with a corresponding energy release. A BLEVE of flammable material is often accompanied by a large aerosol fireball, since an external fire impinging on the vapor space of a pressure vessel is a common cause. However, it is not necessary for the liquid to be flammable to have a BLEVE occur.

**Computational Fluid Dynamics Models:** Dispersion models that treat the partial differential Navier–Stokes equations describing fluid flow by numerically solving them using a grid of nodes or finite elements.

**Concentration:** The relative amount of a substance when combined or mixed with other substances. Concentration can be expressed as mole fraction, mass fraction, or component mole or mass density. Examples: $y_i = 2$ ppm mole fraction; $w_i = 0.50$ mass fraction; $c_i = 0.03$ kmole/m$^3$.

**Condensed-Phase Explosion:** An explosion that occurs when the material is present in the form of a liquid or solid.

**Confined Explosion:** An explosion of a reacting mass inside a closed system (e.g., a vessel or building).

**Confinement:** Obstacles such as walls and ceilings of a building, vessel, pipe, etc. that serve to limit the expansion of a dispersing or exploding vapor cloud.

**Congestion:** Small obstacles in the path of a flame front or dispersing vapor cloud that serve to deflect the flame front or cloud and to generate turbulent mixing.

**Continuous Release:** Emissions that are long in duration compared with the travel time (time for cloud to reach a location of interest) or averaging time.

**Decomposition:** Breakdown of material or substance (by heat, chemical reaction, electrolysis, decay, or other processes) into parts or elements or simpler compounds.

**Deflagration:** The chemical reaction of a substance in which the reaction front advances into the unreacted substance at less than sonic velocity. Where a blast wave is produced that has the potential to cause damage, the term *explosive deflagration* may be used.
Dense Gas: A gas with density exceeding that of air at ambient temperature. Sometimes the expression is used loosely to apply to aerosols such as flashing liquid ammonia. See also heavy gas and negatively buoyant vapors.

Detonation: A release of energy caused by the extremely rapid chemical reaction of a substance in which the reaction front advances into the unreacted substance at greater than sonic velocity.

Duration: The length of time for which an event occurs.

Energy Scaling Factor: The cube root of the TNT equivalent mass, \( W^{1/3} \). [See Eq. (4.76).]

Entrainment: The mixing of air into a vapor cloud.

Expansion Ratio, \( r_v \): The ratio of the volume after combustion to that prior to combustion.

Explosion: A release of energy that causes a blast wave.

Explosion Efficiency, \( \epsilon_t \): The ratio of the mechanical energy released in an explosion to the heat of combustion times the flammable mass in a vapor cloud (net efficiency). Alternately, the ratio of the mechanical energy released in an explosion to the heat of combustion times the total mass of fuel in a vapor cloud (gross efficiency).

Explosion Vent: An intentionally weakly supported panel in the wall of an enclosure designed to give way in the event of an explosion in order to reduce the explosion overpressures and thereby protect the rest of the structure.

Flame Expansion Dimensions: The dimensions in which a burning or exploding gas is free to expand, 1D, 2D, or 3D.

Flammable Limits: The minimum and maximum concentrations of a combustible material (gas, vapor, aerosol, or dust) in air that will propagate a flame. See LFL and UFL.

Flammable Mass: The mass of fuel in a vapor cloud that is in the flammable range, \( m_f \).

Flammable Range: The range of concentrations of a fuel in air that will ignite with a strong ignition source (at a certain probability or percent of trials).

Flash Point: The minimum temperature at which a liquid gives off vapor in sufficient concentration to form an ignitable mixture with air near the surface of the liquid as determined by a specific test method, i.e., open-cup or closed-cup.

Full Volume Deflagration (FVD): A deflagration explosion developed from a flammable cloud of gas, aerosol, or dust that occupies the entire volume in a confined space.

Gaussian Model: A dispersion model based on the concept that atmospheric diffusion is a random mixing process driven by turbulence in the atmosphere. The concentration at any point downwind of a point-source
continuous release is approximated by a concentration profile of the form \( \exp(-0.5y^2/\alpha^2) \) in both the horizontal and the vertical dimensions. There is also a line-source Gaussian solution and a point-source instantaneous release Gaussian solution.

**Gravity Slumping:** The decrease in cloud height of a flowing dense gas due to the effects of gravity (negative buoyancy).

**Heat of Combustion, \( H_c \):** The heat of reaction obtained by burning a unit mass of a substance at the stoichiometric concentration in air to produce fully oxygenated products. If water is a product, then the “gross” heat of combustion includes the heat of condensation of water, so that liquid water is a product. Correspondingly, the “net” heat of combustion does not include the heat of condensation of water, and vapor water is a product. Unless otherwise stated, we refer here to “net” heat of combustion.

**Heat of Reaction:** The net difference in heat of formation of all reactants and of all products in an adiabatic system. The reaction is exothermic if heat is released (heat of reaction is negative), and endothermic if heat is absorbed by the reaction.

**Heavy Gas:** A gas with density exceeding that of air at ambient temperature. See also dense gas and negatively buoyant vapors.

**Ignition Source Density:** The number of ignition sources per unit area (of plant).

**Impulse, \( I \):** The area under the overpressure-time curve for explosions. The area can be calculated for the positive pressure phase or the negative phase of the blast wave.

**Insolation:** Solar radiation heat loading (Watts/m²).

**Instantaneous Release:** Emissions that are short in duration compared with the travel time (time for cloud to reach a location of interest) or compared to the averaging time.

**Integral Model:** A dispersion model which averages or “integrates” the concentration in a given dimension or time so that concentrations can be described by solving an ordinary differential equation instead of a partial differential equation.

**Intermittency:** The fraction of the time that a measured value is zero in a time-series of measurements.

**Jet Discharge:** A release of vapor or aerosol at sufficient pressure that the momentum of the release provides the dominating mechanism for air entrainment and for the centerline trajectory of the release.

**Jet Fire:** A type of fire occurring with a pressurized release of gas and/or liquid.

**Lower Flammable Limit (LFL):** The lowest concentration of combustible material that will propagate a flame from an ignition source through a mixture of
flamable gas, aerosol, or combustible dust in air. Also known as the Lower Explosive Limit (LEL).

**Mach Number, \( M \):** The ratio of the speed of a flame or blast wave to the speed of sound at ambient temperature and pressure.

**Minimum Flammable Mass:** The lowest mass of fuel in the flammable range that will cause a defined level of damage.

**Minimum Ignition Energy:** The lowest energy of an electrical spark discharge that will ignite a flammable mixture of fuel and air under defined test conditions.

**Momentum Flux:** Mathematically, \( \rho u^2 \) (in Newtons/m²), the product of the cloud density and speed squared.

**Momentum Force:** Mathematically, \( \rho u^2 A \) (in Newtons), the product of the cloud density, speed squared, and cross-sectional area.

**Negatively Buoyant Vapors:** Vapors or aerosol with a specific gravity greater than ambient air so the vapors tend to sink to low spots and to spread along the ground by “gravity spreading.”

**NFPA:** Acronym for the National Fire Protection Association (U.S.).

**Nose of Vapor Cloud:** The front surface of vapor cloud, that is, the surface farthest along in the along-wind direction. All surfaces of a vapor cloud are usually defined by a certain concentration such as the LFL.

**Overpressure, \( \Delta P \):** The increase of pressure above ambient in an explosion wave.

**Partial Volume Deflagration (PVD):** A deflagration explosion developed from a flammable cloud of gas, aerosol, or dust that occupies only part of the volume in a confined space.

**Passive Dispersion:** Dispersion caused by the normal turbulence in the atmosphere. See Gaussian model.

**PES:** See Potential Explosion Sites.

**Physical Explosion:** The catastrophic rupture of a pressurized gas/vapor-filled vessel by means other than reaction, or the sudden phase-change from liquid to vapor of a superheated liquid.

**Pool Fire:** The combustion of material evaporating from a layer of liquid at the base of the fire.

**Positively Buoyant Gas:** A gas with density less than that of air at ambient temperature.

**Potential Explosion Site (PES):** A volume within a plant with sufficient congestion and/or confinement that a flammable vapor cloud ignited there could likely develop into an explosion.

**Process Safety Management:** A program or activity involving the application of management principles and analytical techniques to ensure the safety of chemical process facilities. Sometimes called process hazard management.
**Puff Release:** See instantaneous release.

**Rain Out:** When a superheated liquid is released to the atmosphere, a fraction of it will flash into vapor. Another fraction may remain suspended as an aerosol. The remaining liquid, as well as portions of the aerosol, \( \eta_R \), may fall or “rain out” onto the ground.

**Reactants:** Chemicals that are converted into products during the reaction process.

**Reaction:** The process in which some chemicals (reactants) are converted into other chemicals (products).

**Reaction Kinetics:** The factors that determine the rate of reaction.

**Reactivity:** The relative tendency of a substance to undergo chemical reaction (low, medium, or high).

**Risk:** A measure of potential economic loss, human injury, or environmental damage (cost) in terms of the probability of the loss, injury, or damage over a period of time, normally a year. Plotting the cost vs. probability gives one representation. The integral under this curve gives another, called the Societal Risk.

**Runaway Reaction:** A thermally unstable reaction system which shows an accelerating increase of temperature and reaction rate.

**Sachs’ Scaling:** Dimensionless terms for TNT equivalence explosion modeling. See Table 4.9.

**Screening Tool:** A simplified dispersion model with limited capabilities, suitable for screening-level studies.

**Shallow-Layer Model with Terrain Effects:** A dispersion model capable of predicting flows in variable terrain by using a simplification in the model formulation that makes the equations applicable only to a shallow layer of fluid.

**Side-on Overpressure:** The level of overpressure in the pressure wave from an explosion measured perpendicular to the direction of propagation of that pressure wave.

**Standard Deviation (cloud concentration), \( \sigma \):** The square root of the sum of squared values of concentration minus centerline concentration. The cloud half-width can be defined as the distance corresponding to a concentration of two or three standard deviations from the centerline.

**Stand-Off Distance, \( R \):** Distance from the center of an explosion.

**Stratification:** As used here, any concentration profile that develops in an enclosure. The flammable mass will be between the LFL and UFL concentrations along such a concentration profile.

**Superheated Liquids:** Liquids at a temperature above their normal boiling point.
Top-Hat Dispersion Models: Dispersion models with no concentration gradients within the vapor cloud. The concentration is modeled as a well-mixed system within the vapor cloud and zero outside the cloud.

TNT Equivalence Models: Models of explosion characteristics relating vapor cloud explosions to the explosion of an equivalent mass of TNT (trinitrotoluene).

Unconfined Vapor Cloud Explosion: An explosion in a vapor cloud that is outdoors and not confined by walls and a ceiling on all sides. This term is not recommended and is not used in this book, since explosions require some degree of confinement or congestion or a strong directed source.

Upper Flammable Limit (UFL): The highest concentration of combustible material that will propagate a flame from an ignition source through a mixture of flammable gas, aerosol, or combustible dust in air. Also known as the Upper Explosive Limit (UEL).

Vapor Pressure, \( P_v \): The pressure exerted by a saturated vapor in equilibrium with its own liquid.

Volume Blockage Ratio (VBR): The ratio of the volume occupied by congestion elements such as pipes, beams, plates, etc. to the volume of the portion of the plant under consideration.

Volume-Source Explosion Models: Models that predict explosion characteristics based on the volumetric portion of the flammable cloud involved in the explosion (that portion of the flammable cloud that is influenced by congested and/or confined volumes in a plant).
NOMENCLATURE

\[ a_0 \quad = \quad \text{speed of sound at ambient conditions, m/s} \]
\[ a, b \quad = \quad \text{regression constants in Eq. (4.80) or (5.10)} \]
\[ a_{cd} \quad = \quad \text{correlation constant for gas or dust explosions} \]
\[ A \quad = \quad \text{cross-sectional area of puncture, m}^2 \]
\[ A \quad = \quad \text{area in horizontal plane of plant over which obstacle effect on surface roughness length is evaluated, m}^2 \text{ in Eq. (4.48)} \]
\[ A \quad = \quad \text{plan view area of flammable cloud, m}^2 \text{ in Eqs. (4.81)-(4.84) and (5.11)} \]
\[ A \quad = \quad \text{kinetics premultiplier in Eq. (4.51)} \]
\[ A_t \quad = \quad \text{area swept by a flammable cloud dispersed to its full extent, m}^2 \text{ in Eqs. (4.81)-(4.84)} \]
\[ A_j \quad = \quad j\text{th surface area for contaminant deposition in Appendix G, m}^2 \]
\[ \text{AFT} \quad = \quad \text{adiabatic flame temperature, K} \]
\[ b_{0y} \quad = \quad \text{half width of source, m} \]
\[ b_{0z} \quad = \quad \text{half height of source, m} \]
\[ B_c \quad = \quad \text{buoyancy flux defined in Appendix H} \]
\[ c \quad = \quad \text{mean concentration, kg/m}^3 \]
\[ c_{hi} \quad = \quad \text{number of chains of carbon atoms on a fuel molecule} \]
\[ c_{i} \quad = \quad \text{indoor concentration, kg/ m}^3 \]
\[ c_o \quad = \quad \text{source concentration or outdoor concentration, kg/ m}^3 \]
\[ C_D \quad = \quad \text{discharge coefficient (—)} \]
\[ C_p \quad = \quad \text{heat capacity at constant pressure, J/(kg K)} \]
\[ C_v \quad = \quad \text{heat capacity at constant volume, J/(kg K)} \]
\[ d, e \quad = \quad \text{constant parameters} \]
\[ d_p \quad = \quad \text{drop diameter, m} \]
\[ d_N \quad = \quad \text{diameter of nozzle or orifice, m} \]
\[ d_{32} \quad = \quad \text{Sauter mean diameter, m} \]
\[ D \quad = \quad \text{average obstacle size, m} \]
NOMENCLATURE

$D$ = diameter of vessel or pipe, m

$D_h$ = puncture diameter, m

$D_p$ = diameter of pool, m

$E$ = energy in explosion, J

$E_a$ = activation energy for reaction, J/kgmole

$f$ = Fanning friction factor, (—)

$f_m$ = mass fraction of released fuel in flammable region, (—)

$f_x$ = fraction of the distance between the release height and the ceiling

$f_{SP}$ = mass fraction in spray (not raining out)

$f_{x1} f_{x2}$ = functions used to express $\sigma(x)$

$F$ = swelling factor of fuel, m$^3$/m$^3$

$F_1$ = pipe inclination factor defined by Eq. 4.10, (—)

$F_0$ = mass fraction of contaminant removed by air filter, (—)

$F_1$ = mass fraction of contaminant in recirculated air removed by filter, (—)

$F_x$ = along-wind concentration profile for instantaneous puff, (—)

$F_y$ = cross-wind concentration profile, (—)

$F_z$ = vertical concentration profile, (—)

$g$ = gravitational constant, m/s$^2$

$g_0$ = buoyancy-adjusted gravitational constant, m/s$^2$, see Eq. (H.4)

$G$ = mass flux of discharge, kg/(m$^2$s)

$G^*$ = dimensionless mass flux of discharge, (—)

$G_{evap}$ = mass flux for evaporation from a pool, kg/(m$^2$s)

$G_{L}$ = liquid discharge mass flux, calculated with orifice equation, Eqs. (4.3), (4.22)

$G_p$ = mass flux discharge from pipe, kg/(m$^2$s)

$h$ = release height, m

$h$ = average depth of pool, m

$h$ = liquid head above puncture point, m

$h_{mi}$ = effective height of vapor cloud section $i$, m

$h_{i}$ = height of inversion layer, m

$h_{min}$ = minimum average depth of pool at maximum pool diameter, m

$h^*$ = average obstacle height, m in Eq. (4.48)

$h_1$ = height of well-mixed layer from indoor release, see Appendix H, m

$h_2$ = height of linear gradient layer from indoor release, Appendix H, m

$H$ = specific enthalpy, J/kg

$H$ = height of building or room, m

$H_{fg}$ = heat of vaporization, J/kg

$H_{ei}, H_{ai}$ = specific heat of combustion of component $i$, J/kg
NOMENCLATURE

$H_{\text{comb}}$ = total heat of combustion in flammable cloud, J
$H_{\text{cr}}$ = heat of combustion per unit volume, J/m$^3$
$H_v$ = heat flux from the earth, W/m$^2$
$i_s$ = scaled impulse from explosion, see Table 4.7
$I$ = impulse from explosion, Pa s
$j,k,l,m,n = \text{power law coefficients}$
$k_v = \text{Von Karman constant, value } = 0.40 \text{ (—) in Eq. (4.46)}$
$k = \text{polytropic coefficient, slightly less than } \gamma \text{ (—)}$
$k_T = \text{thermal conductivity of substrate (ground or water), W/(m K)}$
$k = \text{turbulent energy generation rate in } k-\epsilon \text{ models}$
$k_c k_p = \text{parameter in Elliptic integral of second kind for continuous and instantaneous releases, respectively (—)}$
$K_v = \text{equivalent number of velocity heads to account for fittings, bends, expansions, etc.}$
$K_g = \text{reactivity of gas expressed as maximum rate of pressure increase times the cube root of the test volume (MPa m/s).}$
$K_d = \text{reactivity of dust expressed as maximum rate of pressure increase times the cube root of the test volume (MPa m/s).}$
$L = \text{Monin-Obukov turbulence scale, } m, \text{ in Eq. (4.46) and Eq. (A.3)}$
$L = \text{length of pipe or length of room or characteristic length of surface, m}$
$L_{\text{ave}} = \text{average carbon chain length, number of carbon atoms}$
$L_c = \text{estimated eddy size discussed in Section 4.2.6, m}$
$L_f = \text{maximum flame path length in congested area, m}$
$L_{\text{FL}} = \text{lower flammable limit, mole fraction of fuel}$
$LNG = \text{liquefied natural gas}$
$\text{LPG = liquefied petroleum gas, mostly propane and propylene}$
$L_r = \text{length of room, m}$
$m_f = \text{mass of flammable material in flammable range in vapor cloud, kg}$
$m_t = \text{total mass of flammable material discharged, kg}$
$m_f = \text{partial order of reaction with fuel component in Eq. (4.51)}$
$m_0 = \text{partial order of reaction with oxygen in Eq. (4.51)}$
$M_c = \text{momentum flux defined in Appendix H}$
$M_i = \text{molecular weight of component } i, \text{ kg/kgmole}$
$M_T = \text{molecular weight of multicomponent fuel–air mixture, kg/kgmole}$
$M = \text{number of methyl groups in a fuel molecule}$
$M_w = \text{Mach number for flame speed, ratio of flame speed to speed of sound in unburned mixture at ambient temperature.}$
$n_i = \text{stoichiometric index in reaction}$
$n_c = \text{exponent in Eq. (4.40)}$
NOMENCLATURE

\[ n = \text{exponent in definition of toxic dosage; see Section 4.2.4} \]
\[ N = \text{number of velocity heads lost in pipe by line friction, bends, fittings, see Eq. (4.9)} \]
\[ N_i = \text{number of carbon atoms in a chain} \]
\[ Nu = \text{Nusselt number, } h d_p / k_T (\text{—}) \text{ where } h \text{ is the heat transfer coefficient, } W/(m^2K) \]
\[ N_{eq} = \text{nonequilibrium term defined by Eq. (4.25)} \]
\[ p = \text{exponent in power law wind profile, Eq. (4.47)} \]
\[ p(c,x) = \text{perimeter length of concentration isopleth, m} \]
\[ P = \text{probability of exceeding the limiting concentration when the mean concentration is } \bar{c}, \text{ see Eq. (4.72)} \]
\[ P = \text{pressure, Pa} \]
\[ \text{PES} = \text{potential explosion site} \]
\[ p_a = \text{ambient pressure, Pa} \]
\[ P_0 = \text{initial stagnation pressure in vessel or pipe, Pa} \]
\[ P_s = \text{saturation vapor pressure, Pa} \]
\[ q_0 = \text{volumetric rate of forced-convection fresh air to a building, m}^3/\text{s} \]
\[ q_1 = \text{volumetric rate of air recirculation in a building, m}^3/\text{s} \]
\[ q_2 = \text{volumetric rate of air infiltrating a building, m}^3/\text{s} \]
\[ q_3 = \text{volumetric rate of air leaving a building through leakage, m}^3/\text{s} \]
\[ q_4 = \text{volumetric rate of forced-convection exhaust air from a building, m}^3/\text{s} \]
\[ Q = \text{heat flux, W/m}^2 \]
\[ Q = \text{probability of nonignition in Eqs. (4.82)-(4.83)} \]
\[ Q_f = \text{probability of nonignition of vapor cloud over the area swept by the cloud diluting to its maximum extent} \]
\[ r = \text{pool radius, m} \]
\[ r_f = \text{rate of fuel oxidation, kg fuel/s} \]
\[ r_m = \text{mole ratio of products of combustion to reactants, see Eq. (4.59)} \]
\[ r_n = \text{nozzle or orifice radius, m} \]
\[ R = \text{radius or characteristic height of vapor cloud, m} \]
\[ R = \text{gas constant, } 8314.3 \text{ J/(kgmole K)} \]
\[ R = \text{sink for contaminant (by deposition or decomposition), kg/s in Eq. (G.1)} \]
\[ Ri = \text{Richardson number, see Eq. (A.1)} \]
\[ Ri_c = \text{Release Richardson number, see Eq. (5.3)} \]
\[ Ri_i = \text{Inlet Richardson number defined by Eq. (H.10)} \]
\[ s = \text{silhouette area of all obstacles in the area, Eq. (4.48)} \]
\[ s = \text{indoor source rate for contaminant, kg/s in Eq. (G.1)} \]
\[ S = \text{entropy, J/(kg K)} \]
\[ S_{fg} = \text{entropy difference between vapor and liquid, } S_C - S_L, \text{ J/(kg K)} \]
NOMENCLATURE

$S_u$ = laminar flame speed, m/s  
$S_t$ = turbulent flame speed, m/s  
$t$ = time, s  
$t_a$ = arrival time of leading edge of explosion pulse, s  
$t_d$ = duration of positive overpressure pulse of explosion, s  
$t_i$ = turbulence time scale, s  
$T$ = temperature, K  
$T_{as}$ = adiabatic saturation temperature, K, see Figure 4.12  
$T_b$ = normal boiling point, K  
$\Delta T_{st}$ = temperature rise in a flame at stoichiometric concentration, K  
$u$ = velocity in jet or plume, m/s  
$u_d$ = mass average drop settling velocity, m/s  
$u_w$ = wind speed, m/s  
$u_v$ = friction velocity, a parameter in vertical wind speed profiles, m/s  
UFL = upper flammable limit, mole fraction of fuel  
$v$ = specific volume of single-phase or possibly two-phase mixture, $\text{m}^3/\text{kg}$  
$v_v$ = specific volume of vapor or gas, $\text{m}^3/\text{kg}$  
$V$ = cloud volume or room volume, $\text{m}^3$  
$V_r$ = volumetric rainout rate to pool, $\text{m}^3/\text{s}$ in Eq. (4.38), (4.39)  
$V$ = velocity in y direction, m/s  
VBR = volume blockage ratio (—)  
$w$ = discharge rate, kg/s  
$w_c$ = effective width of vapor cloud, m  
$w_p$ = instantaneous mass discharge, kg  
$w_i$ = mass fraction of component $i$, kg/kg  
$w_{vi}$ = vapor mass fraction of component $i$, kg/kg  
$W$ = equivalent mass of TNT from explosion, kg of TNT  
$W$ = width of building or room, m  
$W(x)$ = characteristic half width of vapor cloud, m  
$We$ = Weber number defined by Eq. 4.28  
$We_c$ = critical Weber number for droplet breakup, value = 12 to 22.  
$x$ = along-wind distance, m  
$x_o$ = along-wind distance to center of cloud, m  
$\chi$ = mass fraction of vapor or gas in two-phase mixture, kg/kg  
$X$ = surface correction factor in Eq. (4.41)  
$X_r$ = fraction of the volume of an enclosed room occupied by flammable cloud  
$y$ = across wind direction or radial distance of jet impacting flat surface, m
\[ y_i = \text{mole fraction of component } i \text{ in the vapor phase, mole } i/\text{mole total} \]
\[ z = \text{vertical distance, m} \]
\[ z_0 = \text{surface roughness length, m} \]
\[ z_r = \text{release height for pipe break inside a room, m} \]
\[ z_2 = \text{vertical distance from impacting surface for jet impaction, m} \]
\[ Z = \text{scaled radial stand-off distance from center of explosion}. \]

**Subscripts**

\[ \text{air} = \text{air} \]
\[ a, \text{amb} = \text{ambient} \]
\[ \text{basis} = \text{time basis for averaging time, s} \]
\[ b = \text{burned or combustion products} \]
\[ c = \text{choked or heat of combustion} \]
\[ \text{chem} = \text{heat generated by chemical reaction (oxidation)} \]
\[ \text{cl} = \text{centerline} \]
\[ \text{cld} = \text{vapor cloud} \]
\[ \text{cls} = \text{flammable mass in a slice of the vapor cloud of width } \Delta x \]
\[ \text{cond} = \text{heat flux by conduction} \]
\[ \text{conv} = \text{heat flux by convection} \]
\[ \text{cs} = \text{combustible component at saturation} \]
\[ \text{cv} = \text{volumetric heat of combustion} \]
\[ \text{dis} = \text{discharge} \]
\[ \text{dur} = \text{duration of passing vapor cloud, s} \]
\[ \text{erm} = \text{equilibrium rate model} \]
\[ \text{evap} = \text{heat lost by evaporation} \]
\[ f = \text{fuel or flammable portion} \]
\[ \text{fg} = \text{difference between vapor and liquid (i.e., heat of vaporization or density difference)} \]
\[ g = \text{gas or vapor} \]
\[ \text{gross} = \text{explosion efficiency based on total mass released} \]
\[ H = \text{evaluated at constant enthalpy} \]
\[ i = \text{index to components in reaction or to potential explosion site} \]
\[ \text{ideal} = \text{ideal conditions, discharge rate with } C_D = 1 \]
\[ \text{jet} = \text{dimensions of jet} \]
\[ \text{leak} = \text{enthalpy added to pool from rained-out liquid} \]
\[ \text{loss} = \text{heat loss to surroundings} \]
\[ L = \text{liquid} \]
\[ \text{lim} = \text{limit value for concentration (LFL or UFL or fraction thereof)} \]