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Fire safety engineering — Requirements governing algebraic equations — Fire plumes

Ingénierie de la sécurité incendie — Exigences régissant les équations algébriques — Panaches de feu

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 16734 was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

Introduction

This International Standard is intended to be used by fire-safety practitioners who employ fire-safety engineering calculation methods. Examples include fire-safety engineers; authorities having jurisdiction, such as territorial authority officials; fire service personnel; code enforcers; and code developers. It is expected that users of this International Standard are appropriately qualified and competent in the field of fire-safety engineering. It is particularly important that users understand the parameters within which particular methodologies can be used.

Algebraic equations conforming to the requirements of this standard are used with other engineering calculation methods during fire safety design. Such design is preceded by the establishment of a context, including the fire safety goals and objectives to be met, as well as performance criteria when a tentative fire safety design is subject to specified design fire scenarios. Engineering calculation methods are used to determine if these performance criteria will be met by a particular design and if not, how the design shall be modified.

The subjects of engineering calculations include the fire-safe design of entirely new built environments, such as buildings, ships or vehicles as well as the assessment of the fire safety of existing built environments.

The algebraic equations discussed in this standard are very useful for quantifying the consequences of design fire scenarios. Such equations are particularly valuable for allowing the practitioner to determine very quickly how a tentative fire safety design should be modified to meet performance criteria agreed-upon, without having to spend time on detailed numerical calculations until the stage of final design documentation. Examples of areas where algebraic equations have been applicable include determination of heat transfer, both convective and radiant, from fire plumes, prediction of ceiling jet flow properties governing detector response times, calculation of smoke transport through vent openings and analysis of compartment fire hazards such as smoke filling and flashover. With respect to fire plumes, algebraic equations are often used to estimate flame dimensions so that the safe separation distance between a potential fire and a vulnerable target can be calculated. Algebraic plume equations are also useful for estimating rates of flame spread, both horizontal and vertical, within a built environment containing combustible materials.

The algebraic equations discussed in this standard are essential for checking the results of comprehensive numerical models that calculate fire growth and its consequences.

Fire safety engineering — Requirements governing algebraic equations — Fire plumes

1 Scope

1.1 The requirements in this International Standard govern the application of explicit algebraic equation sets to the calculation of specific characteristics of fire plumes.

1.2 This International Standard is an implementation of the general requirements provided in ISO/TR 13387-3 for the case of fire dynamics calculations involving sets of explicit algebraic equations.

1.3 This International Standard is arranged in the form of a template, where specific information relevant to algebraic fire plume equations is provided to satisfy the following types of general requirements:

a) description of physical phenomena addressed by the calculation method;

b) documentation of the calculation procedure and its scientific basis;

c) limitations of the calculation method;

d) input parameters for the calculation method;

e) domain of applicability of the calculation method.

1.4 Examples of sets of algebraic equations meeting all the requirements of this International Standard are be provided in separate annexes to this International Standard for each different type of fire plume. Currently, there is one informative annex containing algebraic equations for quasi-steady state, axisymmetric fire plumes.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/TR 13387-3, *Fire safety engineering — Part 3: Assessment and verification of mathematical fire models*

ISO 13943, *Fire safety — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13943 apply.

NOTE See Annex A for the terms and definitions specific to that annex.

4 Requirements governing description of physical phenomena

4.1 The fire plume resulting from a source fire is a complex, thermo-physical phenomenon that can be highly transient or nearly steady state. It contains regions closer to the source fire where there is usually flaming combustion (unless the source is a smouldering fire) and regions further from the source where there is no combustion taking place, but only a turbulent upward flow dominated by buoyancy forces. The fire plume can be significantly affected by many environmental parameters, e.g., the nature and arrangement of the burning materials that act as a fire source, whether there is flaming or smouldering combustion, the type of boundary confinement, degree of air restriction or vitiation, wind flows or compartment air motion, etc. For a liquid hydrocarbon source fire burning in the open under calm (windless) conditions, the problem of describing the fire plume by algebraic equations is simplified since most of these environmental parameters have a negligible influence.

4.2 General types of source fires, flow-boundary (including symmetry) conditions and other scenario elements to which the analysis is applicable shall be described with the aid of diagrams.

4.3 Fire plume characteristics to be calculated and their useful ranges shall be clearly identified, including those characteristics inferred by association with calculated quantities (e.g., the association of smoke concentration with excess gas temperature based on the analogy between energy and mass conservation) and those associated with radiant heat transfer to targets remote from the plume, if applicable.

4.4 Regions of the fire plume (whether or not flaming/combusting, degree of fire source influence, etc.) to which specific equations apply shall be clearly identified.

4.5 Because different equations describe different plume characteristics (see A.4.3) or apply to different regions (see A.4.4), it shall be shown that if there is more than one method to calculate a given quantity, the result is independent of the method used.

5 Requirements governing documentation

5.1 General requirements governing documentation can be found in ISO/TR 13387-3.

5.2 The procedure followed in performing calculations shall be described through a set of algebraic equations.

5.3 Each equation shall be presented in a separate subclause containing a phrase that describes the output of the equation, as well as explanatory notes and limitations unique to the equation being presented.

5.4 Each variable in the equation set shall be clearly defined, along with appropriate SI units, although equation versions with dimensionless coefficients are preferred.

5.5 The scientific basis for the equation set shall be provided through reference to recognised handbooks, the peer-reviewed scientific literature or through derivations, as appropriate.

5.6 Examples shall demonstrate how the equation set is evaluated using values for all input parameters consistent with the requirements in Clause 4.

6 Requirements governing limitations

6.1 Quantitative limits on direct application of the algebraic equation set to calculate output parameters, consistent with the scenarios described in Clause 4, shall be provided.

6.2 Cautions on the use of the algebraic equation set within a more general calculation method shall be provided, which shall include checks of consistency with the other relations used in the calculation method and the numerical procedures employed. For example, the use of a given equation set for plumes in a zone model can yield different results from another equation set for ceiling jet flows in the zone model, where the plume and ceiling jet zones connect, leading to errors.

7 Requirements governing input parameters

7.1 Input parameters for the set of algebraic equations shall be identified clearly, such as heat release rate or geometric dimensions.

7.2 Sources of data for input parameters shall be identified or provided explicitly within the International Standard.

7.3 The valid ranges for input parameters shall be listed as specified in ISO/TR 13387-3.

8 Requirements governing domain of applicability

8.1 One or more collections of measurement data shall be identified to establish the domain of applicability of the equation set. These data shall have level of quality (e.g., repeatability, reproducibility) assessed through a documented/standardized procedure (see ISO 5725).

8.2 The domain of applicability of the algebraic equations shall be determined through comparison with the measurement data of 8.1, following the principles of assessment, verification and validation of calculation methods.

8.3 Potential sources of error that limit the set of algebraic equations to the specific scenarios given in Clause 4 shall be identified, for example, the assumption of a point fire source.

Annex A
(informative)

Equations for quasi-steady state, axisymmetric fire plumes

A.1 Terms and definitions used in Annex A

The terms and definitions given in ISO 13943 and the following apply:

A.1.1
axisymmetric
mean motion and properties, such as mean temperature rise, are symmetric with respect to a vertical centreline

A.1.2
built environment
any building, structure or transportation vehicle

EXAMPLE Structures other than buildings include tunnels, bridges, offshore platforms and mines.

A.1.3
characteristic plume radius
radius at which the time-average plume temperature rise above the ambient value is one-half the centreline value

A.1.4
combustion efficiency factor
ratio of the heat of combustion, measured under specific fire test conditions, to the net heat of combustion

A.1.5
convective fraction of heat release rate
ratio of the convective heat release rate to the heat release rate

A.1.6
convective heat release rate
component of the heat release rate carried upward by the fire plume motion

NOTE Above the mean flame height, this component is considered invariant with height.

A.1.7
entrained mass flow rate
air drawn in from the surroundings into the fire plume

NOTE The mass flow rate in the plume at a given level can be considered equal to the mass rate of air entrained below that level into the plume (the fire source contributes an insignificant mass to the plume flow, typically less than 1 % of the total at the mean flame height (see Reference [15]).

A.1.8
fire plume
upward turbulent fluid motion generated by a source of buoyancy that exists by virtue of combustion and often includes a lower flaming region

A.1.9
flame
luminous region of fire plume associated with combustion

A.1.10
fuel mass burning rate
mass generation rate of fuel vapours

A.1.11
heat release rate
rate at which heat is actually being released by a source of combustion (such as the fire source)

A.1.12
jet flame
flame that is dominated by momentum, rather than buoyancy, forces

A.1.13
mean flame height
time-average height of flames above the base of a fire, defined as the elevation where the probability of finding flames is 50 %

A.1.14
mean temperature rise
time-average gas temperature increase above the ambient value on the plume centreline

A.1.15
mean vertical gas velocity
time-average velocity of vertical gas motion on the plume centreline

A.1.16
net heat of combustion
amount of heat generated per unit mass lost by a material under conditions of complete combustion and water in the vapour phase

A.1.17
quasi-steady state
assumption that the full effects of heat release rate changes at the fire source are felt everywhere in the flow field immediately

A.1.18
radiant energy release factor
ratio of the combustion heat released in a fire as thermal radiation to the net heat of combustion

A.1.19
spatial-average plume temperature rise at a given height
mean temperature rise in the plume associated with the plume mass flow rate and the plume convective heat release rate

A.1.20
stoichiometric air-fuel mass ratio
ratio of air to fuel mass that corresponds to complete chemical reaction, i.e., with no fuel or oxygen remaining

A.1.21
virtual origin
point source from which the fire plume above the flames appears to originate

NOTE The location of the virtual origin is likely to be above the surface of the burning fuel for the case of flammable liquid pool fires having a diameter of about 10 m or less and below the burning fuel surface for pool diameters larger than 10 m to 20 m [see Equation (A.9)].

A.2 Symbols and abbreviated terms used in Annex A

A_s	fire source plan area (m^2)
$b_{\Delta\mathrm{T}}$	plume radius where the mean temperature rise is one-half the centreline value (m)
c_p	specific heat of air at constant pressure ($\mathrm{kJ\ kg^{-1} \cdot K^{-1}}$)
D	fire source diameter (m)
g	acceleration due to gravity ($\mathrm{m \cdot s^{-2}}$)
ΔH_c	net heat of combustion ($\mathrm{kJ \cdot kg^{-1}}$)
L	mean flame height above base of fire source (m)
$\dot{m}_\mathrm{ent}$	entrained mass flow rate ($\mathrm{kg \cdot s^{-1}}$)
$\dot{m}_{\mathrm{ent},L}$	entrained mass flow rate at the mean flame height ($\mathrm{kg \cdot s^{-1}}$)
$\dot{m}_\mathrm{f}$	fuel mass burning rate ($\mathrm{kg \cdot s^{-1}}$)
N	nondimensional parameter, as defined in A.4.1 (–)
$\dot{Q}$	heat release rate actually measured or specified (kW)
$\dot{Q}''$	heat release rate per unit plan area ($\mathrm{kW \cdot m^{-2}}$)
$\dot{Q}_\mathrm{c}$	convective heat release rate (kW)
s	stoichiometric mass ratio of air to fuel (–)
T_a	ambient temperature (K)
ΔT_0	mean temperature rise above ambient on plume centreline (K)
ΔT_{0L}	mean temperature rise on plume centreline at mean flame height (K)
ΔT_ave	spatial-average plume temperature rise at or above mean flame height (K)
u_0	mean vertical gas velocity on plume centreline ($\mathrm{m \cdot s^{-1}}$)
z	height above base of fire source (m)
z_v	height of virtual origin above base of fire source (m)
ρ_a	ambient air density ($\mathrm{kg \cdot m^{-3}}$)
α	convective fraction of heat release rate, $1-\frac{\chi_\mathrm{R}}{\chi_\mathrm{a}}$ (–)
χ_a	combustion efficiency factor (–)
χ_R	radiant energy release factor (–)

A.3 Description of physical phenomena addressed by the equation set

A.3.1 Mean flame height values and selected properties of axisymmetric fire plumes

Mean flame height values and selected properties of axisymmetric fire plumes at and above the mean flame height are calculated.

A.3.2 Scenario elements to which the equation set is applicable

The set of equations is applicable to plumes rising above quasi-steady state fire sources that are approximately circular or square in plan area in a quiescent environment (i.e., burning is without interference from active protection measures, the wind, etc.). The fire source shall be a horizontal, upward-facing burning surface or a three-dimensional burning array for which the mean flame height is greater than the array height. Applicable fire sources include those outside of enclosed spaces, those inside of enclosed spaces (when the fire source itself and its flames are remote from the boundaries of the enclosed space). An applicable fire source can also consist of a built environment fully involved in fire, when the mean flame height due to flames burning through the top of the built environment (e.g., a collapsed roof) is greater than the height of the built environment. See A.6 for quantitative limitations on these scenario elements.

A.3.3 Fire plume characteristics to be calculated

Equations provide gas temperatures and velocities for locations along the plume vertical centreline (symmetry axis). Mean flame height, plume entrained mass flow rate and characteristic radius based on the rise in gas temperature and average plume temperature rise are also calculated.

A.3.4 Fire plume regions to which equations apply

A distinction is made between regions above the mean flame height and regions below the mean flame height in the fire plume, with equations applicable to the region above only.

A.3.5 Self-consistency of the equation set

The set of equations provided in this annex has been derived and reviewed by G. Heskestad (see A.5) to insure that calculation results from different equations in the set are consistent (i.e., do not produce conflicts).

A.3.6 Standards and other documents where the equation set is used

Equations (A.4), (A.9) and (A.18) are used in NFPA 204[38] for smoke and heat venting.

A.4 Equation-set documentation

A.4.1 Mean flame height

A.4.1.1 The dimensionless formulation for mean flame height, $\frac{L}{D}$, is given by Equations (A.1) to (A.3) from Reference [10] and is applicable to a wide range of atmospheric and fuel conditions relevant to fires in the built environment.

$$\frac{L}{D} = -1{,}02 + 15{,}6 N^{1/5} \qquad \text{(A.1)}$$

$$N = \left[\frac{c_\mathrm{p} T_\mathrm{a}}{g \rho_\mathrm{a}^2 \left(\Delta H_\mathrm{c} / s \right)^3} \right] \frac{\dot{Q}^2}{D^5} \qquad \text{(A.2)}$$

$$\dot{Q} = \dot{m}_\mathrm{f} \chi_\mathrm{a} \Delta H_\mathrm{c} \qquad \text{(A.3)}$$

A.4.1.2 The mean flame height, L, under normal atmospheric conditions $\{g = 9{,}81\ \mathrm{m \cdot s^{-2}}$; $c_\mathrm{p} = 1{,}00\ \mathrm{kJ(kg \cdot K)^{-1}}$; $\rho_\mathrm{a} = 1{,}2\ \mathrm{kg \cdot m^{-3}}$; $T_\mathrm{a} = 293\ \mathrm{K}$; $\frac{\Delta H_\mathrm{c}}{s} = 3\,000\ \mathrm{kJ \cdot kg^{-1}}$, the last quantity an average for many common fuels, as shown in Reference [35], Tables 3-4.19, 3-4.20 and 3-4.21$\}$ is given by Equation (A.4) from Reference [6]:

$$L = -1{,}02D + 0{,}235\dot{Q}^{2/5} \tag{A.4}$$

A.4.2 Virtual origin height above the base of the fire source

A.4.2.1 The dimensionless formulation for virtual origin height, $\frac{z_\mathrm{v}}{D}$, is given by Equations (A.5) to (A.8) from Reference [7] and is applicable to a wide range of atmospheric and fuel conditions relevant to fires in the built environment:

$$\frac{z_\mathrm{v}}{D} = -1{,}02 + 15{,}6(X - Y)\frac{\dot{Q}^{2/5}}{D} \tag{A.5}$$

$$X = \left[\frac{c_\mathrm{p} T_\mathrm{a}}{g \rho_\mathrm{a}^2 \left(\Delta H_\mathrm{c}/s\right)^3}\right]^{1/5} \tag{A.6}$$

$$Y = 0{,}158\left[\left(c_\mathrm{p}\rho_\mathrm{a}\right)^{4/5} T_\mathrm{a}^{3/5} g^{2/5}\right]^{-1/2} \alpha^{2/5} \frac{T_{0L}^{1/2}}{\Delta T_{0L}^{3/5}} \tag{A.7}$$

$$T_{0L} = \Delta T_{0L} + T_\mathrm{a} \tag{A.8}$$

A.4.2.2 The virtual origin height, z_v, in terms of $\dot{Q}$ and D under normal atmospheric conditions $\{g = 9{,}81\ \mathrm{m \cdot s^{-2}}$; $c_\mathrm{p} = 1{,}00\ \mathrm{kJ(kg \cdot K)^{-1}}$; $\rho_\mathrm{a} = 1{,}2\ \mathrm{kg \cdot m^{-3}}$; $T_\mathrm{a} = 293\ \mathrm{K}$; $\alpha = 0{,}7$; $\Delta T_{0L} = 500\ \mathrm{K}$ and $\frac{\Delta H_\mathrm{c}}{s} = 3\,000\ \mathrm{kJ \cdot kg^{-1}}$, the last quantity an average for many common fuels, as shown in Reference [35], Tables 3-4.19, 3-4.20 and 3-4.21$\}$ is given by Equation (A.9), a dimensional correlation from Reference [7] that is not sensitive to fuel type:

$$\frac{z_\mathrm{v}}{D} = -1{,}02 + 0{,}083\frac{\dot{Q}^{2/5}}{D} \tag{A.9}$$

A.4.2.3 The virtual origin height, z_v, in terms of $\dot{Q}_\mathrm{c}$ and L under normal atmospheric conditions $[g = 9{,}81\ \mathrm{m \cdot s^{-2}}$; $c_\mathrm{p} = 1{,}00\ \mathrm{kJ(kg \cdot K)^{-1}}$; $\rho_\mathrm{a} = 1{,}2\ \mathrm{kg \cdot m^{-3}}$; $T_\mathrm{a} = 293\ \mathrm{K}$; $\Delta T_{0L} = 500\ \mathrm{K}$; $\frac{\Delta H_\mathrm{c}}{s} = 3\,000\ \mathrm{kJ \cdot kg^{-1}}]$ is given by Equations (A.10) and (A.11), a dimensional correlation from Reference [7] that is not sensitive to fuel type:

$$z_\mathrm{v} = L - 0{,}175\dot{Q}_\mathrm{c}^{2/5} \tag{A.10}$$

$$\dot{Q}_\mathrm{c} = \alpha\dot{Q} \tag{A.11}$$

A.4.3 Mean centreline temperature rise at and above the mean flame height

A.4.3.1 The dimensionless formulation for mean centreline temperature rise, ΔT_0, at and above the mean flame height is given by Equation (A.12) from Reference [39]:

$$\Delta T_0 = 9{,}1\left(\frac{T_a}{g c_p^2 \rho_a^2}\right)^{1/3} \dot{Q}_c^{2/3} (z - z_v)^{-5/3} \tag{A.12}$$

A.4.3.2 The mean centreline temperature rise, ΔT_0, at and above the mean flame height under normal atmospheric conditions [$g = 9{,}81$ m·s^{-2}; $c_p = 1{,}00$ kJ(kg · K)$^{-1}$; $\rho_a = 1{,}2$ kg · m^{-3}; $T_a = 293$ K] is given by Equation (A.13), a dimensional correlation from Reference [34]:

$$\Delta T_0 = 25{,}0 \dot{Q}_c^{2/3} (z - z_v)^{-5/3} \tag{A.13}$$

A.4.4 Mean centreline vertical gas velocity at and above the mean flame height

A.4.4.1 The dimensionless formulation for mean centreline vertical gas velocity, u_0, at and above the mean flame height is given by Equation (A.14) from Reference [39]:

$$u_0 = 3{,}4\left(\frac{g}{c_p \rho_a T_a}\right)^{1/3} \dot{Q}_c^{1/3} \left(z - z_v\right)^{-1/3} \tag{A.14}$$

A.4.4.2 The mean vertical gas velocity, u_0, at and above the mean flame height under normal atmospheric conditions [$g = 9{,}81$ m·s^{-2}; $c_p = 1{,}00$ kJ(kg · K)$^{-1}$; $\rho_a = 1{,}2$ kg · m^{-3}; $T_a = 293$ K] is given by Equation (A.15), a dimensional correlation from Reference [34]:

$$u_0 = 1{,}03 \dot{Q}_c^{1/3} (z - z_v)^{-1/3} \tag{A.15}$$

A.4.5 Characteristic plume radius at and above the mean flame height

The dimensionless formulation for the plume radius, $b_{\Delta T}$, where the mean temperature rise is one-half the centreline value is given by Equation (A.16) from Reference [39]:

$$b_{\Delta T} = 0{,}12\left(\frac{T_0}{T_a}\right)^{1/2} (z - z_v) \tag{A.16}$$

NOTE The plume radius to the point where the gas velocity is one-half the centreline value is about 10 % larger than the plume radius, $b_{\Delta T}$, to the point where the mean temperature rise is one-half the centreline value.

A.4.6 Plume mass flow rate at and above the mean flame height

A.4.6.1 The dimensionless formulation for the plume mass flow rate, $\dot{m}_{ent}$, at and above the mean flame height ($z \geqslant L$) is given by Equation (A.17) from Reference [15]:

$$\dot{m}_{ent} = 0{,}196\left(\frac{g \rho_a^2}{c_p T_a}\right)^{1/3} \dot{Q}_c^{1/3} \left(z - z_v\right)^{5/3} \left[1 + \frac{2{,}9 \dot{Q}_c^{2/3}}{\left(g^{1/2} c_p \rho_a T_a\right)^{2/3} (z - z_v)^{5/3}}\right] \tag{A.17}$$

A.4.6.2 The plume mass flow rate at and above the mean flame height ($z \geqslant L$) under normal atmospheric conditions [$g = 9{,}81\ \text{m}\cdot\text{s}^{-2}$; $c_\text{p} = 1{,}00\ \text{kJ(kg}\cdot\text{K)}^{-1}$; $\rho_\text{a} = 1{,}2\ \text{kg}\cdot\text{m}^{-3}$; $T_\text{a} = 293\ \text{K}$ in Equation (A.17)] is given by Equation (A.18), a dimensional correlation from Reference [34]:

$$\dot{m}_\text{ent} = 0{,}071\dot{Q}_\text{c}^{1/3}(z - z_\text{v})^{5/3}[1 + 0{,}027\dot{Q}_\text{c}^{2/3}(z - z_\text{v})^{-5/3}] \tag{A.18}$$

A.4.6.3 The dimensionless formulation for the plume mass flow rate at the mean flame height, $\dot{m}_{\text{ent},L}$, [$z = L$ and z_v from Equations (A.5) to (A.8), substituted in Equation (A.17)] is given by Equation (A.19) from Reference [34]:

$$\dot{m}_{\text{ent},L} = 0{,}878\left[\left(\frac{T_{0L}}{T_\text{a}}\right)^{5/6}\left(\frac{T_\text{a}}{\Delta T_{0L}}\right) + 0{,}647\right]\frac{\dot{Q}_\text{c}}{c_\text{p}T_\text{a}} \tag{A.19}$$

A.4.6.4 The plume mass flow rate at the mean flame height, $\dot{m}_{\text{ent},L}$, under normal atmospheric conditions [obtained from Equation (A.19) with $c_\text{p} = 1{,}00\ \text{kJ(kg}\cdot\text{K)}^{-1}$; $T_\text{a} = 293\ \text{K}$; $\Delta T_{0L} = 500\ K$] is given by Equation (A.20), a dimensional correlation from Reference [34]:

$$\dot{m}_{\text{ent},L} = 0{,}005\,9\cdot\dot{Q}_\text{c} \tag{A.20}$$

A.4.7 Spatial-average plume temperature rise at and above the mean flame height

The spatial-average plume temperature rise at and above the mean flame height, ΔT_ave, is given by the dimensionless expression in Equation (A.21) from Reference [34]:

$$\Delta T_\text{ave} = \frac{\dot{Q}_\text{c}}{\dot{m}_\text{ent}\cdot c_\text{p}} \tag{A.21}$$

A.5 Scientific basis for the equation set

The theory of axisymmetric fire plumes traces to early theories by Schmidt[1], Rouse *et al.*[2], Morton *et al.*[3] and Yokoi[4], with refinements for large density deficiencies by Morton[5], and empirical coefficients established by Heskestad[6] from published experiments. The equation for virtual origin (z_v) was developed by Heskestad[7], with consideration of work by other authors, including Hasemi and Tokunaga[8] and Cetegen *et al.*[9]. The flame height equation traces to Heskestad[10]. Contributions to prediction of entrainment have been made by Yih[11], Thomas *et al.*[12], McCaffrey[13], Cetegen *et al.*[14], Heskestad[15], Delichatsios[16], Zukoski[17] and Zhou and Gore[18].

A number of authors have also addressed conditions arising in axisymmetric fire plumes, including Cox and Chitty[19], Dai *et al.*[20], Gengembre *et al.*[21], George *et al.*[22], Heskestad[23],[24],[25], Kung and Stavrianidis[26], McCaffrey[27], Orloff[28], Orloff and de Ris[29], Shabbir and George[30], Tamanini[31] and Thomas[32],[33].

The basis for equations in A.4.1 through A.4.6 is documented by Heskestad[34]. Equations (A.19) and (A.20) are derived by Heskestad[34] using equations in A.4.1 and A.4.2.

A.6 Limitations of the equation set

The equation set should not be applied in the following equations.

A.6.1 Fire sources

The equation set should not be applied to fire sources that are affected by extinguishing agents; rectangular fire sources having a length to width ratio greater than or equal to 2; three-dimensional fire sources having restricted air access or a mean flame height less than 110 % of the height of the three-dimensional source itself; fire sources consisting of a jet flame (such as from a pipe-leak or flow through an orifice from a pressurised fuel reservoir); fire sources consisting of flames distributed to such an extent over the source area that there are multiple fire plumes.

A.6.2 Flame dimensions

The equation set should not be applied within enclosed spaces, when the mean flame height, L, is greater than 50 % of the vertical interior dimension of the enclosed space and/or when the effective fire diameter, D, is greater than 10 % of the minimum plan dimension of the enclosed space.

A.6.3 Proximity to boundaries

The equation set should not be applied within enclosed spaces, when the fire source itself or its flames are within one fire source diameter, D, of a bounding surface.

A.6.4 Aerodynamic disturbances

The equation set should not be applied to plumes that are affected by aerodynamic disturbances, which can arise from obstructions in the flow field or from the effects of wind, forced ventilation or natural ventilation through enclosure openings.

A.6.5 Output parameters

The equation set should not be applied when the calculated mean temperature rise, ΔT_0, is much less (see A.8) than the temperature increase with elevation in the environment before fire initiation (e.g., between the top and bottom of an enclosed space due to temperature stratification) or when the calculated mean temperature rise is greater than ΔT_{0L}.

A.7 Equation-set input parameters

A.7.1 Fire heat release rate

The parameter, $\dot{Q}$, expressed in kilowatts, is the rate of heat actually released by a fire under specific environmental conditions, as measured by a calorimeter that is based on product gas collection to determine O_2, CO_2 and CO generation rates, or as otherwise specified. This parameter is normally obtained from the design fire scenario. Additional sources of information on fire heat release rate and fire calorimetry include Tewarson[35] and Babrauskas[36].

A.7.2 Convective fraction

The dimensionless parameter, α, is typically in the range of 0,6 to 0,7 for exposed solid surfaces or liquid fuels burning in a pool but can be up to 0,8 or greater for oxygenated liquid fuels or for low-molecular-weight gaseous fuels. For three-dimensional fire sources, the parameter is much less than unity early in the fire growth period, increasing to 0,6 to 0,7 during the advanced stages of fire growth. This parameter is normally obtained from the design fire scenario, but additional information is available from Tewarson[35].

A.7.3 Fire source diameter

The parameter, D, expressed in metres, is the diameter for a circular fire source. This parameter is normally obtained from the design fire scenario. For rectangular fire sources, an effective diameter, D, is obtained from Equation (A.22), which uses a circular source having the same area, A_s, expressed in metres squared, as the fire source:

$$D = \sqrt{\frac{4A_s}{\pi}} \tag{A.22}$$

A.7.4 Height in the fire plume

The parameter, z, expressed in metres, is normally obtained from the design fire scenario.

A.7.5 Heat of combustion per unit mass of air

The parameter, $\frac{\Delta H_\mathrm{c}}{s}$, expressed in kilojoules per kilogram, for specific polymers and other materials can be obtained from Tewarson[35] (with the latter values adjusted for combustion efficiency), Babrauskas[36] and the Chemical Engineers' Handbook[37]. The parameter $\frac{\Delta H_\mathrm{c}}{s}$ for fuels not listed in the preceding references can require testing that involves use of a calorimeter to determine ΔH_c and elemental analysis to determine s.

A.7.6 Valid ranges for input parameters

The heat release rate and diameter parameters, $\dot{Q}$ and D, respectively, should normally satisfy the inequality condition in Equation (A.23), based on information in McCaffrey[27]:

$$0{,}04 < \frac{\dot{Q}}{\rho_\mathrm{a} c_\mathrm{p} T_\mathrm{a} \sqrt{g} D^{5/2}} < 2 \times 10^4 \tag{A.23}$$

The valid range for the parameter, z, is normally from the mean flame height to either the elevation of the top surface of an enclosed space or a value corresponding to a temperature rise meeting the requirements of A.8.

A.8 Domain of applicability of the equation set

The domain of applicability of the equation set in this annex can be determined from the scientific literature references given in A.5.

To maintain this domain of applicability, temperature stratification in the ambient environment shall be limited such that the ambient temperature, T_a, at height, z, is related to ambient temperature near the base of the fire, $(T_\mathrm{a})_{\mathrm{z}=0}$ as given by the inequality condition in Equation (A.24) from Reference [34].

$$\left(T_\mathrm{a}\right)_\mathrm{z} - \left(T_\mathrm{a}\right)_{\mathrm{z}=0} < 7 \Delta T_0 \tag{A.24}$$

A.9 Example calculations

A.9.1 Flame height

Consider a 1,8 m diameter pan of a flammable liquid burning with a heat release rate of 2 500 kW m^{-2}. Normal atmospheric conditions prevail (air pressure of 101,3 kPa, air temperature of 293 K). The mean flame height, L, expressed in metres, is obtained from Equation (A.4) as follows:

$$L = -1{,}02 \times 1{,}8 + 0{,}235 \times \left(2\,500 \times \pi \times 1{,}8^2/4\right)^{2/5} = 5{,}97$$

A.9.2 Virtual origin location

Consider the pan fire from A.9.1. Since the heat release rate is given, the virtual origin, z_v, expressed in metres, is obtained from Equation (A.9) as follows:

$$z_\mathrm{v} = -1{,}02 \times 1{,}8 + 0{,}083 \times \left(2\,500 \times \pi \times 1{,}8^2/4\right)^{2/5} = 0{,}921$$

which means that the virtual origin is 0,921 m above the base of the fire, or in this case, 0,921 m above the surface of the flammable liquid.

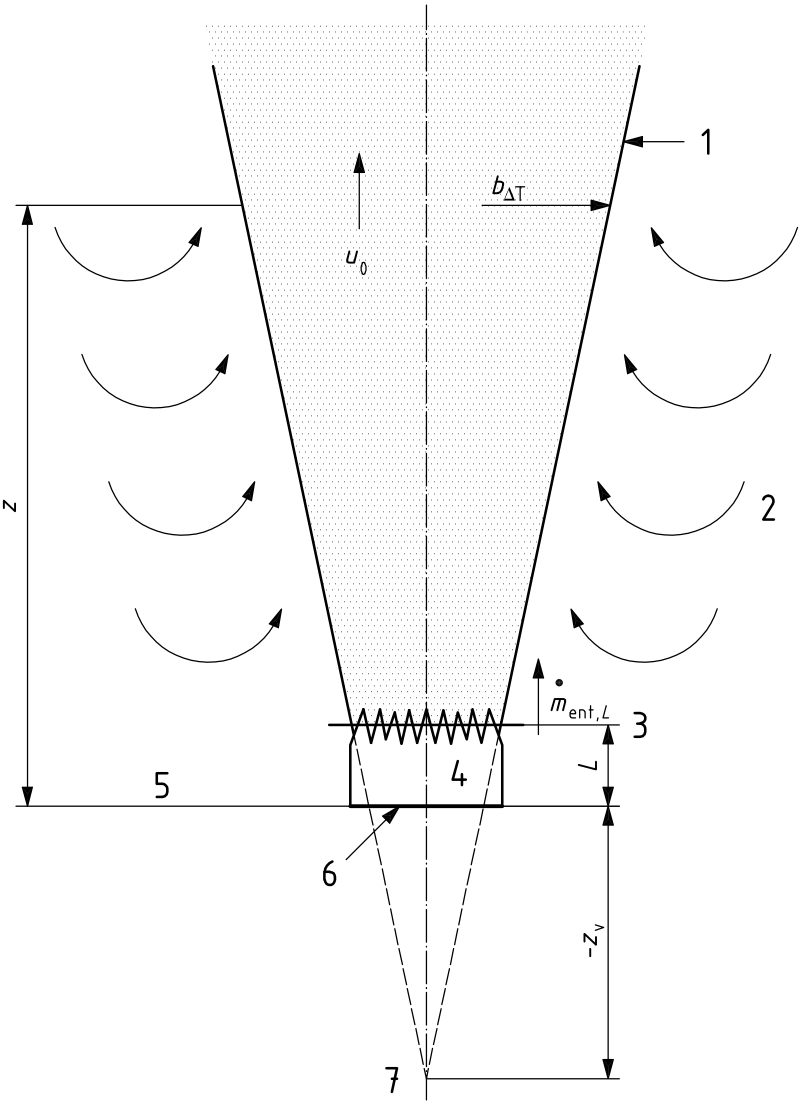
A.9.3 Mean temperature rise at and above the mean flame height

Consider the pan fire from A.9.1 having a convective fraction of heat release rate equal to 0,7. The mean temperature rise on the plume centreline, above the ambient value, at an elevation above the flammable liquid surface of 9 m is obtained from Equation (A.13) as follows:

$$\Delta T_0 = 25 \times \left(0{,}7 \times 2\,500 \times \pi \times 1{,}8^2/4\right)^{2/3} \times \left(9 - 0{,}921\right)^{-5/3} = 208 \text{ K}$$

Hence, the maximum mean gas temperature about 3 m above the mean flame height is 208 + 20 = 228 °C.

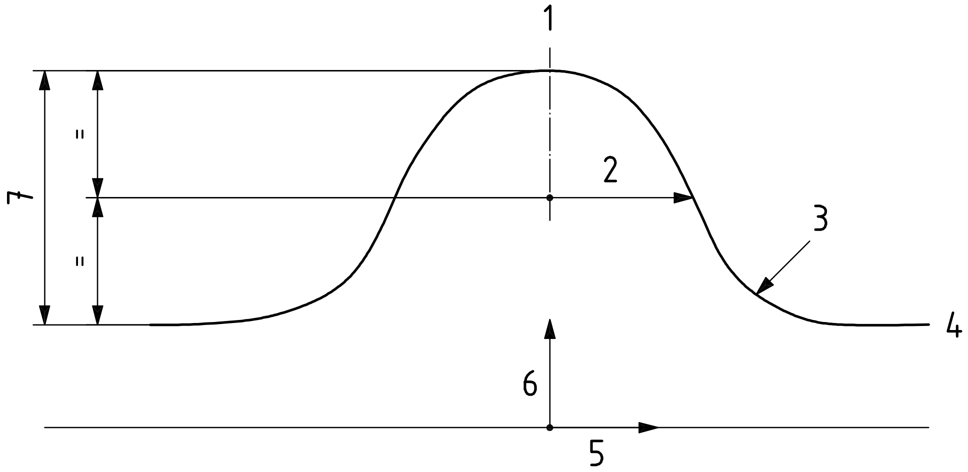
A.10 Descriptive figures



Key

1	indicates characteristic radius of plume	5	base of fire
2	air entrainment	6	plan area of fire, A_s
3	mean flame height	7	virtual origin
4	fire		

Figure A.1 — Illustration of parameters describing the plume flow



Key

1	plume centreline	5	distance
2	characteristic plume radius	6	temperature
3	temperature profile	7	mean temperature rise
4	ambient temperature		

Figure A.2 — Plume flow profile

Bibliography

[1] SCHMIDT, W., *Turbulente Ausbreitung eines Stromes erhitzer Luft*, Z. Angew. Math. Mech., Vol. **21**, pp. 265-278, 351-363

[2] ROUSE, H., YIH, C.S. and HUMPHREYS, H.W., G*ravitational Convection from a Boundary Source*, Tellus, Vol. **4**, pp. 201-210, 1952

[3] MORTON, B.R., TAYLOR, G.I. and TURNER, J.S., *Turbulent Graviational Convection from Maintained and Instantaneous Sources*, Proc. R. Soc. London, Vol. **A234**, pp. 1-23, 1956

[4] YOKOI, S., Report No. 34, Building Research Institute of Japan, 1960

[5] MORTON, B.R., *Modeling of Fire Plumes*, Tenth Symp. (Int.) on Combustion, The Combustion Institute, Pittsburgh, PA, pp. 973-982, 1965

[6] HESKESTAD, G., *Fire Plumes*, SFPE Handbook of Fire Protection Engineering (Ed. P.J. DiNenno), Society of Fire Protection Engineers, Boston, MA, pp. 1-107 to 1-115, 1988

[7] HESKESTAD, G., *Virtual Origins of Fire Plumes*, Fire Safety J., Vol. **5**, pp. 109-114, 1983

[8] HASEMI, Y. and TOKUNAGA, T. *Flame Geometry Effects on the Buoyant Plumes from Turbulent Diffusion Flames*, Fire Sci. Technol., Vol. **4**, pp. 15-26, 1984a

[9] CETEGEN, B.M., ZUKOSKI, E.E. and KUBOTA, T., *Entrainment in the Near and Far Field of Fire Plumes*, Combust. Sci. Technol., Vol. **39**, pp. 305-331, 1984

[10] HESKESTAD, G., *Luminous Heights of Turbulent Diffusion Flames*, Fire Safety J., Vol. **5**, pp. 103-108, 1983

[11] YIH, C.S., *Free Convection Due to a Point Source of Heat*, Proc. 1st US National Congress of Applied Mechanics, pp. 941-947, 1952

[12] THOMAS, P.H., BALDWIN, R. and HESELDEN, A.J.M., *Buoyant Diffusion Flames: Some Measurements of Air Entrainment, Heat Transfer and Flame Merging*, Tenth Symp. (Int.) on Combusiton, The Combustion Institute, Pittsburgh, PA, pp. 983-996, 1965

[13] MCCAFFREY, B.J., *Purely Buoyant Diffusion Flames: Some Experimental Results*, NBSIR 79-1910, National Bureau of Standards, Washington, DC, 1979

[14] CETEGEN, B.M., ZUKOSKI, E.E. and KUBOTA, T., *Entrainment and Flame Geometry of Fire Plumes*, Report G8-9014, California Institute of Technology, Daniel and Florence Guggenheim Jet Propulsion Center, Pasadena, CA, 1982

[15] HESKESTAD, G., *Fire Plume Air Entrainment According to Two Competing Assumptions*, Twenty-first Symp. (Int.) on Combustion, The Combustion Institute, Pittsburgh, PA, pp. 111-120, 1986

[16] DELICHATSIOS, M.A., *Air Entrainment into Buoyant Jet Flames and Pool Fires*, Combustion and Flame, Vol. **70**, pp. 33-46, 1987.

[17] ZUKOSKI, E.E., *Mass Flux in Fire Plumes*, Fire Safety Science – Proc. Fourth Int. Symposium (Ed. T. Kashiwagi), International Association for Fire Safety Science, pp. 137-147, 1994.

[18] ZHOU, X.C. and GORE, J.P., *Air Entrainment Flow Field Induced by a Pool Fire,* Combustion and Flame, Vol. **100**, pp. 52-60, 1995

[19] Cox, G. and Chitty, R., *A Study of the Deterministic Properties of Unbounded Fire Plumes*, Combustion and Flame, Vol. **39**, pp. 191-209, 1980

[20] Dai, Z., Tseng, L.K. and Faith, G.M., *Structure of Round, Fully Developed, Buoyant Turbulent Plumes,* J. Heat Transfer, Vol. **116**, pp. 409-417, 1994

[21] Gengembre, E., Cambray, P., Karmed, D. and Bellet, J.C., *Turbulent Diffusion Flames with Large Buoyancy Effects*, Combustion Sci. and Technology, Vol. **41**, pp. 55-67, 1984

[22] George, W.K., Alpert, R.L. and Tamanini, F., *Turbulence Measurements in an Axisymmetric Buoyant Plume*, Int. J. Heat and Mass Transfer, Vol. **20**, pp. 1145-1154, 1977

[23] Heskestad, G., *Note on Maximum Rise of Fire Plumes in Temperature-Stratified Ambients*, Fire Safety J., Vol. **15**, pp. 271-276, 1989

[24] Heskestad, G., A *Reduced-Scale Mass Fire Experiment*, Combustion and Flame, Vol. **83**, pp. 293-301, 1991

[25] Heskestad, G., *Fire Plume Behavior in Temperature Stratified Ambients,* Combustion Sci. and Technology, Vol. **106**, pp. 207-228, 1995

[26] Kung, H.C. and Stavrianidis, P., *Buoyant Plumes of Large-Scale Pool Fires,* Nineteenth Symp. (Int.) on Combustion, The Combustion Institute, Pittsburgh, PA, pp. 905-912, 1983

[27] McCaffrey, B.J., *Flame Height*, *SFPE Handbook of Fire Protection Engineering*, 2nd Edition (Ed. P.J. DiNenno), Society of Fire Protection Engineers, Boston, MA, pp. 1-298 to 1-305, 1995

[28] Orloff, L., *Simplified Radiation Modeling of Pool Fires*, Eighteenth Symp. (Int.) on Combustion, The Combustion Institute, Pittsburgh, PA, pp. 549-561, 1981

[29] Orloff, L. and de Ris, J.L., *Froude Modeling of Pool Fires*, Nineteenth Symp. (Int.) on Combustion, The Combustion Institute, Pittsburgh, PA, pp. 885-895, 1982

[30] Shabbir, A. and George, W.K., *Experiments on a Round Turbulent Buoyant Plume*, J. Fluid Mech., Vol. **275**, pp. 1-32, 1994

[31] Tamanini, F., *Direct Measurements of the Longitudinal Variation of Burning Rate and Product Yield in Turbulent Diffusion Flames*, Combustion and Flame, Vol. **51**, pp. 231-243, 1983

[32] Thomas, P.H., *The Size of Flames from Natural Fires*, Ninth Symp. (Int.) on Combustion, The Combustion Institute, Pittsburgh, PA, pp. 844-859, 1963

[33] Thomas, P.H., Hinkley, P.L., Theobald, C.R. and Sims, D.L., *Investigation into the Flow of Hot Gases in Roof Venting*, Fire Technical Paper No.7, Joint Fire Research Organisation, London, HMSO, 1963

[34] Heskestad, G., *Fire Plumes, Flame Height and Air Entrainment*, SFPE Handbook of Fire Protection Engineering (Ed. P.J. DiNenno), 3rd Edition, National Fire Protection Association, Quincy, MA, pp. 2-1 to 2-17, 2002

[35] Tewarson, A., *Generation of Heat and Chemical Compounds in Fires*, SFPE Handbook of Fire Protection Engineering (Ed. P.J. DiNenno), 3rd Edition, National Fire Protection Association, Quincy, MA, pp. 3-82 to 3-161, 2002

[36] Babrauskas, V., *Heat Release Rates*, SFPE Handbook of Fire Protection Engineering (Ed. P.J. DiNenno), 3rd Edition, National Fire Protection Association, Quincy, MA, pp. 3-1 to 3-37, 2002

[37] Perry's Chemical Engineers' Handbook (Ed. D.W. Green), 7th Edition, McGraw-Hill, New York, NY, 1997

[38] NFPA 204, *Standard for Smoke and Heat Venting*, 2002 Edition, National Fire Protection Association, Quincy, MA, Clause 9.2.3, 2002

[39] HESKESTAD, G., Fire Safety J., Vol. **7**, p. 25, 1984

[40] ISO 5725 (all parts), *Accuracy (trueness and precision) of measurement methods and results*

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