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Fire safety engineering — Requirements governing algebraic equations — Ceiling jet flows

Ingénierie de la sécurité incendie — Exigences régissant les équations algébriques — Écoulements en jet sous plafond

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ISO 16736:2006(E)

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Tel. + 41 22 749 01 11
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Contents

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 16736 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 International 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 are met by a particular design and if not, how the design can 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 International 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. In this respect, the equations for ceiling jet flows can be used for estimating the response time of fire detectors and the first activated sprinklers, as well as the time for damage to some structural elements (e.g., plastic roof- or sky-lights).

The algebraic equations discussed in this International 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 — Ceiling jet flows

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 ceiling jet flows.

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 ceiling jet flows 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 provided in separate annexes to this International Standard for each different type of ceiling jet flow. Currently, there is one informative annex containing algebraic equations for quasi-steady state, axisymmetric ceiling jet flows.

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 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.

4.2 Ceiling jet flow 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 ceiling jet flow, if applicable.

4.3 Regions of the ceiling jet flow (whether or not in the plume turning region, degree of fire-source influence, etc.) to which specific equations apply shall be clearly identified.

4.4 Because different algebraic equations describe different ceiling jet flow characteristics (see 4.2) or apply to different ceiling jet flow regions (see 4.3), 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 to be 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 function of the equation, 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 recognized 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 ceiling jet flows in a zone model can yield different results from another equation set for plume 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 described.

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 (all parts)].

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 that flaming combustion is not present in the ceiling jet flow.

Annex A
(informative)

Equations for quasi-steady state, axisymmetric ceiling jet flows

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
ceiling
highest elevation boundary of the enclosed space in any built environment, such as a room in a building or a cabin in a vehicle

A.1.4
ceiling jet
gas motion in a layer beneath the surface of a ceiling, driven by the buoyancy of hot gases from fire plume impingement on the ceiling

A.1.5
characteristic depth of ceiling jet temperature profile
depth below the ceiling surface, at a given radius, r, at which the mean temperature rise above ambient in the ceiling jet flow becomes a factor of e^{-1} times the maximum mean temperature rise at that radius

A.1.6
characteristic depth of ceiling jet velocity profile
depth below the ceiling surface, at a given radius, r, at which the mean gas velocity in the ceiling jet flow becomes a factor of e^{-1} times the maximum mean gas velocity at that radius

A.1.7
combustion efficiency factor
ratio of the heat of combustion measured under specific fire test conditions to the net heat of combustion

A.1.8
convective fraction
ratio of the convective heat release rate to the heat release rate

A.1.9
convective heat flux
rate of heat transfer per unit area of a target surface due to the motion of a gas, such as the ceiling jet flow

A.1.10
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.1.11
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.1.12
fire plume turning region
flow area in which there is a transition from a plume flow to a ceiling jet flow, defined by a ratio of radial distance to effective ceiling height, $H - z_v$, equal to 0,15 to 0,2

A.1.13
fire source diameter
effective diameter of the fire source, equal to the actual diameter for a circular source or the diameter of a circle having an area equal to the plan area of a non-circular source

A.1.14
flame
luminous region of fire plume associated with combustion

A.1.15
fuel mass burning rate
mass generation rate of fuel vapours

A.1.16
heat release rate
rate at which heat is actually being released by a source of combustion (such as the fire source)

A.1.17
jet flame
flame that is dominated by momentum, rather than buoyancy, forces

A.1.18
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.1.19
mean gas velocity
time-average gas velocity in the ceiling jet flow at a given radial distance, r

A.1.20
mean temperature rise
time-average gas temperature increase above the ambient temperature value in the ceiling jet flow, at a given radial distance, r

A.1.21
net heat of combustion
amount of heat generated per unit mass lost by a material when exposed to specific fire test conditions

A.1.22
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.1.23
radiant energy release factor
ratio of the combustion heat released in a fire as thermal radiation to the net heat of combustion

A.2 Symbols and abbreviated terms used in Annex A

A_c	ceiling plan area (m^2)
A_s	fire source plan area (m^2)
D	fire source diameter (m)
e	base of natural logarithms
g	acceleration due to gravity ($\mathrm{m \cdot s^{-2}}$)
h	convective heat transfer coefficient ($\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$)
ΔH_c	net heat of combustion ($\mathrm{kJ \cdot kg^{-1}}$)
L	mean flame height above base of fire source (m)
l_T	characteristic depth of ceiling jet temperature profile
l_v	characteristic depth of ceiling jet velocity profile
$\dot{m}_\mathrm{f}$	fuel mass burning rate ($\mathrm{kg \cdot s^{-1}}$)
p	absolute air pressure (kPa)
$\dot{q}'_\mathrm{f}$	convective heat flux ($\mathrm{kW \cdot m^{-2}}$)
$\dot{Q}$	heat release rate actually measured or specified (kW)
$\dot{Q}_\mathrm{c}$	convective heat release rate (kW)
Ra	plume Rayleigh number (–)
r	radial distance from plume centreline (m)
T_a	ambient temperature (K)
y	vertical distance below ceiling (m)
z_H	height of ceiling above base of fire source (m)
z_v	height of virtual origin above base of fire source (m)
ΔT	mean temperature rise (K)
ΔT_c	ceiling temperature rise above the ambient value at a given radial position (K)
ΔT_max	maximum mean temperature rise (K)
V_max	maximum mean gas velocity ($\mathrm{m \cdot s^{-1}}$)
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 (–)
ν	kinematic viscosity of air ($\mathrm{m^2 \cdot s^{-1}}$)
θ	maximum slope angle of the ceiling surface (rad)

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

A.3.1 Selected properties of ceiling jet flows

Selected properties of axisymmetric, quasi-steady state ceiling jet flows are calculated.

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

The set of equations is applicable to the impingement on essentially flat, unobstructed ceilings of fire plumes from quasi-steady state fire sources that are approximately circular or square in plan area. The fire source should be a horizontal, upward-facing burning surface or a three-dimensional burning array for which the mean flame height is more than 110 % of the array height yet less than 10 % of the total ceiling height above the base of the fire source.

A.3.3 Ceiling jet flow characteristics to be calculated

Equations provide maximum gas temperatures and maximum gas velocities for locations at a radius from the plume vertical centreline (symmetry axis). Characteristic ceiling jet flow depth and rates of convective heat transfer to the ceiling are also calculated.

A.3.4 Ceiling jet flow regions to which equations apply

A distinction is made between the flow within or at the exit of the plume turning region and the flow outside of the plume-turning region, with different equations applicable within and outside of this region.

A.3.5 Self-consistency of the equation set

The set of equations provided in this annex have been derived and reviewed by R.L. Alpert (see Clause A.5) to ensure 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

The equation set is discussed in the SFPE Handbook of Fire Protection Engineering[8].

A.4 Equation-set documentation

A.4.1 Mean maximum ceiling jet temperature rise at radius, r

A.4.1.1 The mean maximum ceiling jet temperature rise, ΔT_{max}, within the plume turning region, $\frac{r}{z_{\text{H}} - z_{\text{v}}} \leqslant 0{,}18$, is given in Equations (A.1) to (A.4) by a dimensional correlation from Reference [4]. In these expressions, the virtual origin height, z_{v}, is from Reference [26]:

$$\Delta T_{\text{max}} = \frac{16{,}9}{\alpha^{2/3}} \frac{\dot{Q}_{\text{c}}^{\ 2/3}}{\left(z_{\text{H}} - z_{\text{v}}\right)^{5/3}} \tag{A.1}$$

$$\dot{Q}_c = \alpha \dot{Q} \tag{A.2}$$

$$z_{\text{v}} = -1{,}02D + 0{,}083\dot{Q}_{\text{c}}^{\ 2/5} \tag{A.3}$$

$$\dot{Q} = \dot{m}_{\text{f}} \chi_{\text{a}} \Delta H_{\text{c}} \tag{A.4}$$

NOTE The original equations in Reference [4] are expressed in terms of heat release rate, not the convective component, and do not contain a correction for the position of the virtual plume origin.

A.4.1.2 The mean maximum ceiling jet temperature rise, ΔT_{max}, within the plume turning region, $\frac{r}{z_{\text{H}} - z_{\text{v}}} \leqslant 0{,}18$, under conditions applicable to many burning materials [$\alpha = 0{,}7$ in Equation (A.1); see A.7.2], is given in Equation (A.5):

$$\Delta T_{\text{max}} = 21{,}4 \frac{\dot{Q}_{\text{c}}^{2/3}}{\left(z_{\text{H}} - z_{\text{v}}\right)^{5/3}} \tag{A.5}$$

NOTE The factor of 21,4 in Equation (A.5), which would be 24 if $\alpha = 0{,}6$, differs from the factor of 25 in the otherwise identical equation for maximum mean temperature rise at the turning region elevation in the plume (see Reference [26]) generating the ceiling jet flow. The corresponding maximum mean plume and ceiling jet temperatures in the turning region would be expected to be the same in the absence of turning region heat loss or mixing.

A.4.1.3 The mean maximum ceiling jet temperature rise, ΔT_{max}, outside of the plume turning region, $\frac{r}{z_{\text{H}} - z_{\text{v}}} > 0{,}18$, is given in Equation (A.6) by a dimensional correlation from Reference [4]:

$$\Delta T_{\text{max}} = \frac{5{,}38}{\alpha^{2/3}} \frac{\dfrac{\dot{Q}_{\text{c}}^{2/3}}{\left(z_{\text{H}} - z_{\text{v}}\right)^{5/3}}}{\left(\dfrac{r}{z_{\text{H}} - z_{v}}\right)^{2/3}} \tag{A.6}$$

A.4.1.4 The mean maximum ceiling jet temperature rise, ΔT_{max}, outside of the plume turning region, $\frac{r}{z_{\text{H}} - z_{\text{v}}} > 0{,}18$, under conditions applicable to many burning materials [$\alpha = 0{,}7$ in Equation (A.6); see A.7.2], is given in Equation (A.7):

$$\Delta T_{\text{max}} = 6{,}82 \frac{\dfrac{\dot{Q}_{\text{c}}^{2/3}}{\left(z_{\text{H}} - z_{\text{v}}\right)^{5/3}}}{\left(\dfrac{r}{z_{\text{H}} - z_{\text{v}}}\right)^{2/3}} \tag{A.7}$$

A.4.2 Mean maximum ceiling jet velocity at radius, r

A.4.2.1 The mean maximum ceiling jet velocity, V_{max}, at the exit of the plume turning region, $\frac{r}{z_{H} - z_{\text{v}}} = 0{,}15$, is given in Equation (A.8) by a dimensional correlation from Reference [4]:

$$V_{\text{max}} = \frac{0{,}96}{\alpha^{1/3}} \left(\frac{\dot{Q}_{\text{c}}}{z_{\text{H}} - z_{\text{v}}}\right)^{1/3} \tag{A.8}$$

Within the turning region (see A.10), the velocity of the hot gases generated by a fire changes from the vertical, upward flow in the fire plume to a flow that is parallel to the ceiling in the ceiling jet. In spite of this change of direction, the speed of the flow should be nearly constant (see Reference [7]).

A.4.2.2 The mean maximum ceiling jet velocity, V_{max}, at the exit of the plume turning region, $\frac{r}{z_{\text{H}} - z_{\text{v}}} = 0{,}15$, under conditions applicable to many burning materials [$\alpha = 0{,}7$ in Equation (A.8); see A.7.2], is given in Equation (A.9):

$$V_{\text{max}} = 1{,}08 \left(\frac{\dot{Q}_{\text{c}}}{z_{\text{H}} - z_{\text{v}}} \right)^{1/3} \tag{A.9}$$

A.4.2.3 The mean maximum ceiling jet velocity, V_{max}, outside of the plume turning region, $\frac{r}{z_H - z_v} > 0{,}15$, is given in Equation (A.10) by a dimensional correlation from Reference [4]:

$$V_{\text{max}} = \frac{0{,}195}{\alpha^{1/3}} \frac{\left(\frac{\dot{Q}_{\text{c}}}{z_{\text{H}} - z_{\text{v}}} \right)^{1/3}}{\left(\frac{r}{z_{\text{H}} - z_{\text{v}}} \right)^{5/6}} \tag{A.10}$$

A.4.2.4 The mean maximum ceiling jet velocity, V_{max}, outside of the plume turning region, $\frac{r}{z_{\text{H}} - z_{\text{v}}} > 0{,}15$, under conditions applicable to many burning materials [$\alpha = 0{,}7$ in Equation (A.10); see A.7.2], is given in Equation (A.11):

$$V_{\text{max}} = 0{,}22 \frac{\left(\frac{\dot{Q}_c}{z_{\text{H}} - z_{\text{v}}} \right)^{1/3}}{\left(\frac{r}{z_{\text{H}} - z_{\text{v}}} \right)^{5/6}} \tag{A.11}$$

A.4.3 Time-mean ceiling jet temperature profile outside the plume turning region

A.4.3.1 The change in mean temperature rise, ΔT, with vertical distance, y, below the ceiling outside the plume turning region, $0{,}26 \leqslant \frac{r}{z_{\text{H}} - z_{\text{v}}} \leqslant 2{,}0$, is given by the dimensionless correlation in Equation (A.12) from Reference [19]:

$$\frac{\Delta T}{\Delta T_{\text{max}}} = 4{,}24 \left(\frac{y}{l_{\text{T}}} + 0{,}094 \right)^{0{,}755} \exp\left(-2{,}57 \frac{y}{l_{\text{T}}} \right) \tag{A.12}$$

A.4.3.2 Based on the temperature profile given by the Equation (A.12), the maximum ceiling jet temperature rise would be expected to occur at a vertical distance, y, below the ceiling given in Equation (A.13):

$$\frac{y}{l_{\text{T}}} = 0{,}20 \tag{A.13}$$

A.4.3.3 The characteristic ceiling jet depth based on gas temperature, l_{T}, is given in Equation (A.14) from Reference [19]:

$$\frac{l_{\text{T}}}{z_{\text{H}} - z_{\text{v}}} = 0{,}112 \left[1 - \exp\left(-2{,}24 \frac{r}{z_{\text{H}} - z_{\text{v}}} \right) \right] \tag{A.14}$$

A.4.4 Time-mean ceiling jet velocity profile outside the plume turning region

A.4.4.1 The change in mean ceiling jet velocity, V, with vertical distance, y, below the ceiling outside the plume turning region, $0{,}26 \leqslant \frac{r}{z_\mathrm{H} - z_\mathrm{v}} \leqslant 0{,}75$, is given by the dimensionless correlation in Equation (A.15) from Reference [19]:

$$\frac{V}{V_\mathrm{max}} = 1{,}59 \left(\frac{y}{l_\mathrm{v}} \right)^{0{,}14} \exp\left(-1{,}517 \frac{y}{l_\mathrm{v}} \right) \tag{A.15}$$

A.4.4.2 Based on the velocity profile given by Equation (A.15), the maximum ceiling jet velocity can be expected to occur at the vertical distance, y, below the ceiling given in Equation (A.16):

$$\frac{y}{l_\mathrm{v}} = 0{,}092 \tag{A.16}$$

A.4.4.3 The characteristic ceiling jet depth based on gas velocity, l_v, is given in Equation (A.17) from Reference [19]:

$$\frac{l_\mathrm{V}}{z_\mathrm{H} - z_\mathrm{v}} = 0{,}205 \left[1 - \exp\left(-1{,}75 \frac{r}{z_\mathrm{H} - z_\mathrm{v}} \right) \right] \tag{A.17}$$

A.4.5 Convective heat flux to a ceiling from the ceiling jet flow

A.4.5.1 The convective heat flux, $\dot{q}''_\mathrm{c}$, to a ceiling at a temperature rise above ambient of ΔT_c due to a ceiling jet flow having a maximum mean temperature rise of ΔT_max is given in Equation (A.18):

$$\dot{q}''_\mathrm{c} = h\left(\Delta T_\mathrm{max} - \Delta T_\mathrm{c} \right) \tag{A.18}$$

A.4.5.2 The convective heat transfer coefficient, h, within the plume turning region, $\frac{r}{z_\mathrm{H} - z_\mathrm{v}} \leqslant 0{,}2$, is given in Equations (A.19) to (A.21) from Reference [12], with $g = 9{,}806\ \mathrm{m \cdot s^{-2}}$:

$$h = 2{,}28 \alpha^{2/3} \left(\frac{\dot{Q}_\mathrm{c}}{z_\mathrm{H} - z_\mathrm{v}} \right)^{1/3} Ra^{-1/6} \tag{A.19}$$

$$Ra = \frac{g \dot{Q}_\mathrm{c} \left(z_\mathrm{H} - z_\mathrm{v} \right)^2}{3{,}5 p v^3} \tag{A.20}$$

$$v = 6{,}06 \times 10^{-10} \left(\Delta T_\mathrm{max} + T_\mathrm{a} \right)^{1{,}78} \tag{A.21}$$

A.4.5.3 The convective heat flux, $\dot{q}''_\mathrm{c}$, to a ceiling at ambient temperature within the plume turning region, $\frac{r}{z_\mathrm{H} - z_\mathrm{v}} \leqslant 0{,}2$, is given in Equation (A.22) from Reference [12]:

$$\dot{q}''_\mathrm{c} = 38{,}6 \frac{\dot{Q}_\mathrm{c}}{\left(z_\mathrm{H} - z_\mathrm{v} \right)^2 Ra^{1/6}} \tag{A.22}$$

A.4.5.4 The convective heat transfer coefficient, h, outside the plume turning region, $0{,}2 < \dfrac{r}{z_{\mathrm{H}} - z_{\mathrm{v}}} < 2{,}0$, is given in Equation (A.23) from References [3], [9] and [12]:

$$h = 0{,}892\alpha^{2/3}\left(\frac{\dot{Q}_{\mathrm{c}}}{z_{\mathrm{H}} - z_{v}}\right)^{1/3} Ra^{-1/6}\left(\frac{r}{z_{\mathrm{H}} - z_{\mathrm{v}}}\right)^{-0{,}633} \tag{A.23}$$

A.4.5.5 The convective heat flux, $\dot{q}''_{\mathrm{c}}$, to a ceiling at ambient temperature outside the turning region, $0{,}2 < \dfrac{r}{z_{\mathrm{H}} - z_{\mathrm{v}}} < 2{,}0$, is given in Equation (A.24) from References [3], [9] and [12]:

$$\dot{q}''_{\mathrm{c}} = 4{,}8\,\frac{\dot{Q}_{\mathrm{c}}}{\left(z_{\mathrm{H}} - z_{\mathrm{v}}\right)^{2} Ra^{1/6}}\left(\frac{r}{z_{\mathrm{H}} - z_{\mathrm{v}}}\right)^{-1{,}3} \tag{A.24}$$

A.5 Scientific basis for the equation set

The theory of axisymmetric ceiling jet flows traces to early work by Pickard *et al.*[1] and Thomas[2] and to models developed by Alpert[3], [4], [7] and Heskestad[5], [6]. All of this work is summarized by Alpert[8]. Based on the earlier work of Alpert[3] and their own experiments with a specific 1 m high insulated ceiling and relatively weak (0,75 kW to 2 kW) fire sources, Motevalli and Marks[19] developed the equations for ceiling jet temperature and velocity profiles in A.4.3 and A.4.4. Studies of convective heat transfer due to plume impingement on a ceiling have been conducted by Veldman *et al.*[9], You (Yu) and Faeth[12], Cooper[13] and You (Yu) [14]. The equation for convective heat flux to the ceiling in A.4.5.2 was developed by You (Yu) and Faeth[12] and confirmed by Alpert[17] and Kokkala[20]. Experimental data from the work of Veldman *et al.*[9], You (Yu) and Faeth[12] and Alpert[3] have been used to derive the heat-flux equations in A.4.5.4 and A.4.5.5. Additional information on total heat flux to a flat, unobstructed ceiling is available from Hasemi *et al.*[23].

A.6 Equation-set limitations

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

A.6.1 Fire sources

The equation set should not be applied to fire sources that are transient and/or affected by extinguishing agents; rectangular fire sources having a length to width ratio greater than or equal to two; three-dimensional fire sources having restricted air access or a mean flame height comparable to or less than 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 when the mean flame height, L, is more than 50 % of the ceiling height, z_{H}, and/or the fire source diameter, D, is more than 10 % of the minimum, unobstructed plan dimension.

A.6.3 Aerodynamic disturbances

The equation set should not be applied when ceiling jet flows generated by plumes 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.6.4 Ceiling obstructions and slope

The equation set should not be applied when ceilings containing beams or smoke curtains or other bounding surfaces induce the formation of a flow that is not axisymmetric or a hot-gas layer descending toward the fire source and/or when ceilings are combustible and/or not horizontal (see A.8 for quantitative limits).

A.6.5 Proximity to bounding surfaces

The equation set should not be applied when a fire source or its flames is within one fire source diameter, D, of a bounding surface or when a fire plume axis is within two ceiling heights, $2z_\mathrm{H}$, of a bounding surface.

A.6.6 Output parameters

The equation set should not be applied when the calculated maximum mean temperature rise within the plume turning region is much less than the maximum temperature increase with elevation in the ambient environment, due to temperature stratification before fire initiation (see A.8) or when the calculated maximum mean temperature rise within the plume turning region is greater than a characteristic flame tip temperature.

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 or as otherwise specified. This parameter is normally obtained from the design fire scenario. Additional sources of information on fire heat release rate include Tewarson[24] and Babrauskas[25].

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 could 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[24].

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.25), which determines the circle having the same area, A_s, expressed in metres squared, as the actual fire source.

$$D = \sqrt{\frac{4A_\mathrm{s}}{\pi}} \tag{A.25}$$

A.7.4 Ceiling height

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

A.7.5 Radial distance in the ceiling jet

The parameter, r, expressed in metres, is normally obtained from the design fire scenario. The valid range for this parameter is normally from the minimum value provided by the equations in A.4 to a maximum value of $2z_\mathrm{H}$.

A.7.6 Valid ranges for input parameters

The valid range for the parameter, z_H, is from a minimum value consistent with the flame height limitations in A.6 to a maximum value corresponding to a mean temperature rise in the plume turning region that meets the requirements in A.8.

A.8 Equation-set domain of applicability

A.8.1 The domain of applicability of the equation set in this appendix can be determined from the scientific literature references given in A.5.

A.8.2 To maintain this domain of applicability, the following conditions should apply:

A.8.2.1 Hot gas layer formation is restricted to a depth below the ceiling of $z_H/4$, which requires that the maximum time interval, ΔT_{max}, expressed in seconds, after initiation of a quasi-steady fire is restricted, approximately, to the value given in Equation (A.26) from Reference [26].

$$\Delta T_{max} = 25\left[\left(\frac{z_H}{4} - z_v\right)^{-2/3} - \left(z_H - z_v\right)^{-2/3}\right]\frac{A_c}{\dot{Q}_c^{1/3}} \tag{A.26}$$

A.8.2.2 The slope of the ceiling surface is restricted to an angle, θ, expressed in radians, from the horizontal. As a result of this restriction, the ratio $\frac{V_{max,\theta}}{V_{max,\theta=0}}$ of the maximum ceiling jet velocity at a radial distance of about one ceiling height, z_H, in the steepest upward direction from the plume impingement point to the corresponding velocity when there is no ceiling slope (i.e., $\theta = 0$) is given, approximately, by Equation (A.27) from Reference [8].

$$\frac{V_{max,\theta}}{V_{max,\theta=0}} = \exp\left(3\sin\theta\right) \tag{A.27}$$

For example, to maintain this velocity ratio to a value less than or equal to 1,05 (i.e., a maximum 5 % velocity increase due to a sloped ceiling) requires that the ceiling slope angle be less than or equal to 0,016 rad, or about one degree.

A.8.2.3 Temperature stratification in the ambient environment, as measured by the difference between ambient near-ceiling temperature and ambient temperature near the fire source, $\left(T_a\right)_{z_H} - \left(T_a\right)_{z=0}$, is restricted (see Reference [26]) to a value less than $7\Delta T_0$.

A.9 Example calculations

A.9.1 Mean maximum ceiling jet temperature rise

Consider a 1,8 m diameter pan of a flammable liquid burning with a heat release rate of 2 500 kW m^{-2} beneath a ceiling that is 12 m above the liquid surface. Conditions are such that the convective fraction of the heat release rate is 0,7. The ceiling jet temperature rise, ΔT_{max}, expressed in Kelvin, within the plume turning region is obtained from Equation (A.5) as follows:

$$\Delta T_{\text{max}} = 21{,}4 \times \frac{\left(0{,}7 \times 2\,500 \times \pi \times 1{,}8^2/4\right)^{2/3}}{\left[12 + 1{,}02 \times 1{,}8 - 0{,}083 \times \left(2\,500 \times \pi \times 1{,}8^2/4\right)^{2/5}\right]^{5/3}} = 105$$

The ceiling jet temperature rise, ΔT_{max}, expressed in Kelvin, outside of the plume turning region, a radial distance of 5 m from the plume centreline, is obtained from Equation (A.7) as follows:

$$\Delta T_{\text{max}} = 6{,}82 \times \frac{\dfrac{\left(0{,}7 \times 2\,500 \times \pi \times 1{,}8^2/4\right)^{2/3}}{\left[12 + 1{,}02 \times 1{,}8 - 0{,}083 \times \left(2\,500 \times \pi \times 1{,}8^2/4\right)^{2/5}\right]^{5/3}}}{\left(\dfrac{5}{12 + 1{,}02 \times 1{,}8 - 0{,}083 \times \left(2\,500 \times \pi \times 1{,}8^2/4\right)^{2/5}}\right)^{2/3}} = 57$$

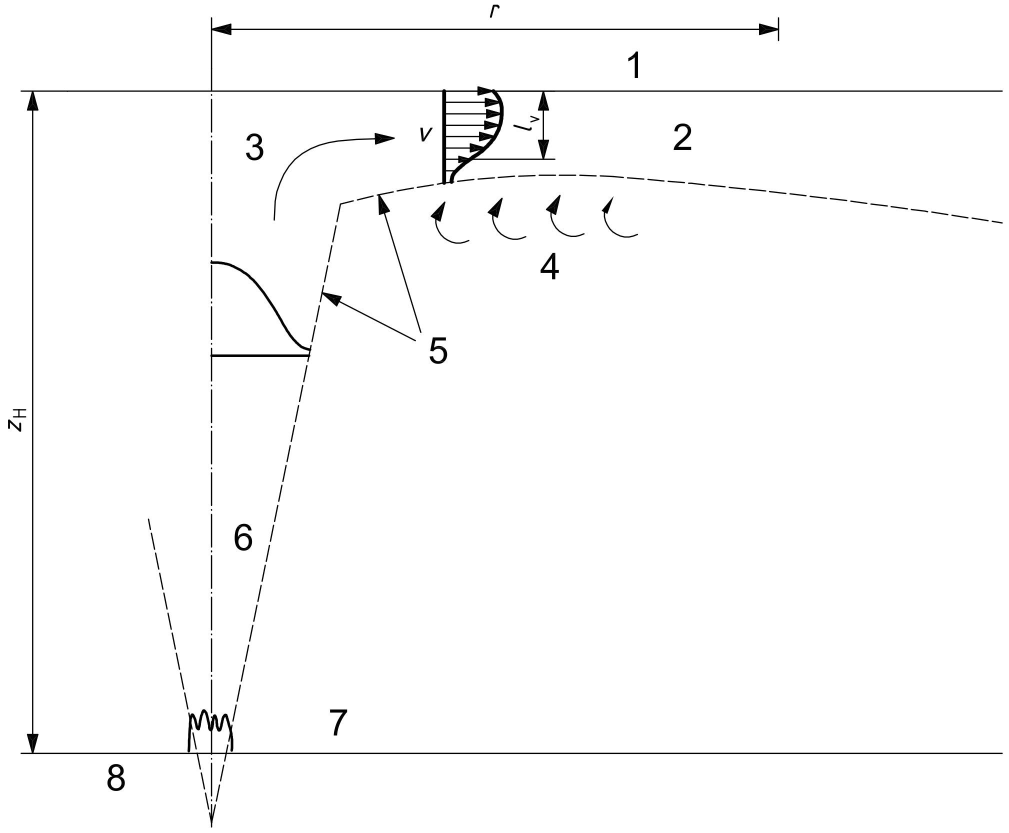
A.9.2 Characteristic ceiling jet depth based on gas temperature

Consider the pan fire configuration from A.9.1. The characteristic ceiling jet depth based on gas temperature, l_{T}, expressed in metres, at a radial distance from the plume centreline of 5 m, is obtained from Equation (A.14) as follows:

$$l_{\text{T}} = \left[12 + 1{,}02 \times 1{,}8 - 0{,}083 \times \left(2\,500 \times \pi \times 1{,}8^2/4\right)^{2/5}\right] \times 0{,}112 \times \left[1 - \exp\left(-2{,}24 \times \frac{5}{12 - 0{,}921}\right)\right] = 0{,}79$$

where $z_{\text{v}} = 0{,}921$ m is the height of the virtual plume origin above the base of the fire source, i.e., the liquid surface.

A.10 Descriptive figure



Key

1 ceiling
2 ceiling jet
3 turning region
4 small air entrainment
5 characteristic radius and depth of plume and ceiling jet respectively
6 fire plume
7 base of fire
8 fire source

Figure A.1 — Illustration of parameters describing the ceiling jet flow

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