
**Fire safety engineering —
Requirements governing algebraic
formulae —**

**Part 3:
Ceiling jet flows**

*Ingénierie de la sécurité incendie — Exigences régissant les formules
algébriques —*

Partie 3: Écoulements en jet sous plafond



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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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

This first edition cancels and replaces ISO 16736:2006, which has been technically revised.

The main changes are as follows:

- the main body has been simplified by making reference to ISO 24678-1;
- a formula for time-mean temperature rise of a ceiling jet in a smoke layer, [Formula \(A.8\)](#), has been added in [Annex A](#);
- comparisons with experimental data have been added in [Annex A](#).

A list of all parts in the ISO 24678 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The ISO 24678 series is intended to be used by fire safety practitioners involved with fire safety engineering calculation methods. It is expected that the users of this document 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 may be used.

Algebraic formulae conforming to the requirements of this document are used with other engineering calculation methods during a fire safety design. Such a 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 trial 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 needs to be modified.

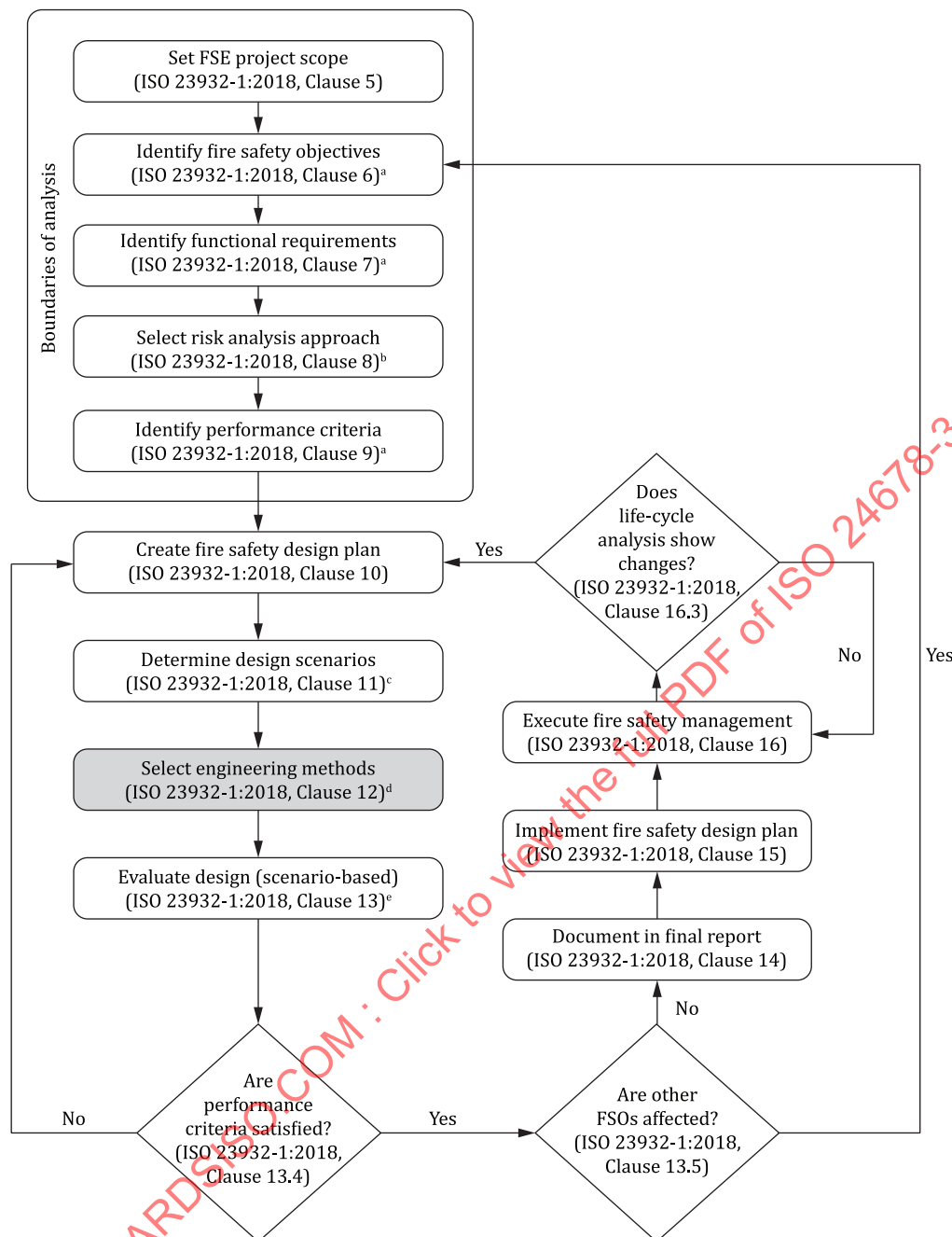
The subjects of engineering calculations include the fire-safe design of entirely new built environments, such as buildings, ships or vehicles, as well as the assessment of the fire safety of existing built environments.

The algebraic formulae discussed in this document can be useful for estimating the consequences of design fire scenarios. Such formulae are valuable for allowing the practitioner to quickly determine how a proposed fire safety design needs to be modified to meet performance criteria and to compare among multiple trial designs. Detailed numerical calculations can be carried out up until the final design documentation. Examples of areas where algebraic formulae have been applicable include determination of convective and radiative heat transfer 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. However, the simple models often have stringent limitations and are less likely to include the effects of multiple phenomena occurring in the design scenarios.

The general principles of fire safety engineering are described in ISO 23932-1, which provides a performance-based methodology for engineers to assess the level of fire safety for new or existing built environments. Fire safety is evaluated through an engineered approach based on the quantification of the behaviour of fire and based on knowledge of the consequences of such behaviour on life safety, property and the environment. ISO 23932-1 provides the process (i.e. necessary steps) and essential elements for conducting a robust performance-based fire safety design.

ISO 23932-1 is supported by a set of fire safety engineering documents on the methods and data needed for all the steps in a fire safety engineering design as summarized in [Figure 1](#) (taken from ISO 23932-1:2018, Clause 4). This set of documents is referred to as the Global fire safety engineering analysis and information system. This global approach and system of standards provides an awareness of the interrelationships between fire evaluations when using the set of fire safety engineering documents. The set of documents includes ISO/TS 13447, ISO 16730-1, ISO 16732-1, ISO 16733-1, ISO/TS 16733-2, ISO 16734, ISO 16735, ISO 16737, ISO/TR 16738, ISO 24678-1, ISO 24679-1, ISO/TS 29761 and other supporting Technical Reports that provide examples of and guidance on the application of these documents.

Each document supporting the global fire safety engineering analysis and information system includes language in the introduction to tie that document to the steps in the fire safety engineering design process outlined in ISO 23932-1. ISO 23932-1 requires that engineering methods be selected properly to predict the fire consequences of specific scenarios and scenario elements (ISO 23932-1:2018, Clause 12). Pursuant to the requirements of ISO 23932-1, this document provides the requirements governing algebraic formulae for fire safety engineering. This step in the fire safety engineering process is shown as a highlighted box in [Figure 1](#) and described in ISO 23932-1.



^a See also ISO/TR 16576 (Examples).

^b See also ISO 16732-1, ISO 16733-1, ISO/TS 16733-2, ISO/TS 29761.

^c See also ISO 16732-1, ISO 16733-1, ISO/TS 16733-2, ISO/TS 29761.

^d See also ISO/TS 13447, ISO 16730-1, ISO/TR 16730-2 to ISO/TR 16730-5 (Examples), ISO 16735, ISO 16736, ISO 16737, ISO/TR 16738, ISO 24678-1, ISO 24678-2, ISO 24678-6 and ISO 24678-7.

^e See also ISO/TR 16738, ISO 16733-1, ISO/TS 16733-2.

NOTE Documents linked to large parts of the fire safety engineering process: ISO 16732-1, ISO 16733-1, ISO 24679-1, ISO/TS 29761, ISO/TR 16732-2 to ISO/TR 16732-3 (Examples), ISO/TR 24679-2 to ISO/TR 24679-4 and ISO/TR 24679-6 (Examples).

**Figure 1 — Flow chart illustrating the fire safety engineering design process
(from ISO 23932-1:2018)**

Fire safety engineering — Requirements governing algebraic formulae —

Part 3: Ceiling jet flows

1 Scope

This document specifies the requirements governing the application of a set of explicit algebraic formulae for the calculation of specific characteristics of ceiling jet flows.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 13943, *Fire safety — Vocabulary*

ISO 24678-1, *Fire safety engineering — Requirements governing algebraic formulae — Part 1: General requirements*

3 Terms and definitions

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1

axisymmetric

in a state in which mean motion and properties, such as mean temperature rise, are symmetric with respect to a vertical centreline

3.2

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

3.3

characteristic depth of ceiling jet temperature profile

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

3.4

characteristic depth of ceiling jet velocity profile

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

3.5

convective fraction of heat release rate

ratio of the convective heat release rate to the net heat release rate

3.6

convective heat release rate

component of the heat release rate carried upward by the fire plume motion

Note 1 to entry: Above the mean flame height, this component is considered invariant with height.

3.7

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 equal to 0,15 to 0,2

3.8

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

3.9

fuel mass burning rate

mass generation rate of fuel vapours

3.10

jet flame

flame that is dominated by momentum, rather than buoyancy forces

3.11

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 %

3.12

mean gas velocity

time-average gas velocity in the ceiling jet flow at a given radial distance

3.13

mean temperature rise

time-average gas temperature rise above the ambient temperature value in the ceiling jet flow, at a given radial distance

3.14

quasi-steady state

state in which it is assumed that the full effects of heat release rate changes at the fire source are felt everywhere in the flow field immediately

3.15

radiant energy release factor

ratio of the combustion heat released in a fire as thermal radiation to the net heat of combustion

3.16

virtual origin

point source from which the fire plume above the flames appears to originate

Note 1 to entry: 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.

4 Requirements governing the description of physical phenomena

4.1 The requirements governing the description of physical phenomena apply as specified in ISO 24678-1 in addition to the following.

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 hot smoke layer under ceiling and 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 fire plume turning region, degree of fire-source influence, etc.) to which specific formulae apply shall be clearly identified.

5 Requirements governing the calculation process

The requirements specified in ISO 24678-1 governing the calculation process apply.

6 Requirements governing limitations

The requirements specified in ISO 24678-1 governing limitations apply.

7 Requirements governing input parameters

The requirements specified in ISO 24678-1 governing input parameters apply.

8 Requirements governing the domain of applicability

The requirements specified in ISO 24678-1 governing the domain of applicability apply.

9 Example of documentation

A set of algebraic formulae meeting the requirements of this document is provided in [Annex A](#).

Annex A (informative)

Formulae for quasi-steady state, axisymmetric ceiling jet flows from a circular or near-circular fire source under unobstructed ceiling

A.1 Scope

This annex provides a formula set for axisymmetric ceiling jet flows. Properties such as ceiling jet velocity and temperature are calculated. The fire source may be circular or near circular shaped.

A.2 Symbols used in [Annex A](#)

A_s	fire source plan area (m ²)
D	fire source diameter (m)
e	base of natural logarithms
g	acceleration due to gravity (m/s ²)
h	convective heat transfer coefficient [kW/(m ² ·K)]
L	mean flame height above base of fire source (m)
l_T	characteristic depth of ceiling jet temperature profile (m)
l_V	characteristic depth of ceiling jet velocity profile (m)
$\dot{m}_f$	fuel mass burning rate (kg/s)
p	absolute air pressure (101,3 kPa)
$\dot{q}_c''$	convective heat flux (kW/m ²)
$\dot{Q}$	heat release rate actually measured or specified (kW)
$\dot{Q}_c$	convective heat release rate (kW)
Ra	plume Rayleigh number (-)
r	radial distance from plume centreline (m)
T_a	ambient temperature (K)
V	time-mean gas velocity (m/s ¹)
$V_{\max}$	time-mean maximum gas velocity (m/s ¹)
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)
α	convective fraction of heat release rate, $1-\chi_R/\chi_a$ (-)
ΔH_c	net heat of combustion (kJ/kg)
ΔT	time-mean temperature rise above the ambient value (K)
ΔT_c	ceiling temperature rise above the ambient value at a given radial position (K)
$\Delta T_{\max}$	time-mean maximum temperature rise above the ambient value (K)
ν	kinematic viscosity of air (m ² /s)
θ	maximum slope angle of the ceiling surface (rad)
χ_a	combustion efficiency factor (-)
χ_R	radiant energy release factor (-)

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

A.3.1 General descriptions of the calculation method

A.3.1.1 Calculation procedure

Estimating the ceiling jet properties involves the following steps:

- determination of characteristics of the fire source (burning surface, heat release rate, etc.);
- determination of flame height;
- calculation of axial temperature and velocity along a ceiling jet flow.

A.3.1.2 Ceiling jet flow characteristics to be calculated

The formula set provides 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.3.1.3 Ceiling jet flow regions to which formulae 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 formulae applicable within and outside of this region.

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

The set of formulae is applicable to the impingement on flat, unobstructed ceilings of fire plumes from quasi-steady state fire sources that are approximately circular or square in plan area. The fire source is a horizontal, upward-facing burning surface or a three-dimensional burning array for which the mean flame height, L , 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 Self-consistency of the formula set

The set of formulae provided in this annex have been derived and reviewed by R. L. Alpert^[28] (see [Clause A.5](#)) to ensure that calculation results from different formulae in the set are consistent (i.e. do not produce conflicts).

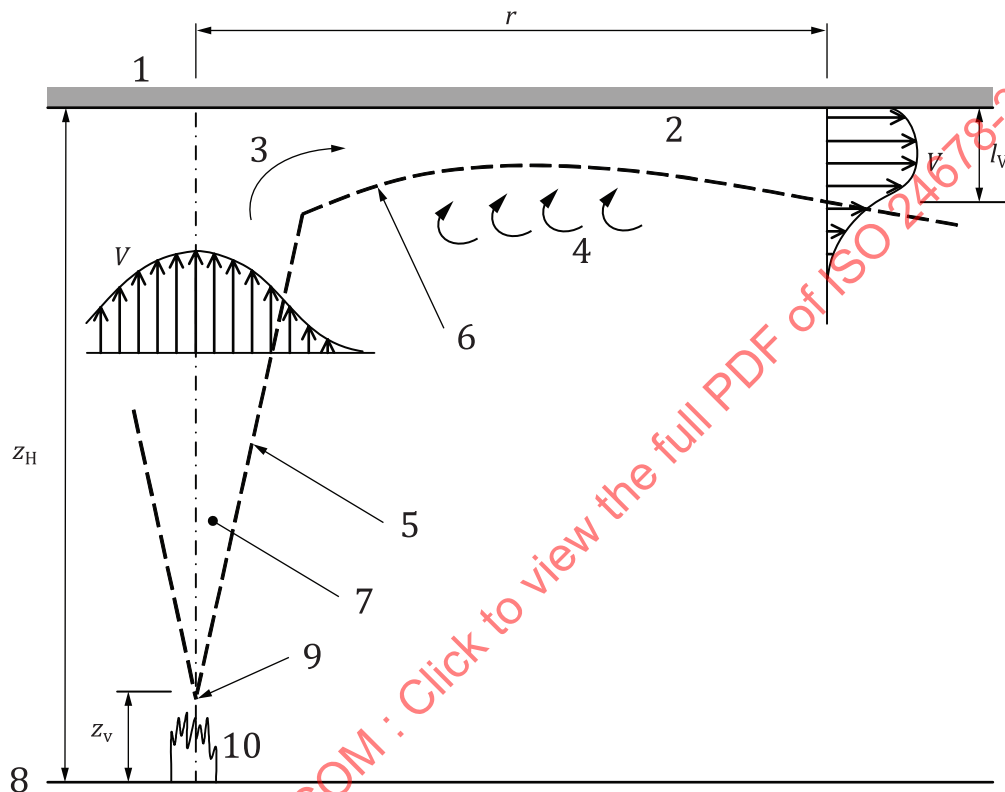
A.3.4 International Standards and other documents where the formula set is used

The formula set is discussed in the SFPE Handbook of Fire Protection Engineering.^[28]

A.4 Formula-set documentation of calculation procedure

A.4.1 General descriptions of ceiling jet flows

Properties of ceiling jet flows as shown in Figure A.1. are calculated. Temperature rise and characteristic velocity are calculated along the ceiling jet in the plume turning region as well as in the ceiling jet region.



Key

- | | |
|----------------------------------|---------------------------------------|
| 1 ceiling | 6 characteristic depth of ceiling jet |
| 2 ceiling jet region | 7 fire plume |
| 3 plume turning region | 8 base of fire |
| 4 small air entrainment | 9 virtual origin |
| 5 characteristic radius of plume | 10 fire source |

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

A.4.2 Time-mean maximum ceiling jet temperature rise

A.4.2.1 Formulae within plume turning region

The time-mean maximum ceiling jet temperature rise, $\Delta T_{\max}$, within the plume turning region, $r < 0,18(z_H - z_v)$, is given in Formulae (A.1) to (A.4) by a dimensional correlation:^[29]

$$\Delta T_{\max} = \frac{16,9}{\alpha^{2/3}} \frac{\dot{Q}_c^{2/3}}{(z_H - z_v)^{5/3}} \quad (\text{A.1})$$

$$\dot{Q}_c = \alpha \dot{Q} \quad (\text{A.2})$$

$$\dot{Q} = \dot{m}_f \chi_a \Delta H_c \quad (\text{A.3})$$

In these expressions, the virtual origin height above the base of fire source is calculated using [Formula \(A.4\)](#):^[30]

$$z_v = -1,02D + 0,083\dot{Q}^{2/5} \quad (\text{A.4})$$

NOTE 1 The original formulae in Reference [29] 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.

Under conditions applicable to many burning materials [$\alpha = 0,7$ in [Formula \(A.1\)](#); see [A.7.2](#)], [Formula \(A.1\)](#) is reduced to [Formula \(A.5\)](#):

$$\Delta T_{\max} = 21,4 \frac{\dot{Q}_c^{2/3}}{(z_H - z_v)^{5/3}} \quad (\text{A.5})$$

NOTE 2 The factor of 21,4 in [Formula \(A.5\)](#), which would be 24 if $\alpha = 0,6$, differs from the factor of 25 in the otherwise identical formula for time-mean maximum temperature rise at the turning region elevation in the plume (see Reference [30]) generating the ceiling jet flow. The corresponding time-mean maximum plume and ceiling jet temperatures in the plume turning region would be expected to be the same in the absence of plume turning region heat loss or mixing.

A.4.2.2 Formulae outside the plume turning region

The time-mean maximum ceiling jet temperature rise, $\Delta T_{\max}$, outside of the plume turning region, $r > 0,18(z_H - z_v)$, is given in [Formula \(A.6\)](#) by a dimensional correlation:^[29]

$$\Delta T_{\max} = \frac{5,38}{\alpha^{2/3}} \frac{\dot{Q}_c^{2/3} (z_H - z_v)^{5/3}}{\left(\frac{r}{z_H - z_v}\right)^{2/3}} \quad (\text{A.6})$$

Under conditions applicable to many burning materials [$\alpha = 0,7$ in [Formula \(A.6\)](#); see [A.7.2](#)], [Formula \(A.6\)](#) is reduced to [Formula \(A.7\)](#):

$$\Delta T_{\max} = 6,82 \frac{\dot{Q}_c^{2/3} r}{z_H - z_v} \quad (\text{A.7})$$

NOTE If a hot smoke layer is developed under ceiling, the ceiling jet is included in the hot smoke layer. In that case, temperature rise can be calculated by [Formula \(A.8\)](#):^[31]

$$\Delta T_{\max, \text{layer}} = \left\{1 - \left(\frac{z_L}{z_H}\right)^{5/3}\right\} (T_s - T_a) + \Delta T_{\max} \quad (\text{A.8})$$

where $\Delta T_{\max}$ is calculated by [Formula \(A.7\)](#).

A.4.3 Time-mean maximum ceiling jet velocity

A.4.3.1 Formulae within plume turning region

The time-mean maximum ceiling jet velocity, $V_{\max}$, at the exit of the plume turning region, $r = 0,15(z_H - z_v)$, is given in [Formula \(A.9\)](#) by a dimensional correlation from Reference [29]:

$$V_{\max} = \frac{0,96}{\alpha^{1/3}} \left(\frac{\dot{Q}_c}{z_H - z_v} \right)^{1/3} \quad (\text{A.9})$$

Within the plume turning region (see [Figure A.1](#)), 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 is nearly constant.^[32]

Under conditions applicable to many burning materials [$\alpha = 0,7$ in [Formula \(A.9\)](#); see [A.7.2](#)], [Formula \(A.9\)](#) is reduced to [Formula \(A.10\)](#):

$$V_{\max} = 1,08 \left(\frac{\dot{Q}_c}{z_H - z_v} \right)^{1/3} \quad (\text{A.10})$$

A.4.3.2 Formulae outside the plume turning region

The time-mean maximum ceiling jet velocity, $V_{\max}$, outside of the plume turning region, $r > 0,15(z_H - z_v)$, is given in [Formula \(A.11\)](#) by a dimensional correlation:^[29]

$$V_{\max} = \frac{0,195}{\alpha^{1/3}} \frac{\left(\frac{\dot{Q}_c}{z_H - z_v} \right)^{1/3}}{\left(\frac{r}{z_H - z_v} \right)^{5/6}} \quad (\text{A.11})$$

Under conditions applicable to many burning materials [$\alpha = 0,7$ in [Formula \(A.11\)](#); see [A.7.2](#)], [Formula \(A.11\)](#) is reduced to [Formula \(A.12\)](#):

$$V_{\max} = 0,22 \left(\frac{\dot{Q}_c}{r^{5/2}} \right)^{1/3} (z_H - z_v)^{1/2} \quad (\text{A.12})$$

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

The change in time-mean temperature rise, ΔT , with vertical distance, y , below the ceiling outside the plume turning region, $0,26(z_H - z_v) \geq r \geq 2,0(z_H - z_v)$, is given by the dimensionless correlation in [Formula \(A.13\)](#):^[33]

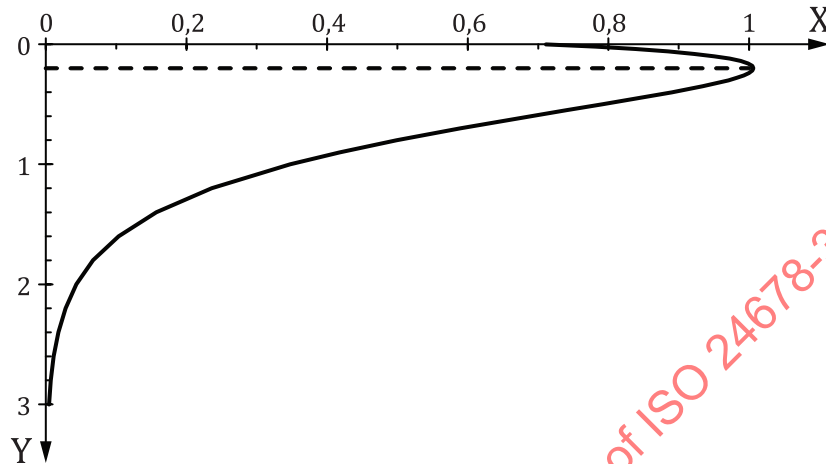
$$\frac{\Delta T}{\Delta T_{\max}} = 4,24 \left(\frac{y}{l_T} + 0,094 \right)^{0,755} \exp \left(-2,57 \frac{y}{l_T} \right) \quad (\text{A.13})$$

where the characteristic depth of ceiling jet temperature profile, l_T , is given in [Formula \(A.14\)](#):^[33]

$$\frac{l_T}{z_H - z_v} = 0,112 \left[1 - \exp \left(-2,24 \frac{r}{z_H - z_v} \right) \right] \quad (\text{A.14})$$

The vertical temperature profile is calculated by [Formula \(A.13\)](#) and shown in [Figure A.2](#). Based on the temperature profile, the maximum ceiling jet temperature rise would be expected to occur at a vertical distance, y , below the ceiling value given in [Formula \(A.15\)](#):

$$\frac{y}{l_T} = 0,20 \quad (\text{A.15})$$



Key

X non-dimensional temperature rise, $\Delta T/\Delta T_{\max}$

Y non-dimensional vertical distance below ceiling, y/l_T

— temperature profile

- - - maximum value

Figure A.2 — Vertical profile of ceiling jet temperature outside the plume turning region

A.4.5 Time-mean ceiling jet velocity profile outside the plume turning region

The change in time-mean ceiling jet velocity, V , with vertical distance, y , below the ceiling outside the plume turning region, $0,26(z_H - z_v) \leq r \leq 0,75(z_H - z_v)$, is given by the dimensionless correlation in [Formula \(A.16\)](#):^[33]

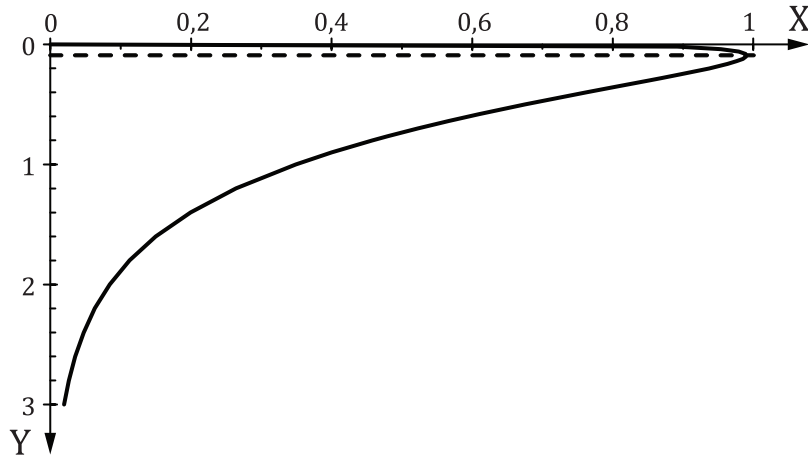
$$\frac{V}{V_{\max}} = 1,59 \left(\frac{y}{l_v} \right)^{0,14} \exp(-1,517 \frac{y}{l_v}) \quad (\text{A.16})$$

where the characteristic depth of ceiling jet velocity profile, l_v , is given in [Formula \(A.17\)](#):^[33]

$$\frac{l_v}{z_H - z_v} = 0,205 \left[1 - \exp(-1,75 \frac{r}{z_H - z_v}) \right] \quad (\text{A.17})$$

The vertical profile of ceiling jet velocity is calculated by [Formula \(A.16\)](#) and shown in [Figure A.3](#). Based on the velocity profile, the maximum ceiling jet velocity can be expected to occur at the vertical distance, y , below the ceiling given in [Formula \(A.18\)](#):

$$\frac{y}{l_v} = 0,092 \quad (\text{A.18})$$



Key

- X non-dimensional horizontal velocity, $V/V_{\max}$
Y non-dimensional vertical distance below ceiling, y/l_v
— velocity profile
- - - maximum value

Figure A.3 — Vertical profile of ceiling jet velocity in the ceiling jet region

A.4.6 Convective heat flux to a ceiling from the ceiling jet flow

A.4.6.1 General

The convective heat flux, $\dot{q}_c''$, to a ceiling at a temperature rise above ambient of ΔT_c due to a ceiling jet flow having a time-mean maximum temperature rise of $\Delta T_{\max}$ is given in [Formula \(A.19\)](#):

$$\dot{q}_c'' = h(\Delta T_{\max} - \Delta T_c) \quad (\text{A.19})$$

A.4.6.2 Formulae within plume turning region

The convective heat transfer coefficient, h , within the plume turning region, $r \leq 0,2(z_H - z_v)$ is given in [Formulae \(A.20\)](#) to [\(A.22\)](#)^[34] with $g = 9,806 \text{ m/s}^2$:

$$h = 2,28 \alpha^{2/3} \left(\frac{\dot{Q}_c}{z_H - z_v} \right)^{1/3} Ra^{-1/6} \quad (\text{A.20})$$

$$Ra = \frac{g \dot{Q}_c (z_H - z_v)^2}{3,5 \rho \nu^3} \quad (\text{A.21})$$

$$\nu = 6,06 \times 10^{-10} (\Delta T_{\max} + T_a)^{1,78} \quad (\text{A.22})$$

The convective heat flux, $\dot{q}_c''$, to a ceiling at ambient temperature within the plume turning region, $r \leq 0,2(z_H - z_v)$, is given in [Formula \(A.23\)](#)^[34]

$$\dot{q}_c'' = 38,6 \frac{\dot{Q}_c}{(z_H - z_v)^2 Ra^{1/6}} \quad (\text{A.23})$$

A.4.6.3 Formulae outside the plume turning region

The convective heat transfer coefficient, h , outside the plume turning region, $0,2(z_H - z_v) < r < 2,0(z_H - z_v)$, is given in [Formula \(A.24\)](#) from References [34]-[36]:

$$h = 0,892 \alpha^{2/3} \left(\frac{\dot{Q}_c}{z_H - z_v} \right)^{1/3} Ra^{-1/6} \left(\frac{r}{z_H - z_v} \right)^{-0,633} \quad (\text{A.24})$$

The convective heat flux, $\dot{q}_c''$, to a ceiling at ambient temperature outside the plume turning region, $0,2(z_H - z_v) < r < 2,0(z_H - z_v)$, is given in [Formula \(A.25\)](#) from References [34]-[36]:

$$\dot{q}_c'' = 4,8 \frac{\dot{Q}_c}{(z_H - z_v)^2} Ra^{1/6} \left(\frac{r}{z_H - z_v} \right)^{-1,3} \quad (\text{A.25})$$

A.5 Scientific basis for the formula set

The theory of axisymmetric ceiling jet flows traces to early work by Pickard *et al.* [37] and Thomas [38] and to models developed by Alpert [29], [32], [35] and Heskestad [39], [40]. All of those works are summarized by Alpert [28]. Based on the earlier work of Alpert [35] 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 [33] developed the formulae for ceiling jet temperature and velocity profiles shown in [A.4.4](#) and [A.4.5](#). Studies of convective heat transfer due to plume impingement on a ceiling have been conducted by You (Yu) and Faeth [34], Veldman *et al.* [36], Cooper [41] and You (Yu) [42]. The formula for convective heat flux to the ceiling as shown in [A.4.6](#) was developed by You (Yu) and Faeth [34] and confirmed by Alpert [43] and Kokkala [44]. Experimental data from the work of You (Yu) and Faeth [34], Alpert [35] and Veldman *et al.* [36] have been used to derive the heat-flux formulae in [A.4.6](#). Additional information on total heat flux to a flat, unobstructed ceiling is available from Hasemi *et al.* [45].

A.6 Formula-set limitations

A.6.1 Fire sources

The formula 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 pressurized 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 formula 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.

NOTE The mean flame height can be calculated by the method described in ISO 16734.

A.6.3 Aerodynamic disturbances

The formula 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 formula set should not be applied when ceilings contain beams or smoke curtains or other bounding surfaces that 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.8.2](#) for quantitative limits).

A.6.5 Proximity to bounding surfaces

The formula 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, $2z_H$, of a bounding surface.

A.6.6 Output parameters

The formula set should not be applied when the calculated time-mean maximum 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.8.3](#)) or when the calculated time-mean maximum temperature rise within the plume turning region is greater than a characteristic flame tip temperature.

A.7 Formula-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 Khan *et al.* ^[46] and Babrauskas. ^[47] Information on reaction-to-fire testing methods available to develop input data for fire source properties is found in ISO 24678-2, Annex B.

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 potentially 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 Khan *et al.* ^[46]

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 [Formula \(A.26\)](#), which determines the circle having the same area, A_s , expressed in m^2 , as the actual fire source.

$$D = \sqrt{\frac{4A_s}{\pi}} \quad (\text{A.26})$$

Additional information is found in ISO 24678-2, Annex B.

A.7.4 Ceiling height

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

A.7.5 Radial distance in the ceiling jet

The parameter, r , expressed in m, is normally obtained from the design fire scenario. The valid range for this parameter is normally from the minimum value provided by the Formulae in [Clause A.4](#) to a maximum value of $2z_H$.

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 [Clause A.6](#) to a maximum value corresponding to a mean temperature rise in the plume turning region that meets the requirements in [A.8.3](#).

A.8 Domain of applicability of the formula set

A.8.1 General

The domain of applicability of the formula set laid out in this annex can be determined from the scientific literature references given in [Clause A.5](#).

A.8.2 Slope of the ceiling surface

Hot gas layer formation is restricted to a depth below the ceiling of $z_H/4$. 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 $V_{\max,\theta} / V_{\max,\theta=0}$ 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 [Formula \(A.27\)](#).^[28]

$$\frac{V_{\max,\theta}}{V_{\max,\theta=0}} = \exp(3\sin\theta) \quad (\text{A.27})$$

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.8.3 Temperature stratification

Temperature stratification in the ambient environment, as measured by the difference between ambient near-ceiling temperature and ambient temperature near the fire source, $(T_a)_{z_H} - (T_a)_{z=0}$, is restricted to a value less than $7\Delta T_{\max}$.^[30]

A.8.4 Comparison with experiments

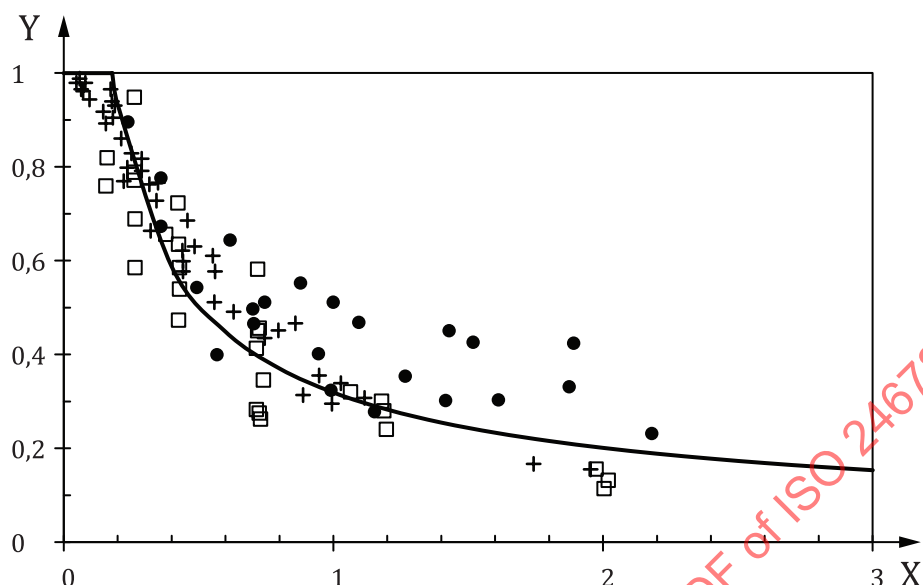
A.8.4.1 Time-mean ceiling jet temperature rise

The time-mean maximum ceiling jet temperature rise is compared with experimental data. The temperature rise at radial distance r is normalized by that in the plume turning region. Dividing [Formula \(A.7\)](#) by [Formula \(A.5\)](#), the relationship described in [Formula \(A.28\)](#) holds:

$$\frac{\Delta T_{\max}(r)}{\Delta T_{\max}(0)} = 0,319 \left(\frac{r}{z_H - z_v} \right)^{-2/3} \approx 0,319 \left(\frac{r}{z_H} \right)^{-2/3} \quad (\text{A.28})$$

[Formula \(A.28\)](#) is plotted in [Figure A.4](#) in comparison with the data by Alpert^[32] ($D = 0,305 - 3,66$ m, $z_H = 2,44 - 15,9$ m, $\dot{Q} = 26 - 13\,500$ kW of Ethanol and wood burner), by Heskestad^[49] ($D = 0,181 - 0,432$ m,

$z_h = 0,39 - 1,56$ m, $\dot{Q} = 17 - 90$ kW of Methanol pool) and by Heskestad and Hamada^[26] ($D = 0,15 - 0,61$ m, $z_H = 0,91 - 2,48$ m, $\dot{Q} = 11,6 - 764$ kW of propane gas burner). The formula corresponds with lower part of data.



Key

- X non-dimensional radial distance from plume axis, r/z_H (-)
- Y non-dimensional temperature rise, $\Delta T_{\max}(r)/\Delta T_{\max}(0)$ (-)
- Formula (A.28)
- Heskestad and Hamada^[26]
- + Heskestad^[49]
- Alpert^[32]

Figure A.4 — Comparison of Formula (A.28) with experimental data

A.8.4.2 Time-mean temperature rise of a ceiling jet within a smoke layer

In a confined space, a smoke layer develops below the ceiling. The ceiling jet is contained in a smoke layer. In such cases, Formula (A.8) applies instead of Formulae (A.5) and (A.7). An experiment was carried out in a room of $12 \text{ m} \times 15 \text{ m} \times 2,25 \text{ m}$ (height).^[27] A 50 kW propane gas fire source was placed on the floor at the centre of the room. Ceiling jet temperatures were measured at 30 mm and 100 mm below the ceiling at radial distances of 0,9m to 5,4 m. The vertical temperature profile was measured to determine smoke layer height and average smoke layer temperature.

The results are shown in Figure A.5. The smoke layer interface was located 1,69 m above the floor. The smoke layer temperature was 288,0 K (14,8 °C). The measured ceiling jet temperature was close to Formula (A.8). Formulae (A.5) and (A.7) predict lower temperatures.

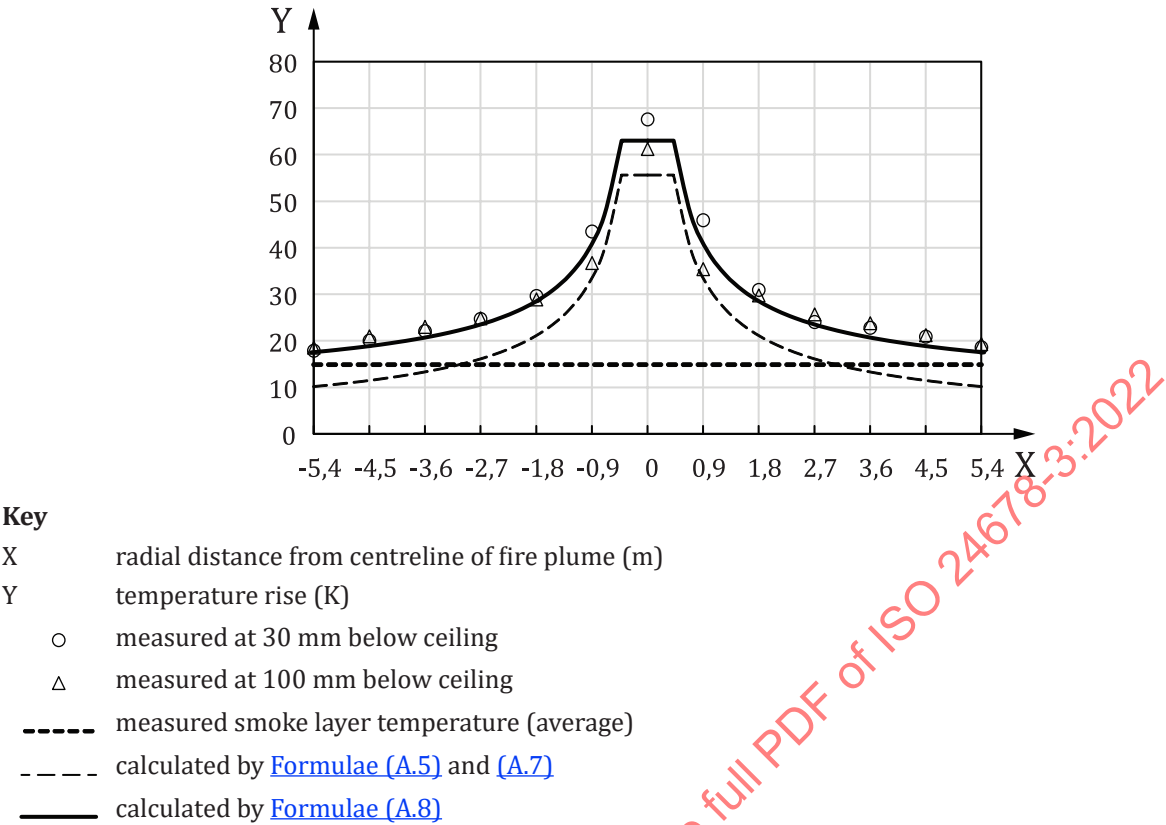


Figure A.5 — Comparison of [Formula \(A.8\)](#) with experimental data

A.9 Calculation example

A.9.1 Calculation condition

Consider a 1,8 m diameter pan of a flammable liquid burning with a heat release rate of 2 500 kW beneath a ceiling that is 12 m above the liquid surface. The convective fraction of the heat release rate is 0,7. The height of virtual origin above fuel base is calculated by [Formula \(A.29\)](#) [based on [Formula \(A.4\)](#)] as:

$$z_v = -1,02 D + 0,083 \dot{Q}^{2/5} = -1,02 \times 1,8 + 0,083 \times 2\,500^{2/5} = 0,0618 \quad (\text{A.29})$$

where z_v is expressed in m.

A.9.2 Time-mean maximum ceiling jet temperature rise

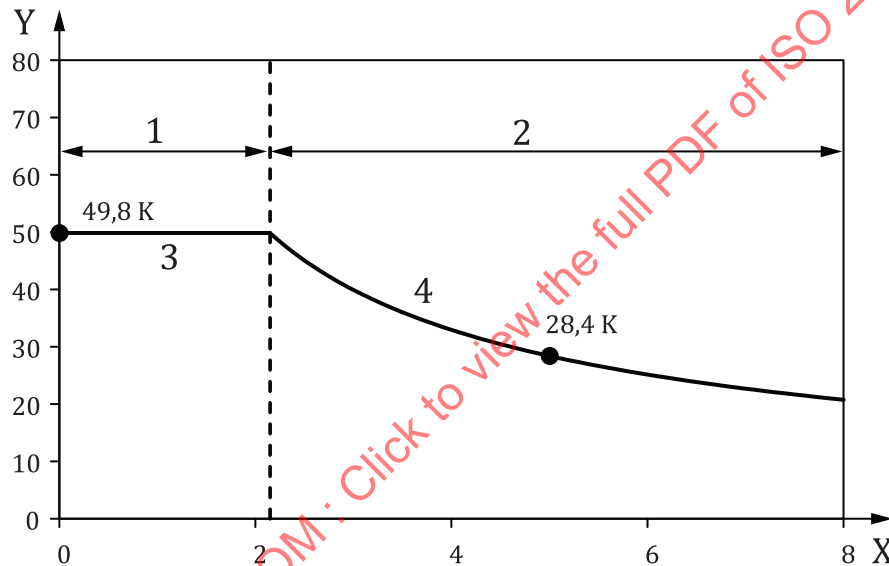
The time-mean maximum ceiling jet temperature rise, $\Delta T_{\max}$, within the plume turning region is obtained by [Formula \(A.30\)](#) [based on [Formula \(A.5\)](#)] as follows:

$$\Delta T_{\max} = 21,4 \frac{\dot{Q}_c^{2/3}}{(z_H - z_v)^{5/3}} = 21,4 \times \frac{(0,7 \times 2\,500)^{2/3}}{(12 - 0,061\,8)^{5/3}} = 49,8 \quad (\text{A.30})$$

where $\Delta T_{\max}$ is expressed in K. The time-mean maximum ceiling jet temperature rise, $\Delta T_{\max}$, outside of the plume turning region was calculated at a radial distance of 5 m from the plume centreline by [Formula \(A.31\)](#) [based on [Formula \(A.7\)](#)] as follows:

$$\Delta T_{\max} = 6,82 \frac{(\frac{\dot{Q}_c}{r})^{2/3}}{z_H - z_v} = 6,82 \times \frac{(\frac{0,7 \times 2\,500}{5})^{2/3}}{12 - 0,061\,8} = 28,4 \quad (\text{A.31})$$

where $\Delta T_{\max}$ is expressed in K. The calculated values are shown in [Figure A.6](#).



Key

- X radial distance from plume axis (m)
- Y time-mean temperature rise (K)
- 1 plume turning region
- 2 ceiling jet region
- 3 [Formula \(A.5\)](#)
- 4 [Formula \(A.7\)](#)

Figure A.6 — Calculation results of time-mean maximum temperature rise