INTERNATIONAL STANDARD

ISO 24678-4

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Fire safety engineering — Requirements governing algebraic formulae —

Part 4:
Smoke layers

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

Partie 4: Couches de fumée

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Contents

Page

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 document 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).

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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 16735:2006, which has been technically revised.

The main changes are as follows:

— the main body has been simplified by making reference to ISO 24678-1;

— the arrival time of smoke front has been introduced in the calculations of smoke filling time 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 subjected 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 simultaneously 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/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.
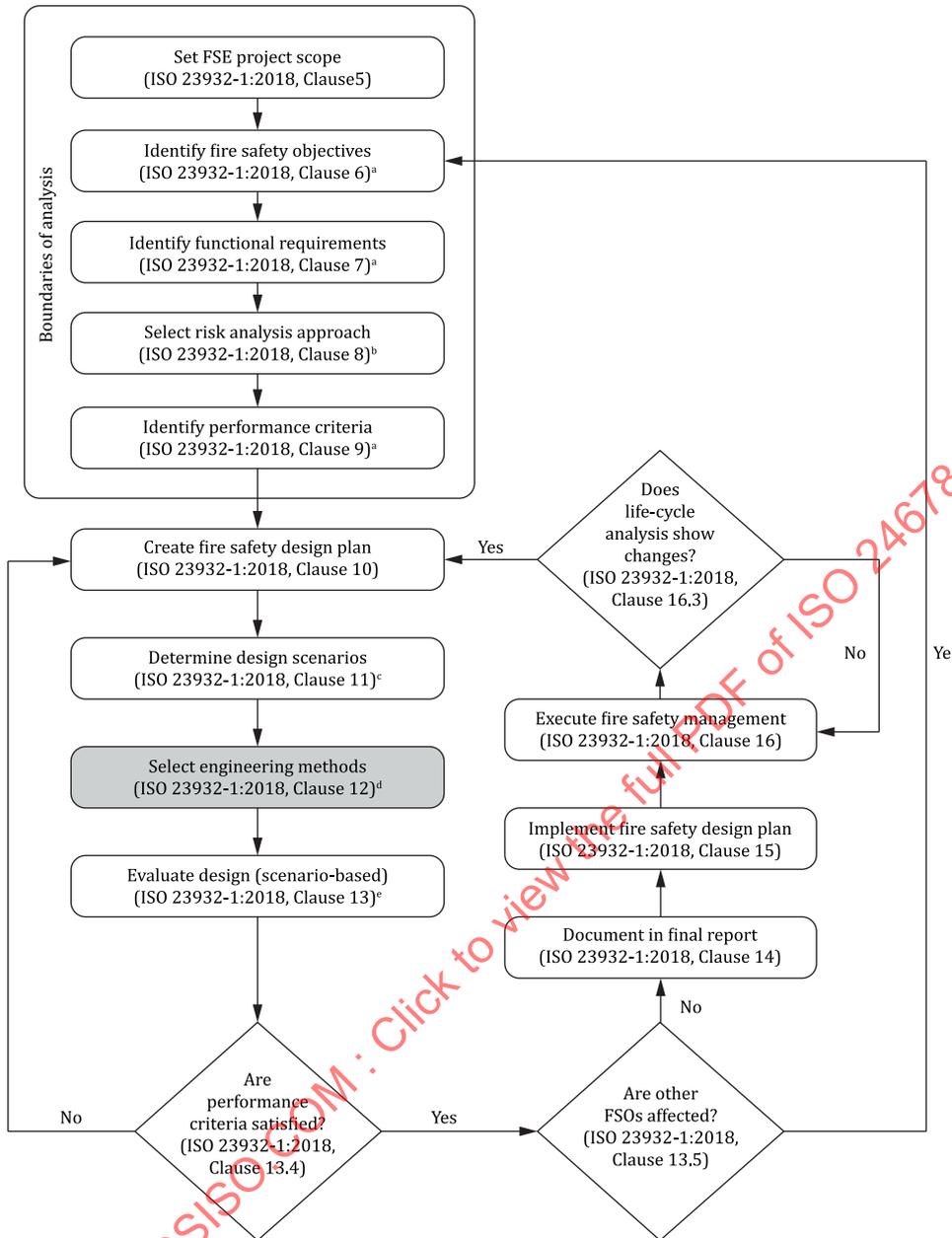
a   See also ISO/TR 16576 (Examples).

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/TR 16738, ISO 24678-1, ISO 24678-2, ISO 24678-3, ISO 24678-4 (this document), ISO 24678-5, ISO 24678-6, ISO 24678-7 and ISO 24678-9.

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

NOTE   Documents linked to large parts of the fire safety engineering design process: ISO 16732-1, ISO 16733-1, ISO 24678-1, ISO 24679-1, ISO/TS 29761, ISO/TR 16732-2 and ISO/TR 16732-3 (Examples), ISO/TR 24679-2 to ISO/TR 24679-4, ISO/TR 24679-6, ISO/TR 24679-8 (Examples).

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

Fire safety engineering — Requirements governing algebraic formulae —

Part 4:
Smoke layers

1   Scope

This document specifies the requirements governing the application of a set of explicit algebraic formulae for the calculation of specific characteristics of smoke layers.

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
boundary**
surface that defines the extent of an enclosure

**3.2
enclosure**
room, space or volume that is bounded by surfaces

**3.3
fire plume**
upward turbulent fluid motion generated by a source of buoyancy that exists by virtue of combustion and often includes an initial flaming region

**3.4
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

**3.5
flow coefficient**
fraction of effective flow area over total area of a vent

3.6
fuel mass burning rate
mass generation rate of fuel vapours

3.7
heat release rate
rate at which heat is actually being released by a source of combustion (such as the fire source)

3.8
interface position
elevation of the smoke layer interface relative to a reference elevation

Note 1 to entry: It is also referred to as the smoke layer height.

3.9
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

3.10
smoke layer
relatively homogeneous volume of smoke that forms and accumulates beneath the boundary having the highest elevation in an enclosure as a result of a fire

Note 1 to entry: This is also referred to as the hot upper layer and the hot gas layer.

3.11
smoke layer interface
horizontal plane separating the smoke layer from the lower, smoke-free layer

3.12
species yield
mass of a combustion product species generated by the combustion of unit mass of combustibles

3.13
thermal inertia
parameter representing the ability of enclosure materials to absorb heat, calculated by the square root of the product of thermal conductivity, density and specific heat of the material

3.14
vent
opening in an enclosure boundary through which air and smoke can flow as a result of naturally- or mechanically-induced forces

3.15
vent flow
flow of smoke or air through a vent in an enclosure boundary

4   Requirements governing the description of physical phenomena

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

4.2   The buoyant smoke layer resulting from a fire source in an enclosure is a complex thermo-physical phenomenon that can be highly transient or nearly steady state. In addition to buoyancy, smoke layers can be influenced by dynamic forces due to wind and mechanical fans.

4.3   Smoke layer 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 mass fraction with excess gas temperature based on the analogy between energy and mass conservation) and those associated with heat exposure to objects and occupants by the smoke layer, if applicable.

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

An example of documentation meeting the requirements in Clauses 4 to 8 is given in Annex A.

Annex A
(informative)

Formulae for smoke layers in an enclosure

A.1 Scope

This annex is intended to describe the methods that can be used to calculate interface position, average temperatures and average mass fractions of specific chemical species of smoke layers that form beneath boundaries during a fire in an enclosure. These calculation methods are based on the principles of mass, species and energy conservations as applied to the smoke layer as a thermodynamic control volume. In this annex, four different sets of formulae are provided. One is for the smoke filling process in a single enclosure during the initial stage of fire. The other three sets are for steady state smoke control by mechanical exhaust or by natural vents.

A.2 Symbols and abbreviated terms used in this annex

A floor area of enclosure (m^2)

A_{side} area of a side vent (m^2)

A_{top} area of a ceiling vent (m^2)

A_{wall} surface area of enclosure boundary in contact with smoke layer (m^2)

B width of a side vent (m)

c specific heat of enclosure boundary material (kJ/kg·K)

c_p specific heat of air at constant pressure (=1,0) (kJ/kg·K)

C_D flow coefficient

D_{wall} thickness of enclosure boundary material (m)

D fire source diameter (m)

g acceleration due to gravity (m/s^2)

h_{wall} effective heat transfer coefficient of enclosure boundary (kW/m^2·K)

H height of enclosure (m)

H_l height of lower bound of a side vent (m)

H_U height of upper bound of a side vent (m)

k thermal conductivity of enclosure boundary material (kW/m·K)

$\sqrt{k\rho c}$ thermal inertia of enclosure boundary material ($kW·s^{1/2}/m^2$·K)

L mean flame height (m)

$\dot{m}_a$ mass flow rate of air coming into an enclosure (kg/s)

$\dot{m}_e$ mass flow rate of smoke exhaust (kg/s)

$\dot{m}_{error}$ error in mass flow rate (kg/s)

$\dot{m}_p$ mass flow rate of gases in fire plume (kg/s)

$\dot{Q}$ heat release rate of a fire source (kW)

$\dot{Q}_0$ heat release rate of a steady fire source (kW)

t time (s)

t_{ar} arrival time of plume front at ceiling (s)

t_c characteristic time for heat absorption by enclosure boundary (s)

T_0 reference temperature, often taken by outside temperature (K)

T_s smoke layer temperature (K)

$\dot{V}_e$ volumetric flow rate of mechanical exhaust system (m^3/s)

Y mass fraction of specific chemical species (kg/kg)

Y_0 mass fraction of specific chemical species at reference state (kg/kg)

z interface position above base of fire source (m)

α fire growth rate of time-squared growing fires (kW/s^2)

β fire growth rate of linearly growing fires (kW/s)

ΔH_c heat of combustion (kJ/kg)

Δp pressure difference (Pa)

η species yield (kg/kg)

λ fraction of heat absorbed by enclosure boundary during smoke filling period

ρ_0 gas density of air at reference temperature (kg/m^3)

ρ_s gas density of smoke (kg/m^3)

ρ density of enclosure boundary material (kg/m^3)

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

A.3.1 General descriptions of calculation method

A.3.1.1 Calculation procedure

Estimating the smoke layer properties involves the following steps:

— determination of characteristics of the fire source (burning area, fuel mass burning rate, etc.);

— calculation of the height of the smoke layer interface;

— calculation of the temperature and mass fraction of chemical species in the smoke layer.

A.3.1.2 Smoke layer properties to be calculated

The formula set provides interface position, average gas temperature and mass fractions of chemical species. Uniform temperature and mass fractions are assumed over the entire smoke layer volume.

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

The formula set is applicable to smoke layers above a fire source in a quiescent environment. If flow-disturbance by non-fire related phenomena is significant, the formula set is not applicable. For example, the effect of airflow caused by heating, ventilation and air conditioning (HVAC) systems or by external wind should be considered if they have a significant effect. If active fire suppression systems, such as sprinklers, interact significantly with the smoke layer, the formula set is not applicable.

The fire source needs to be small enough so that the mean flame height is lower than the interface position and the characteristic plume width is less than the width of the enclosure (subject to additional restrictions imposed by the formulae used to obtain plume characteristics).

Methods to calculate smoke layer properties are developed for two limit stages. One limit stage is a simple enclosure smoke filling process during the initial stage of the fire when the smoke control system is not yet in operation. The other limit stage is a quasi-steady vented condition when the smoke production rate equals the rate of outflow from the smoke layer. An intermediate stage (i.e. smoke filling is still occurring even though a smoke venting system is in operation) is not treated in this Annex.

A.3.3 Self-consistency of the formula set

The formula set provided in this annex has been derived and reviewed by many researchers (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

None specified.

A.4 Formula-set documentation of calculation procedure

A.4.1 General description of calculation methods

A.4.1.1 Basic assumptions

As shown in Figure A.1, a smoke layer is generated over a fire source in an enclosure. Smoke is accumulated in the upper part of an enclosure as a result of burning. It is assumed that smoke forms a layer of fairly uniform temperature and species mass fraction. Based on the principles of mass, species and energy conservations applied to the smoke layer, average values of temperature, species mass fraction and interface position are calculated.[27],[28],[29] Descriptions of fire plumes and vent flows are given in ISO 24678-2 and ISO 24678-5, respectively.

Key
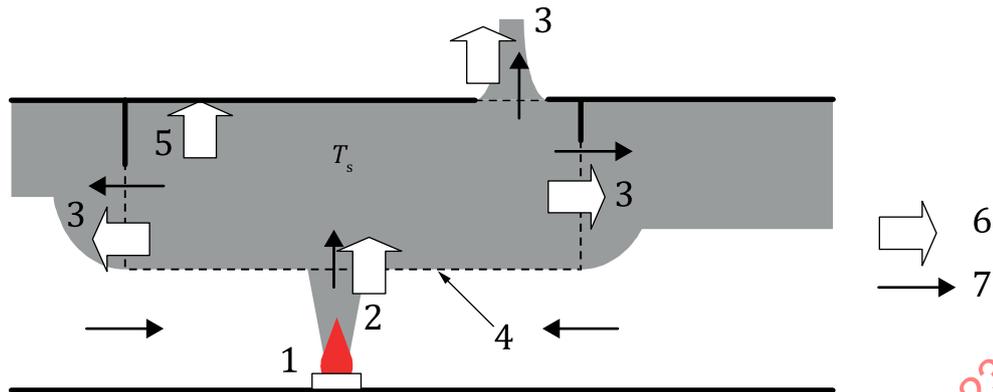
1   fire source
2   plume flow
3   vent flow
4   smoke layer (control volume)
5   heat absorption by enclosure boundary
6   heat flow
7   mass flow

Figure A.1 — General heat and mass conservation of smoke layer in an enclosure with a fire source

A.4.1.2   Mass conservation

Conservation of mass in the smoke layer is considered over an appropriately chosen control volume as shown in Figure A.1 by broken lines. The mass flow rate incoming across each interface (negative for outgoing flow) of the control volume is equal to the rate of mass accumulation in the smoke layer. Plume flow, vent flows and other flows are considered where necessary.

A.4.1.3   Energy conservation

Conservation of energy in the smoke layer is considered in a similar way to mass conservation. The energy flow rate incoming across each interface (negative for outgoing flow) of the control volume is equal to the rate of energy accumulation in the smoke layer. In addition to plume and vent flows, radiation losses and heat absorption by the enclosure boundary are considered appropriately.

NOTE   When it is difficult to determine the radiation heat loss from the flame, the energy flow rate from the fire plume can be approximated by the total heat release rate.

A.4.1.4   Conservation of specific chemical species

Mass conservation of specific chemical species is considered in a similar way to total mass conservation. In addition, if the gas phase chemical reaction can take place in the smoke layer, the reaction rate can be considered appropriately.

A.4.1.5   Mass flow rate of fire plume through interface position

The mass flow rate of the fire plume at the interface position (bottom surface of smoke layer) is given as a function of the heat release rate of the fire and the vertical distance between the base of the fire source and the interface position. An example of a set of explicit formulae for mass flow rate is given in ISO 24678-2.

A.4.1.6 Mass flow rate of smoke through vent

The mass flow rate through a vent is given as a function of the temperatures of the smoke layer and those of the adjacent enclosures, the pressure differences between the smoke layer and the adjacent enclosures, the vent width, and the vent height. Examples of explicit formulae for vent flows are given in ISO 24678-5.

A.4.1.7 Equation of state

Smoke temperature and density are correlated by the equation of state. Typically, smoke is approximated by an ideal gas whose properties are identical with air.

A.4.2 Enclosure smoke filling

A.4.2.1 Scenario element

Until the interface descends to the upper edge of a vent, smoke is accumulated in the upper part of an enclosure as shown in Figure A.2. Due to thermal expansion, excess air is pushed out of the enclosure.

NOTE   This assumption is valid as long as the smoke layer interface is above the upper boundary of the side vent. After the smoke layer interface descends below the upper boundary of the side vent, smoke flows out of enclosure while fresh air flows into the enclosure.

Key
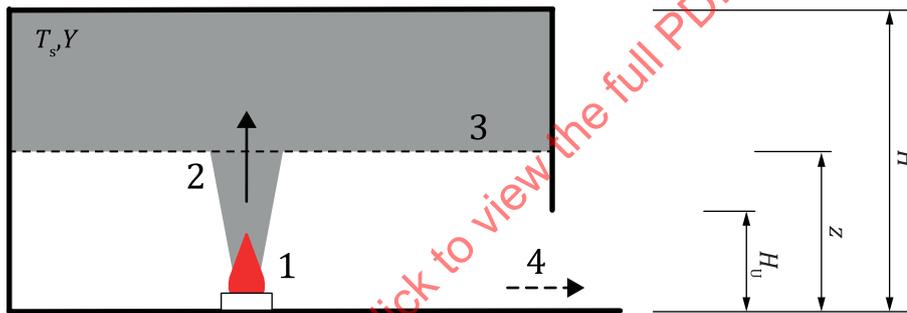
1   fire source
2   plume flow
3   smoke layer
4   excess air pushed out due to thermal expansion

Figure A.2 — Mass conservation during enclosure smoke filling process

The interface position is given by Formula (A.1):

$$-\rho_s A \frac{\partial z}{\partial t} = \dot{m}_p \tag{A.1}$$

The mass flow rate of plume at the interface position, z (m), above the fire source, is given by Formulae (A.2):[30]

$$\dot{m}_p = 0,076 \dot{Q}^{1/3} z^{5/3} \tag{A.2}$$

NOTE   Formula (A.2) is an approximation of the plume formula described in ISO 24678-2:2022, Annex A. This formula is valid only above the mean flame height. If the interface position is lower than the mean flame height, calculation results can be inaccurate.

The formula set is constructed for steady state fires, linearly growing fires and time-squared growing fires, as expressed in Formula (A.3):

$$\dot{Q}(t)=\begin{cases} Q_0 & \text{(steady state fires)} \\ \beta t & \text{(linearly growing fires)} \\ \alpha t^2 & \text{(time-squared growing fires)} \end{cases}$$ (A.3)

A.4.2.2 Interface position

Interface position is calculated so that plume mass flow accumulates in the upper layer of uniform density.[31] By inserting Formulae (A.2) and (A.3) into Formula (A.1) and integrating with respect to time, Formula (A.4) is derived:

$$z(t)=\begin{cases} \left(\dfrac{0,076}{\rho_s A}\dfrac{2}{3}\dot{Q}_0^{1/3}(t-t_{ar})+\dfrac{1}{H^{2/3}}\right)^{-3/2} & \text{(steady state fires)} \\[3mm] \left(\dfrac{0,076}{\rho_s A}\dfrac{1}{2}\beta^{1/3}(t-t_{ar})^{4/3}+\dfrac{1}{H^{2/3}}\right)^{-3/2} & \text{(linearly growing fires)} \\[3mm] \left(\dfrac{0,076}{\rho_s A}\dfrac{2}{5}\alpha^{1/3}(t-t_{ar})^{5/3}+\dfrac{1}{H^{2/3}}\right)^{-3/2} & \text{(time-squared fires)} \end{cases}$$ (A.4)

where the arrival time of plume front to ceiling is given for a steady state fire as shown in Formula (A.5):[32][33]

$$t_{ar}=1,7\dot{Q}_0^{-1/3}H^{4/3}$$ (A.5)

In case of linearly growing and time-squared fires, the explicit form for the arrival time is not known, but Formula (A.5) can be applied by using a conservative estimate of the heat release rate. For linearly growing fires, approximating that heat release rate is constant and equal to βt_{ar} during 0 to t_{ar}, Formula (A.6) applies:

$$t_{ar}=1,7(\beta t_{ar})^{-1/3}H^{4/3}$$ (A.6)

This results in Formula (A.7):

$$t_{ar}=1,49\beta^{-1/4}H$$ (A.7)

Similarly, in case of time-squared fires, Formula (A.8) is applicable:

$$t_{ar}=1,37\alpha^{-1/5}H^{4/5}$$ (A.8)

To calculate interface position, it is necessary to assume the gas density of smoke. For practical applications, $\rho_s=1,0$ gives conservative results for the initial smoke filling process in large enclosures. During the latter stage of smoke filling, thermal expansion is significant. In such cases, Formula (A.9) is applicable for time-squared-fires (i.e. $\dot{Q}=\alpha t^2$):[34],[35]

$$z(X)=H\left(1-\frac{\Lambda X^{9/5}}{1-T_s/T_0}\right)$$ (A.9)

where Formulae (A.10) and (A.11) provide the values for X and Λ:

$$X=0,026\,8\alpha^{1/3}(t-t_{ar})^{5/3}\frac{H^{2/3}}{A}$$ (A.10)

$$\Lambda = 0{,}754(1-\lambda)\alpha^{2/5}\frac{A^{4/5}}{H^{11/5}} \tag{A.11}$$

A.4.2.3 Smoke layer temperature

Heat released by a fire is accumulated in a smoke layer of volume $A(H\text{-}z)$. The smoke layer temperature is calculated using Formula (A.12). A fraction of λ of released heat is assumed to be absorbed by the enclosure boundary.

$$T_s(t)=T_0+\frac{(1-\lambda)}{c_p\rho_s A(H-z)}\begin{cases}\dot{Q}_0(t-t_{ar}) & \text{(steady state fires)} \\ \dfrac{\beta}{2}(t-t_{ar})^2 & \text{(linearly growing fires)} \\ \dfrac{\alpha}{3}(t-t_{ar})^3 & \text{(time-squared fires)}\end{cases} \tag{A.12}$$

NOTE 1   The value of $\lambda = 0{,}3$ is conventionally used during the initial smoke filling. For precise calculations, coupling convective and radiative heat transfer between plume, smoke layer and enclosure boundary is desirable.

NOTE 2   For practical applications, $\rho_s = 1{,}0$ gives acceptable results for the initial smoke filling of large volume enclosures.

During the latter stage of smoke filling, thermal expansion of the smoke layer is significant. In such cases, the smoke layer temperature for t^2-fires is calculated by Formula (A.13):[35]

$$T_s(X)=T_0\exp(-\frac{\Lambda X^{9/5}}{1-(1+X)^{-3/2}}) \tag{A.13}$$

where Λ and X are defined by Formulae (A.10) and (A.11).

A.4.2.4 Mass fraction of specific chemical species

The mass fraction of specific chemical species is calculated so that generated mass is accumulated in the smoke layer and creates a uniform mass fraction, as shown in Formula (A.14):

$$Y(t)=Y_0+\frac{\eta}{\Delta H_c}\frac{1}{\rho_s A(H-z)}\begin{cases}\dot{Q}_0(t-t_{ar}) & \text{(steady fires)} \\ \dfrac{\beta}{2}(t-t_{ar})^2 & \text{(linearly growing fires)} \\ \dfrac{\alpha}{3}(t-t_{ar})^3 & \text{(time-squared fires)}\end{cases} \tag{A.14}$$

A.4.3 Steady state smoke control by a mechanical exhaust system

A.4.3.1 Scenario element

During the smoke control stage, smoke is exhausted by a mechanical exhaust system, as shown in Figure A.3. Smoke layer properties are calculated by quasi-steady state balance of smoke generation and exhaust rates. It is assumed that the vents in the lower part of enclosure boundaries are of sufficient size for the air to be able to flow in easily. In this formula set, the heat release rate is assumed to be

constant. The mass flow rate of fire plume is given by Formula (A.2). With a given volumetric flow rate as a trial design parameter, the mass exhaust rate is calculated by Formula (A.15):

$$\dot{m}_e = \rho_s \dot{V}_e \tag{A.15}$$

Interface position is calculated so that the mass exhaust rate is equal to the plume mass flow rate as shown in Formula (A.16):

$$\dot{m}_e = \dot{m}_p \tag{A.16}$$
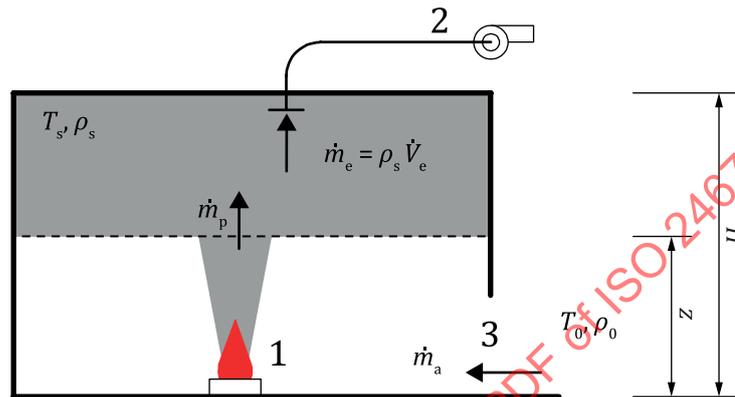
Key

1   fire source
2   mechanical exhaust system
3   air flow through a side vent

Figure A.3 — Conservation of mass during steady state smoke control by a mechanical exhaust system

A.4.3.2   Interface position

The interface position is calculated so that the plume mass flow rate equals the mass exhaust rate, as shown in Formula (A.17):

$$z = \left(\frac{\dot{m}_e}{0,076 \dot{Q}^{1/3}} \right)^{3/5} \tag{A.17}$$

NOTE   To calculate the mass flow rate of smoke exhaust, $\dot{m}_e$, the gas density of the smoke layer (i.e. smoke layer temperature) needs to be known. This can be calculated iteratively by combining with Formulae (A.18), (A.19) and (A.20). Refer to A.9.2 for the detailed procedure.

A.4.3.3   Smoke layer temperature

The smoke layer temperature is calculated so that heat flow to the smoke layer equals the sum of heat loss due to ventilation and absorption by enclosure boundary, as shown in Formula (A.18):

$$T_s = \frac{\dot{Q}}{c_p \dot{m}_p + h_{wall} A_{wall}} + T_0 \tag{A.18}$$

The effective heat transfer coefficient is calculated depending on the construction materials of the enclosure boundary. Heat transfer is approximated either by thermally thick behaviour (semi-infinite

body approximation) or by thermally thin behaviour (steady state temperature profile over thin material); see Formula (A.19):

$$h_{\text{wall}} = \begin{cases} \sqrt{\dfrac{k\rho c}{\pi t_{\text{c}}}} & (\sqrt{\dfrac{\pi k t_{\text{c}}}{\rho c}} < D_{\text{wall}}) \\[2ex] \dfrac{k}{D_{\text{wall}}} & (D_{\text{wall}} \leq \sqrt{\dfrac{\pi k t_{\text{c}}}{\rho c}}) \end{cases}$$

(A.19)

NOTE   Characteristic time, t_{c}, is often taken as 1 000 (s).

A.4.3.4 Gas density of smoke layer

The gas density of the smoke layer is calculated by the equation of state shown in Formula (A.20):

$$\rho_{\text{s}} = \frac{353}{T_{\text{s}}}$$

(A.20)

NOTE   For engineering calculations, smoke layer gas is often approximated by a perfect gas.

A.4.3.5 Mass fraction of specific chemical species

The mass fraction of specific chemical species is calculated so that the rate of generation equals the rate of exhaust, as shown in Formula (A.21):

$$Y = \frac{\eta}{\Delta H_{\text{c}}} \frac{\dot{Q}}{\dot{m}_{\text{e}}} + Y_0$$

(A.21)

A.4.4 Steady state smoke control by a ceiling vent

A.4.4.1 Scenario element

Smoke is exhausted by a natural ceiling vent as shown in Figure A.4. It is assumed that fresh air flows into the lower part of enclosure. The smoke layer properties are calculated by the quasi-steady state balance of heat and mass. The mass balance of air and smoke is given by Formula (A.22):

$$\dot{m}_{\text{a}} = \dot{m}_{\text{p}} = \dot{m}_{\text{e}}$$

(A.22)

In this formula set, the heat release rate is assumed to be constant over time. The mass flow rate of plume is given by Formula (A.2). Mass flow rate through a vent is calculated in accordance with ISO 24678-5.

Key
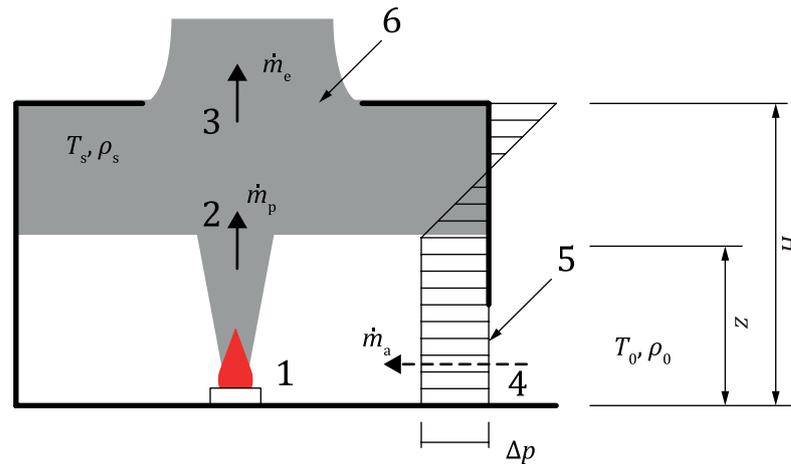
1   fire source
2   plume flow
3   flow through a ceiling vent
4   flow through a side vent
5   side vent
6   ceiling vent

Figure A.4 — Conservation of mass during steady state smoke control by a ceiling vent

A.4.4.2   Interface position

The interface position is calculated by Formula (A.17).

NOTE   To calculate the interface position, the mass exhaust rate is needed. This is calculated by combining with Formulae (A.18), (A.19), (A.20), (A.23) and (A.24). Refer to A.9.3 for details.

A.4.4.3   Smoke layer temperature

The smoke layer temperature is calculated by Formulae (A.18) and (A.19).

A.4.4.4   Gas density of smoke layer

The gas density of smoke layer is calculated by Formula (A.20).

A.4.4.5   Mass flow rate of smoke exhaust by a ceiling vent

The mass flow rate of smoke exhaust is calculated by Formula (A.23):

$$\dot{m}_{\mathrm{e}} = C_{\mathrm{D}} A_{\mathrm{top}} \sqrt{2\rho_{\mathrm{s}} \{(\rho_0 - \rho_{\mathrm{s}})g(H-z) - \Delta p\}} \tag{A.23}$$

A.4.4.6   Pressure difference at the bottom of a side vent

The pressure difference at the bottom of the side vent is calculated by Formula (A.24):

$$\Delta p = \frac{1}{2\rho_0} \left(\frac{\dot{m}_{\mathrm{p}}}{C_{\mathrm{D}} A_{\mathrm{side}}} \right)^2 \tag{A.24}$$

A.4.4.7 Mass fraction of specific chemical species

The mass fraction of specific chemical species is calculated by Formula (A.21).

A.4.5 Steady state smoke control by a side vent

A.4.5.1 Scenario element

During the smoke control stage, smoke is exhausted by a side vent as shown in Figure A.5. It is assumed that fresh air flows through the lower part of the side vent, while smoke flows out through the upper part of the side vent. The smoke layer properties are calculated by a quasi-steady state balance of smoke generation and outflow rates as described by Formula (A.22). In this formula set, the heat release rate is assumed to be constant over time. The mass flow rate of plume is given by Formula (A.2). Mass flow rate through a vent is calculated in accordance with ISO 24678-5.

Key
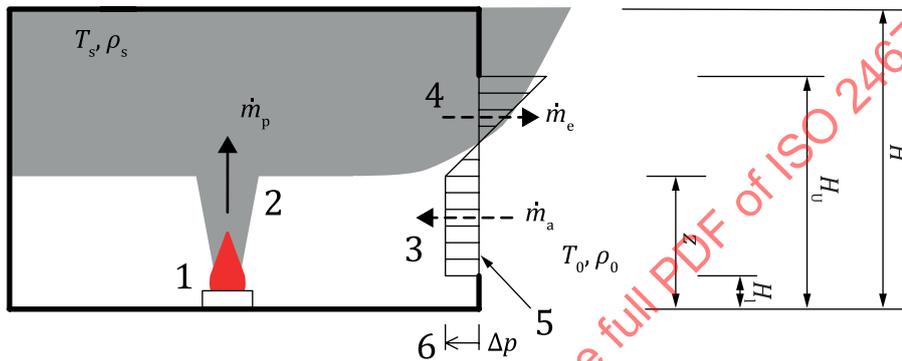
1. fire source
2. plume flow
3. air flow through a side vent
4. smoke flow through a side vent
5. side vent
6. pressure difference at the bottom of a side vent

Figure A.5 — Conservation of mass during steady state smoke control by a side vent

A.4.5.2 Mass flow rate of plume

The mass flow rate of plume is calculated by Formula (A.2).

NOTE   To calculate the mass flow rate of plume, the interface position is needed. It is calculated by combining with Formulae (A.18), (A.19), (A.20), (A.25), (A.26) and (A.27) to satisfy the mass balance between smoke exhaust rate and incoming air flow rate. Refer to A.9.4 for details.

A.4.5.3 Smoke layer temperature

The smoke layer temperature is calculated by Formulae (A.18) and (A.19).

A.4.5.4 Gas density of smoke layer

The gas density of smoke layer is calculated by Formula (A.20).

A.4.5.5 Mass flow rate of smoke exhausted by a side vent

Mass flow rate of smoke exhausted by a side vent is calculated considering the vertical pressure distribution, as shown in Formula (A.25):

$$\dot{m}_e = \frac{2}{3}C_D B\sqrt{2\rho_s(\rho_0-\rho_s)g}\{H_U-(z+\frac{\Delta p}{(\rho_0-\rho_s)g}\}^{3/2}$$

(A.25)

A.4.5.6 Pressure difference at the bottom of a side vent

The pressure difference at the bottom of a side vent is calculated so that the mass exhaust rate, $\dot{m}_e$, equals the mass flow rate of plume, $\dot{m}_p$. Replacing $\dot{m}_e$ with $\dot{m}_p$ in Formula (A.25) and rearranging with respect to Δp, the Formula (A.26) is applied to calculate the pressure difference:

$$\Delta p = (\rho_0-\rho_s)g(H_U-z)-(\frac{3}{2}\frac{(\rho_0-\rho_s)g}{C_D B\sqrt{2\rho_s}}\dot{m}_p)^{2/3}$$

(A.26)

A.4.5.7 Mass flow rate of air incoming through lower part of a side vent

The mass flow rate of air through the lower part of a side vent is calculated using the pressure difference calculated by Formula (A.26); see Formula (A.27):

$$\dot{m}_a = C_D B(z-H_l)\sqrt{2\rho_0\Delta p}+\frac{2}{3}C_D B\sqrt{2\rho_0(\rho_0-\rho_s)g}(\frac{\Delta p}{(\rho_0-\rho_s)g})^{3/2}$$

(A.27)

A.4.5.8 Mass fraction of specific chemical species

The mass fraction of specific chemical species is calculated by Formula (A.21).

A.5 Scientific basis for the formula-set

The formula set is based on general heat and mass conservation relationships. The research on smoke filling dates back to the basic study of fluid dynamics of Turner et al. on formation of sharp density interface in an enclosure.[36] Zukoski[37],[38] developed similar formulae specific to the smoke filling process during the early stage of fire. Following the theoretical studies by Zukoski, an experimental study was carried out by Mulholland et al.[39] to verify the assumptions of small density change. Experimental work by Tanaka and Yamana[31] found that measured data are well reproduced if the small density change is taken into account. Efforts have been paid to extend the analytical formulae to include the effect of volume expansion.[34],[35]

A.6 Formula-set limitations

A.6.1 Fire plume

The mass flow rate in the formula set assumes compatibility with formula-set limitations described in ISO 24678-2, with respect to the fire source, flame dimensions, proximity to boundaries, aerodynamic disturbances, etc.

A.6.2 Uniformity of smoke layer

The formula set assumes uniformity of layer properties. If the variation of layer properties is significant compared to the mean values, the application of the formula set is not recommended. Examples of such situations are narrow, vertical shaft-like enclosures and very long corridors.

A.7 Formula-set input parameters

A.7.1 Heat release rate

The parameter, $\dot{Q}$, is the rate of heat actually released by a fire under a specific environmental condition, as measured by a calorimeter that is based on product gas collection to determine O_2, CO_2 and CO generation rates as specified by ISO 24473, or as otherwise specified. This parameter is normally obtained from the design fire scenario. See ISO 24678-2:2022, Annex B, for more information.

A.7.2 Species yield

The species yield, η, depends on the type of fuel and equivalence ratio[41] as described in ISO 19703:2018. As this formula set assumes small fires in comparison with enclosure size, values for well-ventilated fires can be used. If data on smoke density or smoke obscuration data are needed, the ISO 5659-2 single smoke chamber test (static smoke measurement method) and/or ISO 5660-1 dynamic smoke measurement by cone calorimeter can be used.

A.7.3 Flow coefficient of vents

Formulae for smoke layer properties are coupled with formulae for vent flow. Refer to ISO 24678-5:2023, Annex B for example values of flow coefficients to be used for vent flow formulae.

A.7.4 Heat absorption by enclosure boundary during initial stage

The parameter λ is required for the calculation of the initial smoke filling process. Conventionally the value of $\lambda = 0{,}3$ is used. However, the parameter value depends largely on the construction of the enclosure boundary. In an enclosure with large thermal inertia (e.g. concrete structures) or with lightweight, non-insulating construction (e.g. glass house), heat absorption to the enclosure boundary may be significant. To set accurate values, details of radiation and convection heat transfer within the enclosure should be considered.

A.7.5 Thermal inertia of enclosure boundary

For the calculation of smoke layer temperature, heat absorption can be considered by the thermal inertia $\sqrt{k\rho c}$ of enclosure materials. Theoretically it is calculated by the square root of the product of thermal conductivity, density and specific heat of the material. Examples of the values are shown in Table A.1.

Table A.1 — Examples of the values of thermal inertia [45],[46]

Material	Thermal conductivity k (W/m·K)	Density ρ (kg/m³)	Specific heat c (kJ/kg·K)	Thermal inertia $\sqrt{k\rho c}$ (kW·s$^{1/2}$/m²·K)
aerated concrete	0,26	500	0,96	0,35
aluminium	206	2 710	0,895	22,35
alumina silicate block	0,14	260	1,0	0,19
brick (lightweight)	0,28	1 520	0,838	0,60
brick (normal weight)	0,8	2 600	0,8	1,29
calcium silicate board	0,12	700	1,12	0,31
cement mortar	1,39	2 110	0,796	1,53
concrete (lightweight)	0,66	1 720	1,006	1,07
concrete (normal weight)	1,51	2 300	0,88	1,75
concrete block	0,73	1 900	0,84	1,08

Table A.1 *(continued)*

Material	Thermal conductivity k (W/m·K)	Density ρ (kg/m³)	Specific heat c (kJ/kg·K)	Thermal inertia $\sqrt{k\rho c}$ (kW·s$^{1/2}$/m²·K)
expanded polystyrene	0,34	20	1,5	0,10
fibre insulation board	0,053	240	1,25	0,13
glass	0,79	2 540	0,754	1,23
glass fibre insulation	0,37	60	0,8	0,13
gypsum board	0,17	960	1,1	0,42
normal weight concrete	1,6	2 400	0,75	1,70
particle board	—	—	—	0,27
perlite mortar	0,21	918	0,796	0,39
plaster	0,51	1 940	0,838	0,91
plywood	—	—	—	0,11-0,76
rockwool board	0,04	300	0,155	0,04
steel	80,3	7 860	0,442	16,70

A.7.6 Effectiveness of mechanical smoke venting

The formula set in A.4.3 assumes that the mechanical venting system extracts smoke only. However, if the smoke layer is not sufficiently thick, the lower layer air is entrained into the mechanical smoke exhaust.[47] In such cases, the volume exhaust rate needs to be reduced by considering the air entrainment ratio.[48]

A.8 Domain of applicability of the formula set

A.8.1 General

The domain of applicability of the formula set in this annex is determined from the scientific literature given in Clause A.5.

A.8.2 Smoke filling

The formula set has been compared with an experiment in a large-scale atrium conducted by Tanaka and Yamana.[31] In this experiment, the floor area of the atrium was 720 m². Ceiling height was 26,3 m. The heat release rate was approximately 1 300 kW. The results are shown in Figure A.6 a) and Figure A.6 b). As shown in Figure A.6 a), the calculated interface position is slightly lower than in the experiment but the general tendency agrees well. As shown in Figure A.6 b), the calculated smoke layer temperature is slightly higher than the experiment. Formulae (A.4) and (A.18) give conservative results both in interface position and smoke layer temperature.

a) Interface position
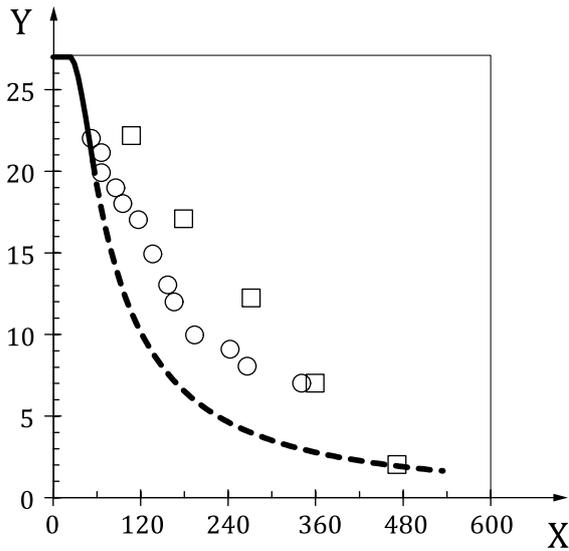
b) Smoke layer temperature

Key
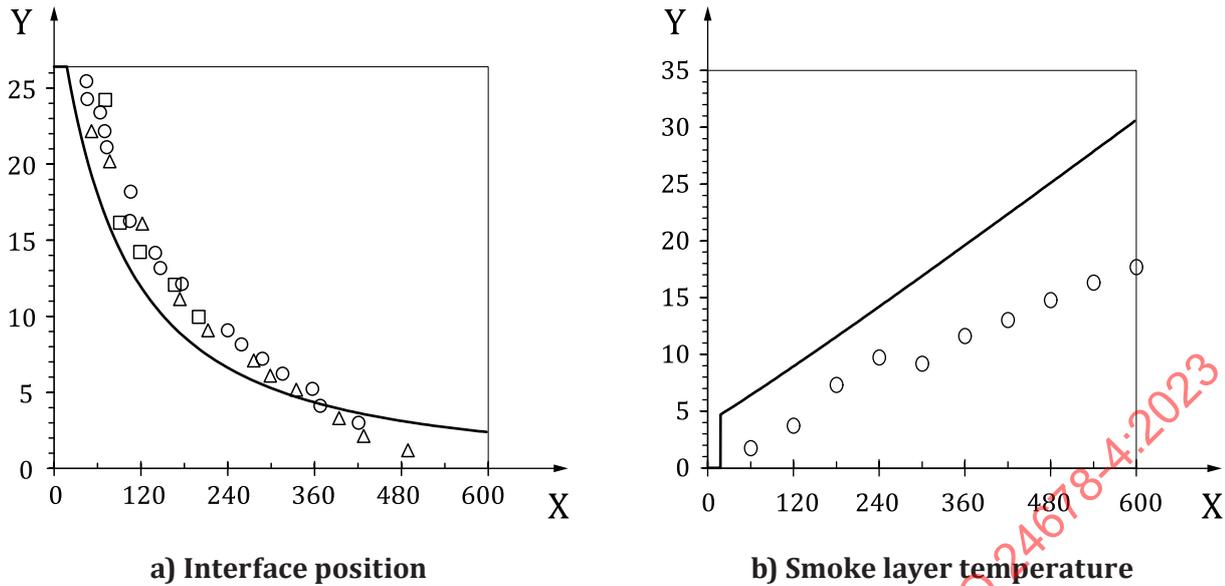
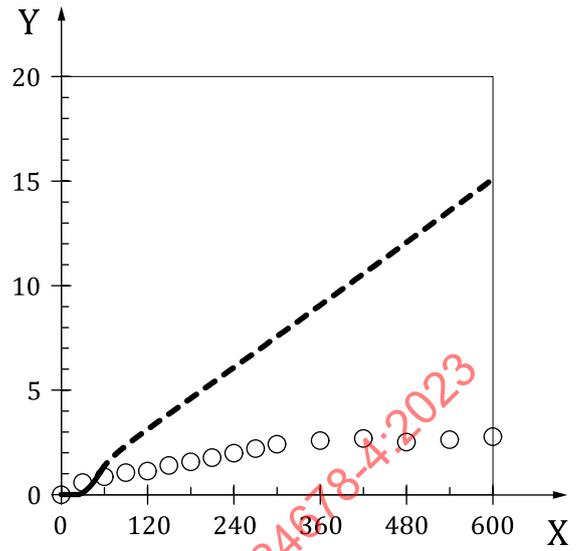|	
X	time (s)
Y	interface position (m)
○	measured by temperature rise
□	measured by photometer
△	measured by eye observation
——	calculated by Formula (A.4) for steady state fire source

Key

X	time (s)
Y	smoke layer temperature rise above ambient value (K)
○	measured by thermocouples
——	calculated by Formula (A.18) for steady state fire source

Figure A.6 — Comparison of calculation results with an experiment by Tanaka and Yamana[31]

Similar experiments were conducted by Chow *et al.* in an atrium 27 m high, with a floor area of 267 m². [49] In Experiment A, the heat release rate was increased in a t^2-manner up to 265 kW at 30 s. After that, the heat release rate was maintained constant. The results of the comparison are shown in Figure A.7. The interface position is calculated as being lower than in the experiment. The smoke layer temperature is calculated as being higher than in the experiment. A similar comparison was made for Experiment B using the same atrium but a different heat release rate, which was increased in a t^2-manner up to 440 kW at 52,1 s. After that, the heat release rate was maintained constant. The results are shown in Figure A.8 in comparison with Formulae (A.4) and (A.18).

a) Interface position

b) Smoke layer temperature

Key

X	time (s)
Y	interface position (m)
○	measured by temperature rise
□	measured by visual observation
——	calculated for t^2-fire source
- - -	calculated for steady state fire source

Key

X	time (s)
Y	smoke layer temperature rise above ambient value (K)
○	measured by thermocouples
——	calculated for t^2-fire source
- - -	calculated for steady state fire source

Figure A.7 — Comparison of calculation results with the experiment A with 265 kW of heat release rate by Chow *et al*.[49]

a) Interface position
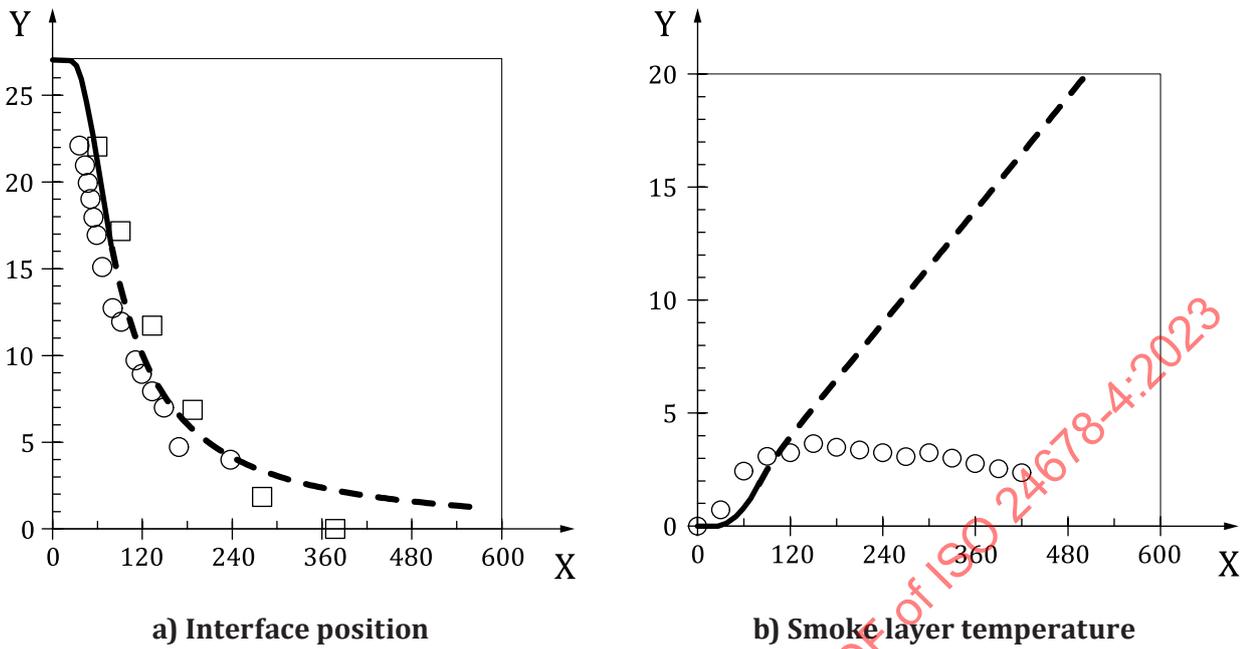
Key

X   time (s)

Y   interface position (m)

○   measured by temperature rise

□   measured by visual observation

——   calculated for t^2-fire source

- - -   calculated for steady state fire source

b) Smoke layer temperature

Key

X   time (s)

Y   smoke layer temperature rise above ambient value (K)

○   measured by thermocouples

——   calculated for t^2-fire source

- - -   calculated for steady state fire source

Figure A.8 — Comparison of calculation results with the experiment B with 440 kW of heat release rate by Chow *et al.*[49]

In a small compartment, Mulholand *et al.* carried out smoke filling experiments.[50] The compartment size was 3,7 m × 3,7 m. Ceiling height was 2,05 m above the fuel surface. Heat release rate was 16,2 kW. As shown in Figure A.9, the agreement of interface position, calculated by Formula (A.4), is satisfactory. The temperature is calculated conservatively by Formula (A.18).

a) Interface position

Key

X   time (s)

Y   interface position (m)

○   measured by temperature rise

☐   measured by smoke extinction coefficient

——   calculated by Formula (A.4)

b) Smoke layer temperature

Key

X   time (s)

Y   smoke layer temperature rise above ambient value (K)

○   measured
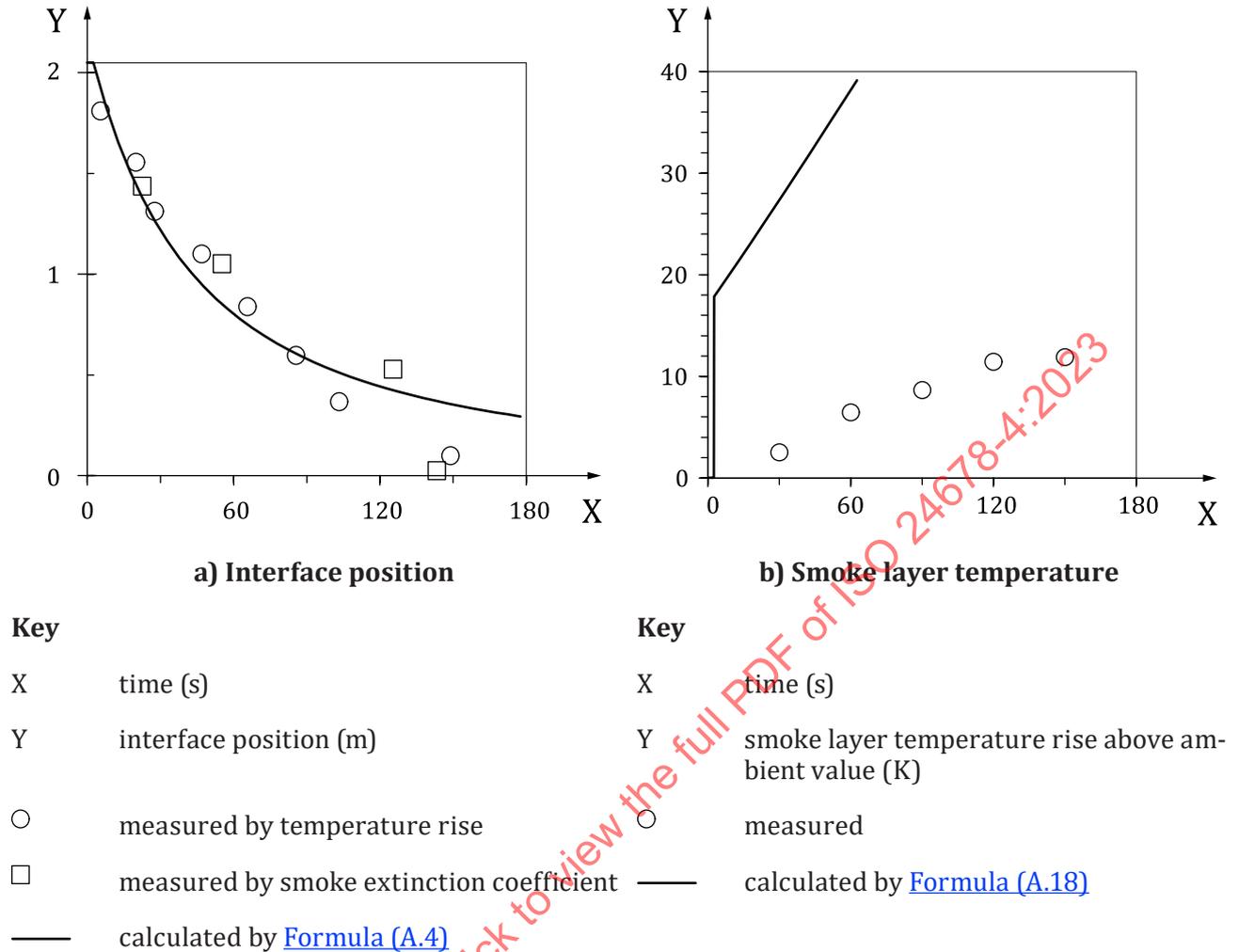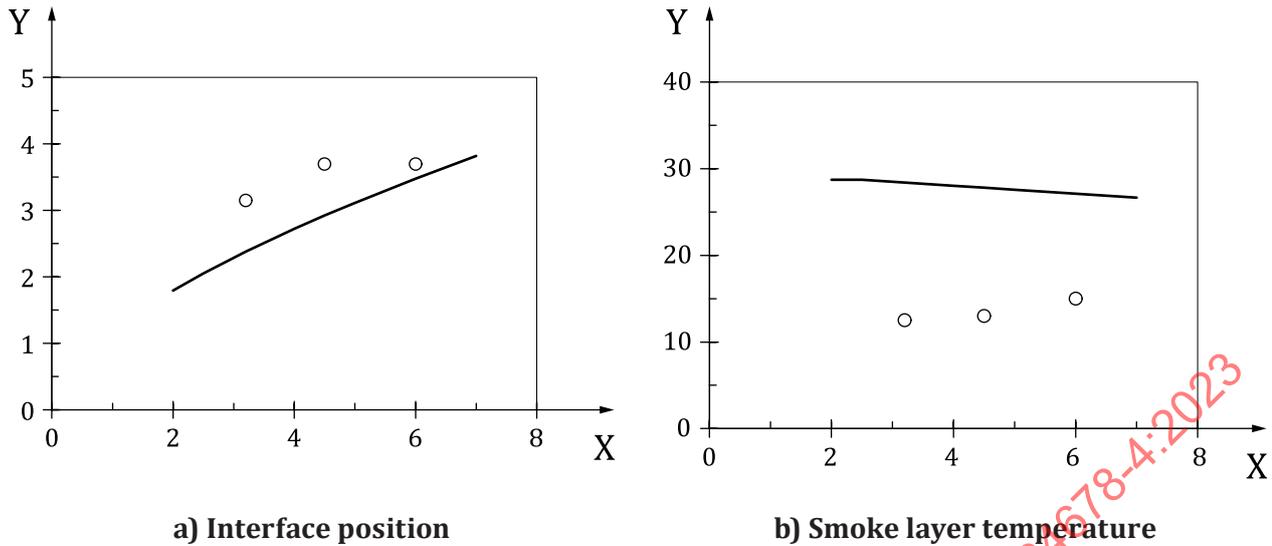
——   calculated by Formula (A.18)

Figure A.9 — Comparison of calculation results with an experiment by Mulholand et al.[50]

A.8.3   Steady state smoke control by mechanical exhaust system

Tanaka and Yamana[31] also conducted mechanical venting experiments in the same atrium as for the smoke filling experiment in A.8.2. The floor area of the atrium was 720 m². The ceiling height was 26,3 m. The heat release rate was approximately 1 300 kW. Smoke was extracted from the upper part of the atrium at 3,2; 4,5 and 6,0 m³/s. At the quasi-steady state, the interface position was located at 3,3 m, 3,8 m and 3,8 m above the fire source. The calculated results are compared in Figure A.10. The Formulae (A.17) and (A.18) give conservative results both for interface position and smoke layer temperature.

a) Interface position

Key

X   smoke exhaust rate (m^3/s)

Y   interface position (m)

○   measured

────   calculated by Formula (A.17)

b) Smoke layer temperature

Key

X   smoke exhaust rate (m^3/s)

Y   smoke layer temperature rise above ambient value (K)

○   measured

────   calculated by Formula (A.18)

Figure A.10 — Comparison of calculation results with mechanical smoke exhaust experiments by Tanaka and Yamana[31]
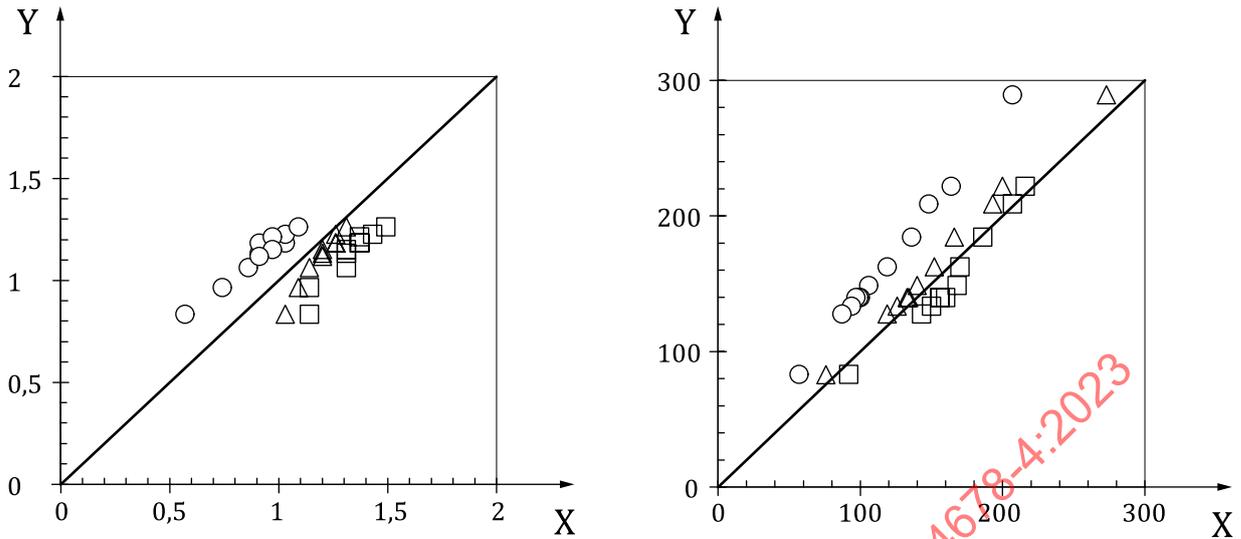
A.8.4   Steady state smoke control by a ceiling vent

Tanaka and Yamana[31] also conducted the natural venting experiments in the same atrium as in A.8.2. The floor area of the atrium was 720 m^2. The ceiling height was 26,3 m. The heat release rate was approximately 1 300 kW. Smoke was exhausted from a vent located close to ceiling. The vent area was 6,46 m^2. At the bottom of the atrium, an air supply vent was equipped. The area of the air supply vent was 3,23 m^2. The interface position was located at 3,8 m above the floor. The calculation result by Formula (A.17) was 3,4 m, which yields a conservative estimate.

A.8.5   Steady state smoke control by a side vent

The calculation formulae are compared with a series of room experiments by Steckler *et al.*[51] The compartment size was 2,8 m × 2,8 m. Ceiling height was 2,13 m. A doorway opening was located on a wall. The height of opening was 1,83 m. The width was varied in the range of 0,24 m to 0,99 m. The heat release rate ranged from 31,6 kW to 150 kW. The fire source was located either at the centre of the room, in the corner of the room or adjacent to a wall. The internal surface of the test chamber was lined with ceramic fibre.

The interface position and smoke layer temperature were calculated by the method described in A.4.5. The results are compared in Figure A.11. In cases where the fire source is located at the centre of the room, the interface position is calculated as being slightly higher than in experiments, but the smoke layer temperature is calculated as being higher than in experiments. In cases where the fire source is located in a corner or adjacent to a wall, smoke layer height is calculated as being lower than in experiments. This is because the mass entrainment rate was reduced by the walls close to fire plume. The smoke layer temperature happens to coincide with the experimental measurements.

a) Interface position

Key

X   measured interface position (m)

Y   calculated interface position (m)

○   fire source located at centre of a room

□   fire source located in corner of a room

△   fire source located adjacent to a wall

b) Smoke layer temperature

Key

X   measured smoke layer temperature rise (K)

Y   calculated smoke layer temperature rise (K)

○   fire source located at centre of a room

□   fire source located in corner of a room

△   fire source located adjacent to a wall

Figure A.11 — Comparison of calculation results with room experiments by Steckler *et al.*[51]

A.9 Calculation examples

A.9.1 Smoke filling

A fire source is located in an enclosure shown in Figure A.2. The heat release rate is given by $\dot{Q} = 0,05t^2$ ($\alpha = 0,05$ kW/s^2). The fire source diameter, D, is 1,0 m. The floor area of the enclosure, A, is 100 m^2. The enclosure height, H, is 8,0 m. Heat absorption by enclosure boundary is assumed by $\lambda = 0,3$. The ratio of CO_2 yield to heat of combustion, $(\eta/\Delta H_c)$, has been set as $(7,61 \times 10^{-5})$ kg/kJ. The interface position, temperature and CO_2 mass fraction at 60 s are calculated.

The arrival time of plume front to ceiling is calculated by Formula (A.28) [based on Formula (A.8)] as:

$$t_{ar} = 1,37\alpha^{-1/5}H^{4/5} = 1,37 \times 0,05^{-1/5} \times 8,0^{4/5} = 13,2 \tag{A.28}$$

where t_{ar} is expressed in s.

Using Formula (A.29) [based on Formula (A.4)], interface position is:

$$z = \left(\frac{0,076}{\rho_s} \frac{\alpha^{1/3}}{A} \frac{2}{5}(t - t_{ar})^{5/3} + \frac{1}{H^{2/3}} \right)^{-3/2}$$

$$= \left(\frac{0,076}{1,0} \frac{0,05^{1/3}}{100} \frac{2}{5} (60-13,2)^{5/3} + \frac{1}{8,0^{2/3}} \right)^{-3/2} = 5,57 \tag{A.29}$$

where z is expressed in m.

Putting z into Formulae (A.30) and (A.31) [based on Formulae (A.12) and (A.14) respectively], smoke layer temperature and CO_2 mass fraction are:

$$T_s = \frac{(1-\lambda)}{c_p \rho_s A(H-z)} \frac{\alpha}{3} (t-t_{ar})^3 + T_0$$

$$= \frac{(1-0,3)}{1,0 \times 1,0 \times 100 \times (8,0-5,57)} \frac{0,05}{3} \times (60,0-13,2)^3 + 20 = 24,9 \tag{A.30}$$

$$Y = \frac{\eta}{\rho_s A(H-z)} \frac{\alpha}{3} (t-t_{ar})^3 + Y_0$$

$$= \frac{7,61 \times 10^{-5}}{1,0 \times 100 \times (8,0-5,57)} \frac{0,05}{3} \times (60,0-13,2)^3 + 0,000\ 3 = 0,000\ 84 \tag{A.31}$$

where T_s is expressed in °C and Y is expressed in kg/kg.

To make use of Formula (A.2), the mean flame height needs to be smaller than the interface position. In this particular case, mean flame height is well below the interface position as calculated by ISO 24678-2; see Formula (A.32):

$$L = -1,02D + 0,235\dot{Q}^{2/5} = -1,02 \times 1,0 + 0,235 \times (0,05 \times 60^2)^{2/5} = 0,86 \tag{A.32}$$

where L is expressed in m.

In a similar manner, smoke layer height, temperature and CO_2 mass fractions were calculated as shown in Figure A.12. For the formula set to be valid, the interface position must be above the mean flame height and the top of the doorway opening. In this example, mean flame height and smoke layer height are almost identical at 128 s; see Formulae (A.33) and (A.34):

$$z = \left(\frac{0,076}{1,0} \frac{0,05^{1/3}}{100} \frac{2}{5} (128-13,2)^{3/5} + \frac{1}{8,0^{2/3}} \right)^{-3/2} = 2,42 \tag{A.33}$$

$$L = -1,02D + 0,235\dot{Q}^{2/5} = -1,02 \times 1,0 + 0,235 \times (0,05 \times 128^2)^{2/5} = 2,42 \tag{A.34}$$

where z is expressed in m and L is expressed in m. Thus, the use of this formula set is limited up to 128 s.
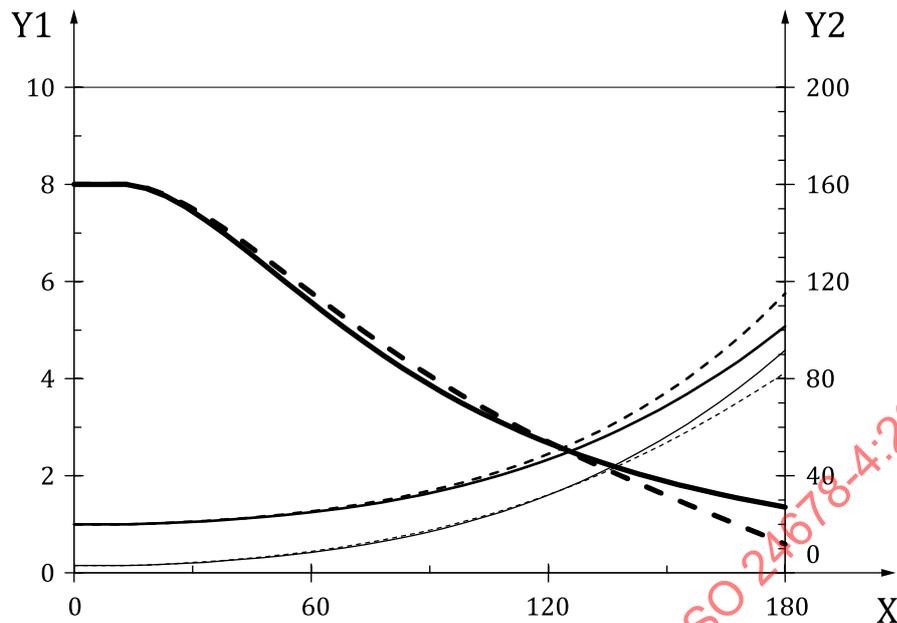
Key

X   time (s)

Y1   interface position (m)

Y2   smoke layer temperature (°C) or mass fraction of CO_2 (g/kg)

⎯⎯⎯   interface position calculated by Formula (A.4)

– –   interface position calculated by Formula (A.9)

⎯⎯⎯   smoke layer temperature calculated by Formula (A.12)

- - - -   smoke layer temperature calculated by Formula (A.13)

⎯⎯⎯   mass fraction of CO_2 calculated by Formula (A.14) with Formula (A.12)

·········   mass fraction of CO_2 calculated by Formula (A.14) with Formula (A.13)

Room floor area is A = 100 m².

Ceiling height is H = 8 m.

Heat release rate is $\dot{Q} = 0,05t^2$.

Fraction of heat absorbed by enclosure boundary is λ = 0,3.

Figure A.12 — Calculation results of height of interface position, smoke layer temperature and CO_2 mass fraction during smoke filling process in an enclosure

A.9.2   Steady state smoke control by a mechanical exhaust system

A fire source is located at the centre of an enclosure as shown in Figure A.3. The floor area of the enclosure, A, is 100 m² (10 m × 10 m). Enclosure height, H, is 8,0 m. Heat release rate of the fire source, $\dot{Q}$, is 300 kW. Fire source diameter, D, is 1,0 m. The mechanical exhaust rate, V_e, is 4,0 m³/s. The enclosure boundary is made of a concrete slab of 100 mm thickness. Thermal properties of concrete are assumed as k = 0,001 5 kW/m·K, ρc=2 026 kJ/m³·K. Reference temperature, T_0, is 20 °C (293 K) which corresponds to 1,205 kg/m³ of reference gas density, ρ_0. The ratio of CO_2 yield to heat of combustion, $(\eta/\Delta H_c)$, was set as (7,61×10⁻⁵) kg/kJ.

The formula set for interface position and temperature are inter-related. These formulae are solved iteratively. After finding solutions for interface position and temperature, mass fraction of CO_2 is calculated in a straightforward way.

1) Assume the interface position, for example, by 50 % of the total enclosure height, as shown in Formula (A.35):

$$z = \frac{H}{2} = 4,0 \tag{A.35}$$

where z is expressed in m.

2) Calculate the mass flow rate of the plume at the interface position as shown in Formula (A.36) [based on Formula (A.2)]:

$$\dot{m}_p = 0,076\dot{Q}^{1/3}z^{5/3} = 0,076 \times 300^{1/3} \times 4^{5/3} = 5,13 \tag{A.36}$$

where $\dot{m}_p$ is expressed in kg/s.

3) Calculate the effective heat transfer coefficient using Formula (A.19).

The enclosure boundary is assumed to be thermally thick, as shown in Formula (A.37):

$$\sqrt{\frac{\pi k t_c}{\rho c}} = \sqrt{\frac{3,14 \times 0,001\,5 \times 1\,000}{2\,026}} = 0,048 < 0,1 \tag{A.37}$$

where $\sqrt{\dfrac{\pi k t_c}{\rho c}}$ is expressed in m. The effective heat transfer coefficient is shown in Formula (A.38):

$$h_{wall} = \sqrt{\frac{k\rho c}{\pi t_c}} = \sqrt{\frac{0,001\,5 \times 2\,026}{3,14 \times 1\,000}} = 0,031 \tag{A.38}$$

where h_{wall} is expressed in kW/m$^2\cdot$K.

4) Calculate the smoke layer temperature as shown in Formulae (A.39) and (A.40) [based on Formula (A.18)]:

$$A_{wall} = 100 + 40 \times (8-4) = 260 \tag{A.39}$$

$$T_s = \frac{\dot{Q}}{c_p m_p + h_{wall} A_{wall}} + T_0 = \frac{300}{1,0 \times 5,13 + 0,031 \times 260} + 20 = 42,7 \tag{A.40}$$

where A_{wall} is expressed in m^2 and T_s is expressed in °C.

5) Calculate the gas density of smoke layer as shown in Formula (A.41) [based on Formula (A.20)]:

$$\rho_s = \frac{353}{T_s} = \frac{353}{42,7 + 273} = 1,118 \tag{A.41}$$

where ρ_s is expressed in kg/m^3.

6) Calculate the mass flow rate by mechanical exhaust system as shown in Formula (A.42) [based on Formula (A.15)]:

$$\dot{m}_e = \rho_s \dot{V}_e = 1,118 \times 4,0 = 4,47 \tag{A.42}$$

where $\dot{m}_e$ is expressed in kg/s.

7) Correct the interface position by Formula (A.43) [based on Formula (A.17)] so that the plume mass flow rate equals the mass exhaust rate:

$$z = \left(\frac{\dot{m}_e}{0,076\dot{Q}^{1/3}}\right)^{3/5} = \left(\frac{4,47}{0,076 \times 300^{1/3}}\right)^{3/5} = 3,68 \tag{A.43}$$

where z is expressed in m.

8) Repeat procedures 2) to 7) until the mass flow rate of the plume and mass exhaust rate coincide.

In this particular example, three iterations are sufficient to obtain the following solutions:

$z = 3,68$

$T_s = 43,2$

$\dot{m}_p = \dot{m}_e = 4,47$

where z is expressed in m, T_s is expressed in °C, and $\dot{m}_p$ and $\dot{m}_e$ are expressed in kg/s.

9) To make use of Formula (A.2), the mean flame height needs to be smaller than the interface position. In this particular case, the condition is satisfied; see Formula (A.44):

$$L = -1,02D + 0,235\dot{Q}^{2/5} = -1,02\times1,0 + 0,235\times300^{2/5} = 1,28 < 3,68 \tag{A.44}$$

Formula (A.44) was calculated according to ISO 24678-2:2022, Annex A, where L is expressed in m.

10) Calculate the species mass fraction using the values obtained in 8). In case of wooden fuels under well-ventilated conditions, the ratio of carbon dioxide yield to heat of combustion is $\eta/\Delta H_c = (7,61\times10^{-5})$ kg/kJ. Thus, the Formula (A.45) [based on Formula (A.21)] applies:

$$Y = \frac{\eta}{\Delta H_c}\frac{\dot{Q}}{\dot{m}_e} + Y_0 = 7,61\times10^{-5}\times\frac{300}{4,47} + 0,000\,3 = 0,005\,41 \tag{A.45}$$

where Y is expressed in kg/kg.

A.9.3 Steady state smoke control by a ceiling vent

The fire source is located in an enclosure shown in Figure A.4. The floor area, A, is 100 m² (10 m × 10 m). The enclosure height, H, is 8,0 m. The area of the ceiling vent, A_{top}, is 2,0 m². The area of the side vent for air intake, A_{side}, is 4,0 m². The heat release rate of the fire source, $\dot{Q}$, is 300 kW. The ratio of CO_2 yield to heat of combustion, $(\eta/\Delta H_c)$, is $(7,61\times10^{-5})$ kg/kJ. The fuel diameter, D, is 1,0 m. Reference temperature, T_0, is 20 °C (293 K). The enclosure boundary is made of concrete identical to that in the example of A.9.2.

The formulae for interface position and temperature are inter-related. These two formulae are solved by an iterative procedure. After getting solutions for interface position and temperature, mass fraction of CO_2 can be calculated in a straightforward way.

1) Assume the interface position, for example, by 50 % of total enclosure height, as shown in Formula (A.46):

$$z = \frac{H}{2} = \frac{8,0}{2} = 4,0 \tag{A.46}$$

where z is expressed in m.

2) Calculate the mass flow rate of plume at the interface position using Formula (A.47) [based on Formula (A.2)):

$$\dot{m}_p = 0,076\dot{Q}^{1/3}z^{5/3} = 0,076\times300^{1/3}\times4,0^{5/3} = 5,13 \tag{A.47}$$