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Fire safety engineering — Requirements governing algebraic equations — Smoke layers

Ingénierie de la sécurité incendie — Exigences régissant les équations algébriques — Couches de fumée

Reference number
ISO 16735:2006(E)

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Foreword

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

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

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

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

ISO 16735 was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

Introduction

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

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

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

The algebraic equations discussed in this International Standard are very useful for quantifying the consequences of design fire scenarios. Such equations are particularly valuable for allowing the practitioner to determine very quickly how a tentative fire safety design should be modified to meet agreed-upon performance criteria, without having to spend time on detailed numerical calculations until the stage of final design documentation. Examples of areas where algebraic equations have been applicable include determination of heat transfer – both convective and radiant – from fire plumes, prediction of ceiling jet flow properties governing detector response times, calculation of smoke transport through vent openings and analysis of compartment fire hazards such as smoke transport and flashover. With respect to smoke layers, algebraic equations are often used to estimate the time for smoke to fill a given fraction of a compartment, as well as the temperature and concentrations within the smoke layer.

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

INTERNATIONAL STANDARD **ISO 16735:2006(E)**

Fire safety engineering — Requirements governing algebraic equations — Smoke layers

1 Scope

1.1 The requirements given in this International Standard govern the application of algebraic equation sets to the calculation of specific characteristics of smoke layers generated by fires.

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

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

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

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

c) limitations of the calculation method;

d) input parameters for the calculation method;

e) domain of applicability of the calculation method.

1.4 Examples of sets of algebraic equations meeting all the requirements of this International Standard are provided in separate annexes for each different type of smoke layer scenario. Annex A contains general information and conservation requirements for smoke layers and Annex B contains specific algebraic equations for calculation of smoke layer characteristics.

2 Normative references

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

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

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

ISO 13943, *Fire safety — Vocabulary*

ISO 16734:2006, *Fire safety engineering — Requirements governing algebraic equations — Fire plumes*

ISO 16737, *Fire safety engineering — Requirements governing algebraic equations — Vent flows*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13943 shall apply. See Annex A for the terms and definitions specific to that Annex.

4 Requirements governing description of physical phenomena

4.1 The buoyant smoke layer resulting from a source fire in an enclosed space is a complex thermo-physical phenomenon that can be highly transient or nearly steady-state. Smoke layers may contain regions involved in flaming combustion and regions where there is no combustion taking place. In addition to buoyancy, smoke layers can be influenced by dynamic forces due to mechanical fans.

4.2 General types of source fires, enclosure boundary conditions and other scenario elements to which the analysis is applicable shall be described with the aid of diagrams.

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 concentration 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.

4.4 Physical phenomena (e.g., simple smoke filling, mechanical smoke exhaust, etc.) to which specific equations apply shall be clearly identified.

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

5 Requirements governing documentation

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

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

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

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

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

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

6 Requirements governing limitations

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

6.2 Cautions on the use of the algebraic-equation set within a more general calculation method shall be provided, which shall include checks of consistency with the other relations used in the calculation method and the numerical procedures used.

7 Requirements governing input parameters

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

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

7.3 The valid ranges for input parameters shall be listed (see ISO 13387-3).

8 Requirements governing domain of applicability

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

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

8.3 Potential sources of error that limit the set of algebraic equations to the specific scenarios given in Clause 4 shall be identified.

Annex A
(informative)

General aspect of smoke layers

A.1 Terms and definitions

The terms and definitions given in ISO 13943 and the following shall apply.

A.1.1
boundary
surface that defines the extent of an enclosure

A.1.2
enclosure
room, space or volume that is bounded by surfaces

A.1.3
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

A.1.4
flame
luminous region of fire plume associated with combustion

A.1.5
heat release rate
rate at which heat is being released by a source of combustion (such as the fire source)

A.1.6
interface position
elevation of the smoke layer interface relative to a reference elevation, typically the lowest boundary of the enclosure

NOTE Also referred to as the smoke layer height.

A.1.7
quasi-steady state
assumption that the full effects of heat release rate changes at the fire source are felt everywhere in the immediate flow field

A.1.8
smoke
airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass

A.1.9
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 Also referred to as the hot upper layer and the hot gas layer.

A.1.10
smoke layer interface
horizontal plane separating the smoke layer from the lower, smoke-free layer

A.1.11
vent
opening in an enclosure boundary through which air and smoke can flow as a result of naturally- or mechanically-induced forces

A.1.12
vent flow
flow of smoke or air through a vent in an enclosure boundary

A.2 Description of physical phenomena addressed by the equation set

A.2.1 General description of calculation method

This annex is intended to describe the methods that can be used to calculate interface positions, average temperatures and average concentrations of specific chemical species of smoke layers that form beneath boundaries during fires in enclosures. These calculation methods are based on the principles of mass, species and energy conservation as applied to the smoke layer as a thermodynamic control volume.

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 concentration. Based on the principles of mass, species and energy conservation applied to the smoke layer, average values of temperature, smoke concentration and interface positions are calculated. Descriptions of fire plumes and vent flows are given in ISO 16734 and ISO 16737, respectively.

A.2.2 Smoke layer characteristics to be calculated

Equations provide average smoke layer temperature, species concentration and interface position.

A.3 Equation-set documentation

A.3.1 General

As shown in Figure A.1, a smoke layer is generated over a fire source in an enclosure. The conservation of mass, heat and specific chemical species are given in A.3.2 to A.3.4.

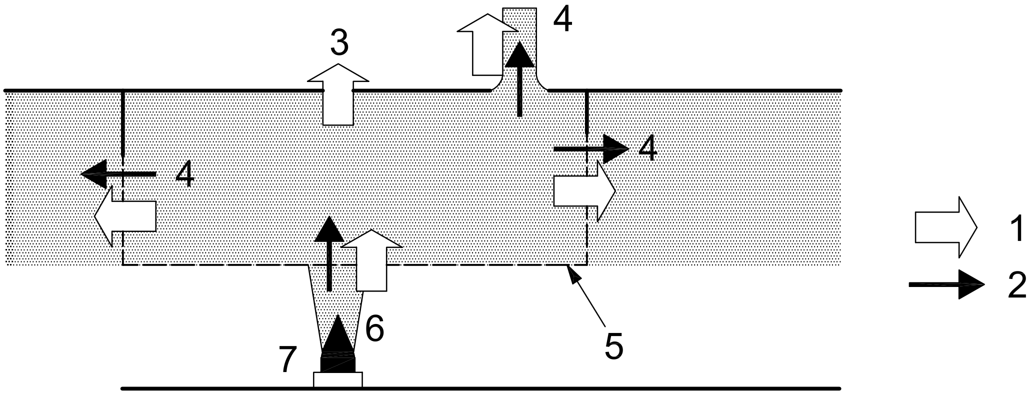
A.3.2 Mass conservation

Conservation of mass in the smoke layer shall be 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 shall be equal to the rate of mass accumulation of the smoke layer. Plume flow, vent flows and other flows shall be considered where necessary.

A.3.3 Energy conservation

Conservation of energy in the smoke layer shall be considered in a similar way to mass conservation. The energy flow rate incoming across the layer interface (negative for outgoing flow) shall be 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 shall be considered appropriately.

NOTE When it is difficult to determine the radiation heat loss from the flame, the energy flow rate can be approximated by heat release rate as will be applied in Annex B.



Key

1 heat flow
2 mass flow
3 wall heat absorption
4 vent flow
5 control volume
6 plume flow
7 fire source

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

A.3.4 Conservation of specific chemical species

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

A.3.5 Mass flow rate of fire plume across interface

The mass flow rate of the fire plume at the interface (bottom surface of smoke layer) shall be 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 layer interface. An example of a set of explicit equations for this plume characteristic is given by ISO 16734.

A.3.6 Mass flowrate of smoke through vent

The mass flowrate through a vent is given as a function of the temperature of the smoke layer and that of the adjacent compartment, pressure differences between the layer and the adjacent compartment, vent width and vent height. An example of a set of equations for this vent characteristic is given in ISO 16737.

A.3.7 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.

Annex B
(informative)

Specific equations for smoke layer meeting requirements of Annex A

B.1 Symbols and abbreviated terms used in Annex B

See Table B.1.

Table B.1

Symbol	Description	Unit
A	Floor area of enclosure	$\mathrm{m^2}$
A_{vent}	Area of opening for smoke exhaust	$\mathrm{m^2}$
A_{open}	Area of opening for intake of fresh air	$\mathrm{m^2}$
A_{wall}	Surface area of enclosure boundary in contact with smoke layer	$\mathrm{m^2}$
C_{D}	Flow coefficient	1
C_{v}	Volumetric heat capacity of enclosure boundary materials	$\mathrm{kJ{\cdot}m^{-3}{\cdot}K^{-1}}$
c_{p}	Specific heat of air at constant pressure (= 1,0)	$\mathrm{kJ{\cdot}kg^{-1}{\cdot}K^{-1}}$
D_{wall}	Thickness of enclosure boundary material	m
D	Diameter of fire source	m
g	Acceleration due to gravity	$\mathrm{m{\cdot}s^{-2}}$
h_{wall}	Effective heat transfer coefficient of enclosure boundary	$\mathrm{kW{\cdot}m^{-2}{\cdot}K^{-1}}$
H	Height of enclosure	m
H_{l}	Height of lower boundary of opening	m
H_{u}	Height of upper boundary of opening	m
k	Thermal conductivity of enclosure boundary materials	$\mathrm{kW{\cdot}m^{-1}{\cdot}K^{-1}}$
L	Mean flame height	m
$\dot{m}_{\mathrm{a}}$	Mass flow rate of air coming into enclosure	$\mathrm{kg{\cdot}s^{-1}}$
$\dot{m}_{\mathrm{e}}$	Mass flow rate of smoke exhaust	$\mathrm{kg{\cdot}s^{-1}}$
$\dot{m}_{p}$	Mass flow rate of gases in fire plume	$\mathrm{kg{\cdot}s^{-1}}$
Δp	Pressure difference	Pa
$\dot{Q}$	Heat release rate of fire source	kW
$\dot{Q}_{\mathrm{c}}$	Convective heat release rate of fire source, $(1-\chi)\dot{Q}$	kW
t	Time	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
$\dot{V}_{\mathrm{e}}$	Volumetric flow rate of mechanical exhaust system	$\mathrm{m^3{\cdot}s^{-1}}$
Y	Concentration of specific chemical species	$\mathrm{kg{\cdot}kg^{-1}}$

Table B.1 (*continued*)

Symbol	Description	Unit
Y_0	Concentration of specific chemical species at reference state	$\text{kg}\cdot\text{kg}^{-1}$
z	Interface height above base of fire source	m
α	Fire growth rate	$\text{kW}\cdot\text{s}^{-2}$
χ	Fraction of heat released that is emitted as thermal radiation	1
η	Species yield	kg/kJ
λ	Fraction of heat absorbed by enclosure boundary during smoke filling period	1
ρ_0	Air density at reference temperature	$\text{kg}\cdot\text{m}^{-3}$
ρ_s	Smoke density	$\text{kg}\cdot\text{m}^{-3}$

B.2 Description of physical phenomena addressed by the equation set

B.2.1 General

These calculation methods permit the calculation of average temperatures, smoke concentrations and interface positions that develop as a result of several fire scenarios. Other methods may be used to calculate these quantities, provided that such methods have been validated and verified for the range of conditions to which such methods are applied.

B.2.2 Scenario elements to which the equation-set is applicable

The equation set is applicable to smoke layers above fire sources in a quiescent environment. If flow-disturbance by non-fire related phenomena is significant, the equation set is not applicable. For example, the effect of airflow caused by 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 equation set is not applicable.

The fire source must 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 equations used to obtain plume characteristics).

Methods of calculating smoke layer conditions are developed for two limit stages. One limit stage is a simple enclosure smoke filling process during the initial stage of the fire (typically t^2-fires) when smoke control equipment 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.

B.2.3 Smoke layer characteristics to be calculated

Equations provide gas temperatures, species concentration and interface position.

B.2.4 Smoke layer conditions to which equations apply

Explicit equations are given for transient smoke filling process in an enclosure without smoke exhaust and quasi-steady state under mechanical or natural smoke exhaust.

B.2.5 Self-consistency of the equation set

The set of equations is developed to be self-consistent.

B.2.6 Standards and other documents where the equation set is used

None specified.

B.3 Equation-set documentation

B.3.1 Scope of equation sets

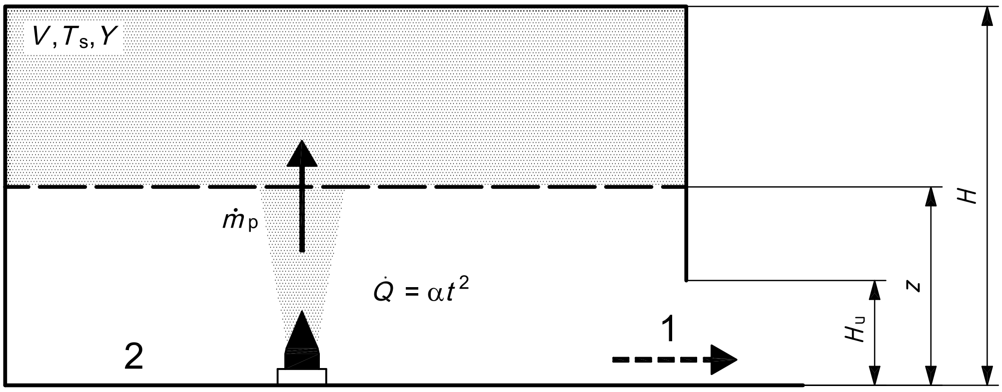
In this Annex, four different sets of equations are provided. One is for the smoke filling process in a single enclosure during the early stage of fire. The other three sets are for steady state smoke control by mechanical exhaust or by natural vents.

B.3.2 Enclosure smoke filling process

B.3.2.1 Process to which equation applies

Until the smoke layer interface moves down to the upper edge of a vertical opening, smoke is accumulated in the upper part of an enclosure as shown in Figure B.1. Due to thermal expansion, excess air is pushed out of the enclosure.

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



Key

1 excess air due to thermal expansion

2 floor area A

Figure B.1 — Mass conservation during enclosure smoke filling process

The equation set is constructed for the heat release rate given by

$$\dot{Q}(t) = \alpha t^n \tag{B.1}$$

where $n = 0$ represents a steady burning fire, $n = 2$ represents a growing fire in accordance with square of time.

A fraction of χ is released by radiation. Convective heat release rate is represented by

$$\dot{Q}_c = (1-\chi)\dot{Q} = (1-\chi)\alpha t^n \tag{B.2}$$

Mass flow rate of plume at a height z above the fire source is given in bibliographic reference [1].

$$\dot{m}_{\mathrm{p}} = 0{,}076(1-\chi)^{1/3}\dot{Q}^{1/3}z^{5/3} \tag{B.3}$$

NOTE This equation can be interpreted as an approximation of the plume equation in Annex A of ISO 16734. This equation is valid only above the mean flame height. If the resulting interface position is below the mean flame height, calculation results might be inaccurate.

B.3.2.2 Interface position

Interface position is calculated so that plume mass flow accumulates in the upper layer of uniform density.

$$z(t) = \left(\frac{0{,}076}{\rho_{\mathrm{s}}} \frac{(1-\chi)^{1/3}\alpha^{1/3}}{A} \frac{2}{n+3} t^{(1+\frac{n}{3})} + \frac{1}{H^{2/3}} \right)^{-3/2} \tag{B.4}$$

NOTE To calculate interface position, smoke density must be assumed. For practical applications, ρ_{s} = 1,0 gives conservative results for initial smoke filling process in large volume enclosures (see bibliographic reference [2]). During the latter stage of smoke filling, thermal expansion is significant. In this case, the following equation, from [3] and [4], is applicable for t^2-fires (i.e., $Q = \alpha t^2$):

$$z(X) = H\left(1 - \frac{\Lambda X^{9/5}}{1 - T_{\mathrm{s}}/T_0}\right) \tag{B.5}$$

where

$$X = 0{,}026\,8 \frac{H^{2/3}}{A} \alpha^{1/3} (1-\chi)^{1/3} t^{5/3} \tag{B.6}$$

$$\Lambda = 0{,}754 \frac{A^{4/5}}{H^{11/5}} \frac{(1-\lambda)\alpha^{2/5}}{(1-\chi)^{3/5}} \tag{B.7}$$

Smoke layer temperature, T_{s}, is calculated from (B.9) in the next section.

B.3.2.3 Smoke layer temperature

Smoke layer temperature is calculated so that heat released by fire is used to heat up a smoke layer of volume, $A(H-z)$. Heat absorption by enclosure boundary is neglected.

$$T_{\mathrm{s}}(t) = \frac{(1-\lambda)}{c_{\mathrm{p}}\rho_{\mathrm{s}}A(H-z)} \frac{\alpha t^{n+1}}{n+1} + T_0 \tag{B.8}$$

NOTE 1 The symbol λ is the fraction of heat absorption by enclosure boundary. Unless calculation of thermal radiation exchange between plume, smoke layer and enclosures is coupled, it is recommended to assume that λ = 0, which means that all the heat is used to heat up the smoke layer.

NOTE 2 For practical applications, ρ_{s} = 1,0 gives acceptable results for initial smoke filling of large volume enclosures.

NOTE 3 During the latter stage, when thermal expansion of smoke layer is significant, smoke layer temperature for t^2-fires is calculated from the following equation:

$$T_{\mathrm{s}}(X) = T_0 \exp\left(-\frac{\Lambda X^{9/5}}{1-(1+X)^{-3/2}} \right) \tag{B.9}$$

where Λ and X are calculated from Equations (B.6) and (B.7).

B.3.2.4 Concentration of specific chemical species

Concentration of specific chemical species is calculated so that generated mass is distributed in the smoke layer uniformly.

$$Y(t) = \frac{\eta}{\rho_{\mathrm{s}} A(H-z)} \frac{\alpha t^{n+1}}{n+1} + Y_0 \tag{B.10}$$

B.3.2.5 Calculation example

- A fire source $\dot{Q} = 0{,}05t^2$ (α = 0,05 kW/s^2, n = 2, D = 1m) is located in an enclosure shown in Figure B.1.
- Floor area of enclosure, A, is 100 m^2.
- Enclosure height, H, is 8 m. Doorway opening height, H_{u}, is 2 m.
- It is assumed that radiative fraction of heat release, χ, is 0,333.
- Heat absorption by enclosure boundary is neglected (λ = 0).
- CO$_2$ yield, η, is 7,61 × 10^{-5} kg/kJ.
- Interface height, temperature and CO$_2$ concentration at 60 s are calculated.

Using Equation (B.4), interface height is

$$z = \left(\frac{0{,}076}{\rho_{\mathrm{s}}} \frac{(1-\chi)^{1/3} \alpha^{1/3}}{A} \frac{2}{n+3} t^{\left(1+\frac{n}{3}\right)} + \frac{1}{H^{2/3}} \right)^{-3/2}$$

$$= \left(\frac{0{,}076}{1{,}0} \frac{(1-0{,}333)^{1/3} \times 0{,}05^{1/3}}{100} \frac{2}{2+3} 60^{\left(1+\frac{2}{3}\right)} + \frac{1}{8^{2/3}} \right)^{-3/2} = 5{,}04 \tag{B.11}$$

Using this result in Equations (B.8) and (B.10), smoke layer temperature and CO$_2$ concentration are

$$T_{\mathrm{s}} = \frac{(1-\lambda)}{c_{\mathrm{p}} \rho_{\mathrm{s}} A(H-z)} \frac{\alpha t^{n+1}}{n+1} + T_0 = \frac{(1-0{,}0)}{1{,}0 \times 1{,}0 \times 100 \times (8-5{,}04)} \frac{0{,}05 \times 60^{2+1}}{2+1} + 20 = 32{,}2 \tag{B.12}$$

$$Y = \frac{\eta}{\rho_{\mathrm{s}} A(H-z)} \frac{\alpha t^{n+1}}{n+1} + Y_0 = \frac{7{,}61 \times 10^{-5}}{1{,}0 \times 100 \times (8-5{,}04)} \frac{0{,}05 \times 60^{2+1}}{2+1} + 0{,}000\ 3 = 0{,}001\ 23 \tag{B.13}$$

To make use of the plume Equation (B.3), the flame height must be below the interface height. In this particular case, mean flame height is well below the interface height, since

$$L = -1{,}02D + 0{,}235\dot{Q}^{2/5} = -1{,}02 \times 1{,}0 + 0{,}235 \times (0{,}05 \times 60^2)^{2/5} = 0{,}86 \tag{B.14}$$

which was calculated according to Annex A of ISO 16734:2006.

In a similar manner, smoke layer height, temperature and CO_2 concentrations are calculated as shown in Figure B.2. For the equation set to be valid, the bottom of the smoke layer 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 126 s as

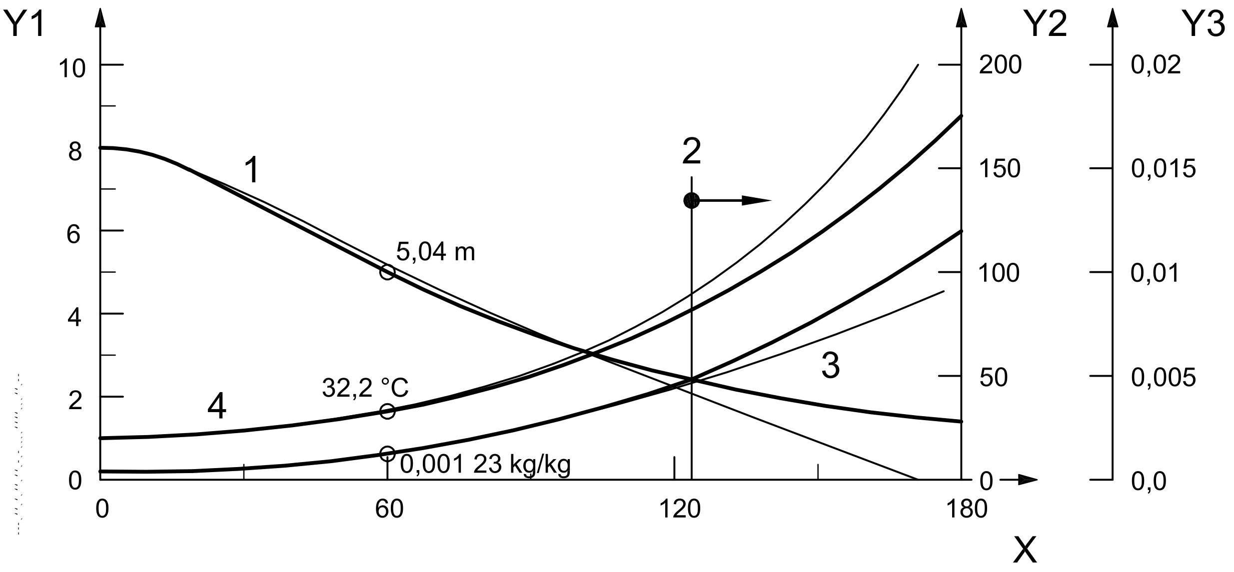
$$z = \left(\frac{0{,}076}{1{,}0} \frac{(1-0{,}333)^{1/3} \times 0{,}05^{1/3}}{100} \frac{2}{2+3} 126^{\left(1+\frac{2}{3}\right)} + \frac{1}{8^{2/3}} \right)^{-3/2} = 2{,}39 \qquad \text{(B.15)}$$

$$L = -1{,}02D + 0{,}235\dot{Q}^{2/5} = -1{,}02 \times 1{,}0 + 0{,}235 \times (0{,}05 \times 126^2)^{2/5} = 2{,}38 \qquad \text{(B.16)}$$

At 142 seconds, smoke layer height almost coincides with the top of the doorway opening, as

$$z = \left(\frac{0{,}076}{1{,}0} \frac{(1-0{,}333)^{1/3} \times 0{,}05^{1/3}}{100} \frac{2}{2+3} 142^{\left(1+\frac{2}{3}\right)} + \frac{1}{8^{2/3}} \right)^{-3/2} = 2{,}01 \qquad \text{(B.17)}$$

Thus the use of this equation set is limited to the period prior to 126 s.



Key

X time (min)
Y1 interface height (m)
Y2 smoke layer temperature (°C)
Y3 CO_2 concentration (kg/kg)

1 interface height
2 out-of-valid range ($t > 126$ s)
3 CO_2 concentration
4 smoke layer temperature 32,2 °C

Figure B.2 — Calculation results of interface position, smoke layer temperature and CO_2 concentration during smoke filling process in an enclosure

The calculations in Figure B.2 are valid for A = 100 m^2, H = 8 m, $\dot{Q} = 0{,}05t^2$, χ = 0,333, λ = 0,0. Bold lines were calculated from Equations (B.4), (B.8) and (B.10). Thin lines were calculated from Equations (B.5), (B.9) and (B.11) considering thermal expansion of the smoke layer.

B.3.3 Steady state smoke control by mechanical exhaust system

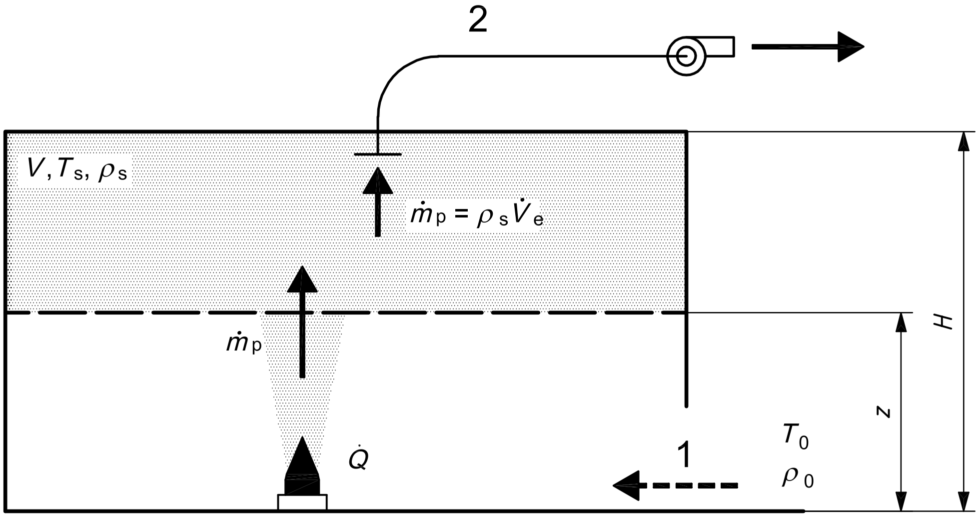
B.3.3.1 Process to which equation applies

During the smoke control stage, smoke is exhausted by a mechanical exhaust system, as shown in Figure B.3. Smoke layer properties are calculated by quasi-steady state balance of generation and exhaust rates. It is assumed that enclosure boundaries have enough openings in the lower part so that air can flow in easily. In this equation set, heat release rate is assumed constant. Mass flow rate of fire plume is given by Equation (B.3). Given a volumetric flow rate as a trial design parameter, mass exhaust rate is calculated by

$$\dot{m}_\mathrm{e} = \rho_\mathrm{s} \dot{V}_\mathrm{e} \, . \qquad \text{(B.18)}$$

Interface height is calculated so that mass exhaust rate is equal to plume mass flow rate.

$$\dot{m}_\mathrm{e} = \dot{m}_\mathrm{p} \qquad \text{(B.19)}$$



Key

1 induced air

2 exhaust system

Figure B.3 — Conservation of mass during smoke control by mechanical exhaust system

B.3.3.2 Interface position

Interface position is calculated so that plume mass flow rate equals the mass exhaust rate.

$$z = \left(\frac{\dot{m}_\mathrm{e}}{0{,}076 \dot{Q}^{1/3}} \right)^{3/5} \qquad \text{(B.20)}$$

NOTE To calculate interface position, smoke layer density (i.e, temperature) must be known. It can be guessed conservatively or calculated by combining the following equations as will be shown in an example in this section.

B.3.3.3 Smoke layer density

Smoke layer density is calculated by equation of state:

$$\rho_s = \frac{353}{T_s} \tag{B.21}$$

NOTE For most of engineering calculations, smoke layer is often approximated by perfect gas. Smoke layer temperature is calculated by the equation in the next section.

B.3.3.4 Smoke layer temperature

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 surfaces.

$$T_s = \frac{\dot{Q}}{c_p m_p + h_{wall} A_{wall}} + T_0 \tag{B.22}$$

B.3.3.5 Effective heat transfer coefficient

An 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).

$$h_{wall} = \begin{cases} \dfrac{\sqrt{\pi}}{2}\sqrt{\dfrac{kC_v}{t_c}} & (D_{wall} \geqslant 4\sqrt{\dfrac{kt_c}{C_v}}) \\ \dfrac{k}{D_{wall}} & (D_{wall} \leqslant 4\sqrt{\dfrac{kt_c}{C_v}}) \end{cases} \tag{B.23}$$

NOTE Characteristic time t_c is often taken as 1 000 s.

B.3.3.6 Concentration of specific chemical species

Concentration of specific chemical species is calculated so that the rate of generation equals the rate of exhaust.

$$Y = \frac{\eta \dot{Q}}{\dot{m}_e} + Y_0 \tag{B.24}$$

B.3.3.7 Calculation example

A fire source is located at the centre of an enclosure in Figure B.3.

- The floor area of the enclosure, A, is 100 m^2 (10 m × 10 m).
- Enclosure height, H, is 8 m. Heat release rate of the fire source, $\dot{Q}$, is 300 kW.
- Radiative fraction of fire source, χ, is 0,333.
- Fire source diameter, D, is 1,0 m.
- The mechanical exhaust rate, V_e, is 4 m^3/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, C_v = 2 026 kJ/m^3·K.

— Reference temperature, T_0, is 20 °C (293 K) which corresponds to 1,205 kg/m^3 of reference density, ρ_0.

The equation set for interface position and temperature are inter-related. These equations are solved by iteration. After getting solutions for interface position and temperature, species concentration is calculated in a straightforward way.

1) Assume interface height, as 50 % of total enclosure height, as follows:

$$z = \frac{H}{2} = 4{,}0 \qquad \text{(B.25)}$$

2) Calculate mass flow rate of the plume at the interface height from Equation (B.3):

$$\dot{m}_\text{p} = 0{,}076(1-\chi)^{1/3}\dot{Q}^{1/3}z^{5/3} = 0{,}076\times(1-0{,}333)^{1/3}\times 300^{1/3}\times 4^{5/3} = 4{,}48 \qquad \text{(B.26)}$$

3) Calculate effective heat transfer coefficient from Equation (B.23):

The enclosure boundary is assumed to have thermally thick behaviour, as follows:

$$4\sqrt{\frac{k}{C_\text{v}}t_\text{c}} = 4\sqrt{\frac{0{,}001\,5}{2\,026}\times 1\,000} = 0{,}108 \geqslant 0{,}1\,(\text{m}) \qquad \text{(B.27)}$$

Thus the effective heat transfer coefficient is

$$h_\text{wall} = \frac{\sqrt{\pi}}{2}\sqrt{\frac{kC_\text{v}}{t_\text{c}}} = \frac{\sqrt{3{,}14}}{2}\times\sqrt{\frac{0{,}001\,5\times 2\,026}{1\,000}} = 0{,}049 \qquad \text{(B.28)}$$

4) Calculate smoke layer temperature from Equation (B.22):

$$A_\text{wall} = 100 + 40\times(8-4) = 260 \qquad \text{(B.29)}$$

$$T_\text{s} = \frac{\dot{Q}}{c_\text{p}m_\text{p} + h_\text{wall}A_\text{wall}} + T_0 = \frac{300}{(1{,}0\times 4{,}48)+(0{,}049\times 260)} + 20 = 37{,}4 \qquad \text{(B.30)}$$

5) Calculate smoke density from Equation (B.21):

$$\rho_\text{s} = \frac{353}{T_\text{s}} = \frac{353}{37{,}4+273} = 1{,}137 \qquad \text{(B.31)}$$

6) Calculate mass flow rate by mechanical exhaust system from Equation (B.18):

$$\dot{m}_\text{e} = \rho_\text{s}\dot{V}_\text{e} = 1{,}137\times 4{,}0 = 4{,}55 \qquad \text{(B.32)}$$

7) Correct interface height so that plume mass flow rate equals the mass exhaust rate from Equation (B.20):

$$z = \left(\frac{\dot{m}_\text{e}}{0{,}076(1-\chi)^{1/3}\dot{Q}^{1/3}}\right)^{3/5} = \left(\frac{4{,}55}{0{,}076\times(1-0{,}333)^{1/3}\times 300^{1/3}}\right)^{3/5} = 4{,}04 \qquad \text{(B.33)}$$

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

In this particular example, three iterations are sufficient to obtain the solution given below,

z = 4,04 m, T_s = 37,4 °C, $\dot{m}_\text{p} = \dot{m}_\text{e} =$ 4,55 kg/s (B.34),(B.35),(B.36)

9) To make use of the plume Equation (B.3), mean flame height must be smaller than the interface height. In this particular case, the condition is satisfied, since:

$$L = -1{,}02D + 0{,}235\dot{Q}^{2/5} = -1{,}02 \times 1{,}0 + 0{,}235 \times 300^{2/5} = 1{,}28 < 4{,}04 \qquad \text{(B.37)}$$

which was calculated according to Annex A of ISO 16734:2006.

10) Calculate species concentration using the values obtained Equation (B.24). For wood fuels under well-ventilated conditions, carbon dioxide yield is $\eta = 7{,}61 \times 10^{-5}$ kg/kJ:

$$Y = \frac{\eta\dot{Q}}{\dot{m}_\mathrm{e}} + Y_0 = \frac{(7{,}61 \times 10^{-5}) \times 300}{4{,}55} + 0{,}000\,3 = 0{,}005\,32 \qquad \text{(B.38)}$$

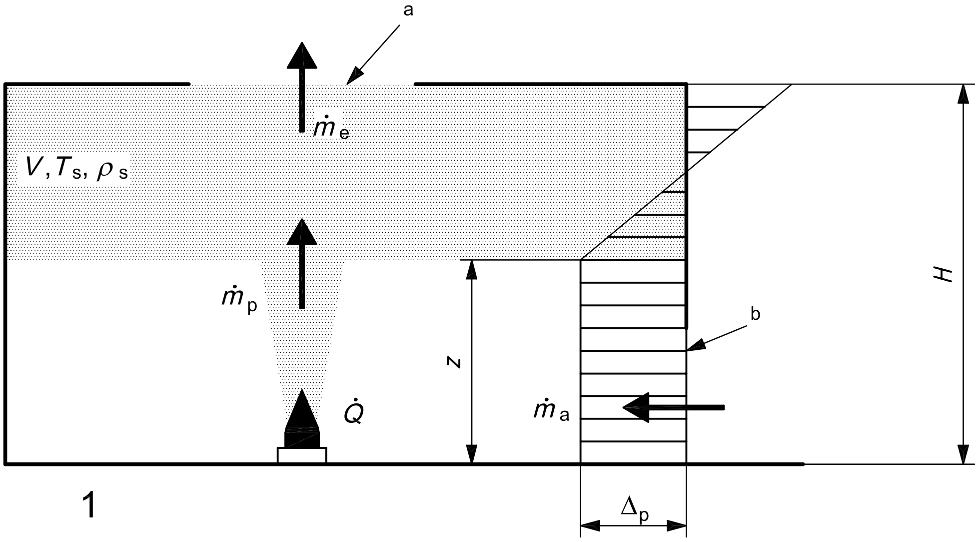
B.3.4 Steady state smoke control by horizontal vent

B.3.4.1 Process to which equation applies

Smoke is exhausted by natural venting as shown in Figure B.4. It is assumed that fresh air can flow into the lower part of the enclosure. The smoke layer properties are calculated by quasi-steady state balance of heat and mass. The balance of mass flow rates is given by:

$$\dot{m}_\mathrm{a} = \dot{m}_\mathrm{p} = \dot{m}_\mathrm{e} \qquad \text{(B.39)}$$

In this equation set, heat release rate is assumed constant over time. Plume mass flow rate is given by Equation (B.3). Mass flow rate through a vent is calculated in accordance with ISO 16737.



Key

1 floor area A

a A_vent

b A_open

Figure B.4 — Conservation of mass during smoke control by horizontal vent

B.3.4.2 Interface position

Use Equation (B.20) to calculate interface position.

NOTE Mass exhaust rate is calculated from Equation (B.40).

B.3.4.3 Smoke layer density

Use Equation (B.21) to calculate smoke layer density.

B.3.4.4 Smoke layer temperature

Use Equation (B.22) to calculate smoke layer temperature.

B.3.4.5 Effective heat transfer coefficient

Use Equation (B.23) to calculate effective heat transfer coefficient.

B.3.4.6 Mass flow rate of smoke exhaust by horizontal vent

Mass flow rate of smoke exhaust is calculated by conventional equation for flow through openings.

$$\dot{m}_{\mathrm{e}} = C_{\mathrm{D}} A_{\mathrm{vent}} \sqrt{2\rho_{\mathrm{s}} \left[(\rho_0 - \rho_{\mathrm{s}}) g (H - z) - \Delta p \right]} \qquad \text{(B.40)}$$

B.3.4.7 Pressure difference at floor level

Pressure difference at floor level is calculated by the conventional equation for flow through openings applied to a lower opening.

$$\Delta p = \frac{1}{2\rho_0} \left(\frac{\dot{m}_{\mathrm{p}}}{C_{\mathrm{D}} A_{\mathrm{open}}} \right)^2 \qquad \text{(B.41)}$$

B.3.4.8 Concentration of specific chemical species

Use Equation (B.24) to calculate concentration of specific chemical species, Y.

B.3.4.9 Calculation example

The fire source is located in an enclosure in Figure B.4.

- Floor area, A, is 100 m^2 (10 m × 10 m). Enclosure height, H, is 8 m.
- The area of the horizontal vent, A_{vent}, is 2 m^2.
- The lower opening for air intake, A_{open}, is 4 m^2.
- Heat release rate of the fire source, $\dot{Q}$, is 300 kW.
- Radiative fraction, χ, is 0,333.
- CO_2 yield, η, is $7{,}51 \times 10^{-5}$ kg/kJ.
- Fire source diameter, D, is 1,0 m.
- Reference temperature, T_0, is 20 °C (293 K).

The enclosure boundary is made of concrete identical with that in the example of B.3.3.7.

The equations for interface position and temperature are inter-related. These two equations are solved by an iterative process. After obtaining solutions for interface position and temperature, species concentration can be calculated in a straightforward way.

1) Assume interface height is 50 % of total enclosure height, as follows:

$$z = \frac{H}{2} = \frac{8{,}0}{2} = 4{,}0 \tag{B.42}$$

2) Calculate mass flow rate of plume at the interface height from Equation (B.3):

$$\dot{m}_\mathrm{p} = 0{,}076(1-\chi)^{1/3}\dot{Q}^{1/3}z^{5/3} = 0{,}076 \times (1-0{,}333)^{1/3} \times 300^{1/3} \times 4{,}0^{5/3} = 4{,}48 \tag{B.43}$$

3) Calculate effective heat transfer coefficient from Equation (B.23).

By the same procedure as in 3) of B.3.3.7

$$h_\mathrm{wall} = 0{,}049 \tag{B.44}$$

4) Calculate smoke layer temperature from Equation (B.22):

$$A_\mathrm{wall} = 100 + \left[40 \times (8-4{,}0)\right] - 2{,}0 = 258 \tag{B.45}$$

$$T_\mathrm{s} = \frac{\dot{Q}}{c_\mathrm{p}m_\mathrm{p} + h_\mathrm{wall}A_\mathrm{wall}} + T_0 = \frac{300}{(1\times 4{,}48)+(0{,}049\times 258)} + 20 = 37{,}5 \tag{B.46}$$

5) Calculate smoke density from Equation (B.21):

$$\rho_\mathrm{s} = \frac{353}{T_\mathrm{s}} = \frac{353}{37{,}5+273} = 1{,}137 \tag{B.47}$$

6) Calculate pressure difference at reference height from Equation (B.41):

$$\Delta p = \frac{1}{2\rho_0}\left(\frac{m_\mathrm{p}}{C_\mathrm{D}A_\mathrm{open}}\right)^2 = \frac{1}{2\times 1{,}205} \times \left(\frac{4{,}48}{0{,}7\times 4{,}0}\right)^2 = 1{,}06 \tag{B.48}$$

7) Calculate mass flow rate through a horizontal vent from Equation (B.40):

$$\dot{m}_\mathrm{e} = C_\mathrm{D}A_\mathrm{vent}\sqrt{2\rho_\mathrm{s}\left[(\rho_0-\rho_\mathrm{s})g(H-z)-\Delta p\right]}$$

$$= 0{,}7\times 2{,}0\times\sqrt{2\times 1{,}137\times\left[(1{,}205-1{,}137)\times 9{,}8\times(8{,}0-4{,}0)-1{,}06\right]} = 2{,}68 \tag{B.49}$$

8) Correct interface height so that plume mass flow rate balances mass exhaust rate from Equation (B.20):

$$z = \left(\frac{\frac{\dot{m}_e+\dot{m}_p}{2}}{0{,}076(1-\chi)^{1/3}\dot{Q}^{1/3}}\right)^{3/5} = \left(\frac{\frac{2{,}68+4{,}48}{2}}{0{,}076\times(1-0{,}333)^{1/3}\times 300^{1/3}}\right)^{3/5} = 3{,}50 \tag{B.50}$$

NOTE For numerical stability, mass exhaust rate, $\dot{m}_\text{e}$, in Equation (B.20) is replaced by $(\dot{m}_\text{e} + \dot{m}_\text{p})/2$ during the iterative calculation. After convergence, mass balance $\dot{m}_\text{e} = \dot{m}_\text{p}$ holds. The final result is unaffected by this alteration.

9) Repeat procedures 2) to 8) until plume mass flow rate and mass exhaust rate are equal, $\dot{m}_\text{p} = \dot{m}_\text{e}$.

In this particular example, four iterations are sufficient to obtain the solution given below:

$$z = 3{,}35\ \text{m},\ T_\text{s} = 37{,}4\ °\text{C},\ \dot{m}_\text{e} = \dot{m}_\text{p} = 3{,}34\ \text{kg/s} \qquad \text{(B.51),(B.52),(B.53)}$$

10) To make use of the plume Equation (B.3), the flame height must be below the interface height. In this particular case, mean flame height is 1,28 m as in 9) of section B.3.3.7.

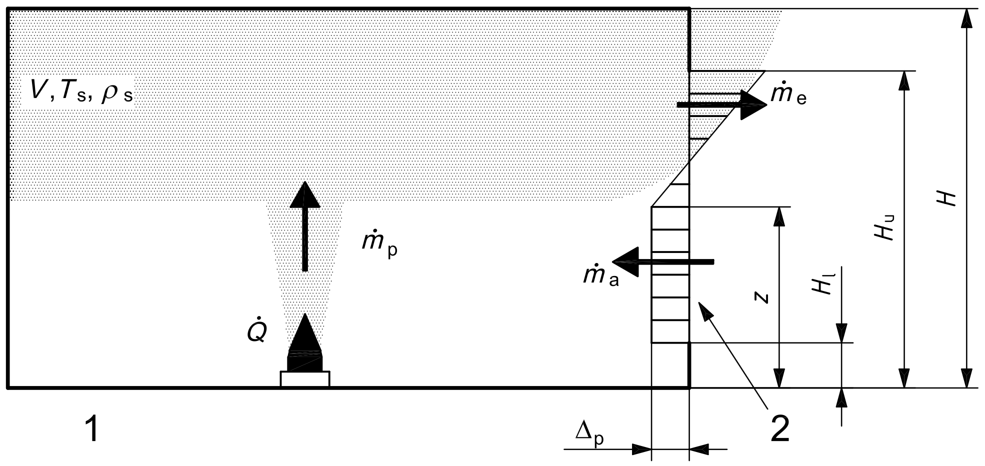
11) Calculate species concentration using the values obtained in 7) above from Equation (B.24):

$$Y = \frac{\eta \dot{Q}}{\dot{m}_\text{e}} + Y_0 = \frac{(7{,}61 \times 10^{-5}) \times 300}{3{,}34} + 0{,}000\ 3 = 0{,}007\ 16 \qquad \text{(B.54)}$$

B.3.5 Steady state smoke control by vertical vent

B.3.5.1 Process to which equation applies

During the smoke control stage, smoke is exhausted by a vertical vent as shown in Figure B.5. It is assumed that fresh air flows into the lower part of the vent, while smoke flows out from the upper part of the vent. The smoke layer properties are calculated by quasi-steady state balance of smoke/heat generation and exhaust/outflow rates. In this equation set, heat release rate is assumed constant over time. Plume mass flow rate is given by Equation (B.3). Mass flow rate through a vent is calculated in accordance with ISO 16737.



Key

1 floor area A

2 opening width B

Figure B.5 — Conservation of mass during smoke control by vertical vent

B.3.5.2 Interface position

Use Equation (B.20) to calculate interface position.

NOTE In this equation set, interface position is calculated implicitly so that steady state mass balance $\dot{m}_\text{p} = \dot{m}_\text{a} = \dot{m}_\text{e}$ is satisfied. See example in this section for details.

B.3.5.3 Smoke layer density

Use Equation (B.21) to calculate smoke layer density.

B.3.5.4 Smoke layer temperature

Use Equation (B.22) to calculate smoke layer temperature.

B.3.5.5 Effective heat transfer coefficient

Use Equation (B.23) to calculate effective heat transfer coefficient.

B.3.5.6 Pressure difference at lower level of opening

Pressure difference at lower level of opening is calculated so that the mass exhaust rate, $\dot{m}_\mathrm{e}$, equals the mass flow rate of plume, $\dot{m}_\mathrm{p}$.

$$\Delta P = (\rho_0 - \rho_\mathrm{s})g(H_\mathrm{u} - z) - \left(\frac{3}{2} \frac{(\rho_0 - \rho_\mathrm{s})g}{C_\mathrm{D} B \sqrt{2\rho_\mathrm{s}}} \dot{m}_\mathrm{p} \right)^{2/3} \tag{B.55}$$

B.3.5.7 Mass flow rate of air through lower part of opening

Mass flow rate of air through the lower part of the opening is calculated using the pressure difference calculated from Equation (B.55).

$$\dot{m}_a = C_D B(z - H_l)\sqrt{2\rho_0 \Delta p} + \frac{2}{3} C_D B \sqrt{2\rho_0(\rho_0 - \rho_s)g} \left(\frac{\Delta p}{(\rho_0 - \rho_s)g} \right)^{3/2} \tag{B.56}$$

B.3.5.8 Concentration of specific chemical species

Use Equation (B.24) to calculate concentration of specific chemical species.

B.3.5.9 Calculation procedure and example

As in Figure B.5, the fire is located in an enclosure with a vertical vent.

- Floor area, A, is 100 m^2.
- Height of the vertical vent is 5 m, located 1 m above the floor (H_l = 1 m, H_u = 6 m).
- Vent width, B, is 4 m.
- Heat release rate of the fire source, $\dot{Q}$, is 300 kW.
- Radiative fraction, χ, is 0,333.
- CO$_2$ yield, η, is 7,51 × 10^{-5} kg/kJ.
- Fire source diameter, D, is 1,0 m.

The enclosure boundary is made of concrete identical with that in the example in section B.3.3.7.

The equations for interface position and temperature are inter-related. This equation set is solved by an iterative process. After obtaining solutions for interface position and temperature, species concentration can be calculated in a straightforward way.

1) Assume a lower bound of interface height, z_1, to be 1/3 of the opening height:

$$z_1 = H_\text{l} + \frac{H_\text{u} - H_\text{l}}{3} = 1{,}0 + \frac{6{,}0 - 1{,}0}{3} = 2{,}67 \tag{B.57}$$

2) Calculate the mass flow rate of the plume at the interface height from Equation (B.3):

$$\dot{m}_\text{p} = 0{,}076(1-\chi)^{1/3}\dot{Q}^{1/3}z_1^{5/3} = 0{,}076 \times (1-0{,}333)^{1/3} \times 300^{1/3} \times 2{,}67^{5/3} = 2{,}28 \tag{B.58}$$

3) Calculate an effective heat transfer coefficient from Equation (B.23) by the same procedure as in 3) of B.3.3.7:

$$h_\text{wall} = 0{,}049 \tag{B.59}$$

4) Calculate smoke layer temperature from Equation (B.22):

$$A_\text{wall} = 100 + 40 \times (8 - 2{,}67) - 4 \times (6 - 2{,}67) = 300$$

$$T_\text{s} = \frac{\dot{Q}}{c_\text{p}m_\text{p} + h_\text{wall}A_\text{wall}} + T_0 = \frac{300}{1{,}0 \times 2{,}28 + 0{,}049 \times 300} + 20 = 37{,}7 \tag{B.60}$$

5) Calculate smoke density from Equation (B.21):

$$\rho_\text{s} = \frac{353}{T_\text{s}} = \frac{353}{37{,}7 + 273} = 1{,}136 \tag{B.61}$$

6) Calculate the pressure difference at the lower level of the opening from Equation (B.55):

$$\Delta P = (\rho_\text{a} - \rho_\text{s})g(H_\text{u} - z_1) - \left[\frac{3}{2}\frac{(\rho_\text{a} - \rho_\text{s})g}{C_\text{D}B\sqrt{2\rho_\text{s}}}\dot{m}_\text{p}\right]^{2/3}$$

$$= (1{,}205 - 1{,}136) \times 9{,}8 \times (6{,}0 - 2{,}67) - \left[\frac{3}{2}\frac{(1{,}205 - 1{,}136) \times 9{,}8}{0{,}7 \times 4{,}0 \times \sqrt{2 \times 1{,}136}} \times 2{,}28\right]^{2/3} = 1{,}58 \tag{B.62}$$

7) Calculate mass flow rate of air through the lower part of the opening from Equation (B.56):

$$\dot{m}_\text{a} = C_\text{D}B(z_1 - H_\text{l})\sqrt{2\rho_\text{a}\Delta p} + \frac{2}{3}C_\text{D}B\sqrt{2\rho_\text{a}(\rho_\text{a} - \rho_\text{s})g}\left[\frac{\Delta p}{(\rho_\text{a} - \rho_\text{s})g}\right]^{3/2}$$

$$= 0{,}7 \times 4{,}0 \times (2{,}67 - 1{,}0) \times \sqrt{2 \times 1{,}205 \times 1{,}58}$$

$$+ \frac{2}{3} \times 0{,}7 \times 4{,}0\sqrt{2 \times 1{,}205 \times (1{,}205 - 1{,}136) \times 9{,}8} \times \left[\frac{1{,}58}{(1{,}205 - 1{,}136) \times 9{,}8}\right]^{3/2}$$

$$= 17{,}6 \tag{B.63}$$

8) Calculate error in mass flow rate:

$$\dot{m}_{\text{error},1} = \dot{m}_\text{p} - \dot{m}_\text{a} = 2{,}28 - 17{,}6 = -15{,}3$$

9) Plume mass flow rate should balance with the mass flow rate of air. To find the correct solution, procedures 2) to 8) are repeated for upper bound of interface height z_2. For the first estimate, upper bound of interface height is taken by 2/3 of opening height as:

$$z_2 = H_\text{l} + \frac{2}{3}(H_\text{u} - H_\text{l}) = 1{,}0 + \frac{2}{3}(6{,}0 - 1{,}0) = 4{,}33 \qquad \text{(B.64)}$$

For this interface height, the following values are calculated:

$$\dot{m}_\text{p} = 5{,}13 \text{ kg/s}, \; T_\text{s} = 37{,}8 \text{ °C}, \; \rho_\text{s} = 1{,}136 \text{ kg/m}^3, \; \Delta P = -0{,}022 \text{ Pa} \qquad \text{(B.65),(B.66),(B.67),(B.68)}$$

As the assumed interface position is too high, the pressure difference is given by a negative value. For this situation, no air enters into the enclosure:

$$\dot{m}_\text{a} = 0{,}0. \qquad \text{(B.69)}$$

NOTE This situation is not physical with respect to a steady state mass balance for the enclosure. During the iteration process, when there is a negative pressure difference, $\dot{m}_\text{a}$ is set equal to zero. For the final solution, the mass balance is satisfied.

The error in mass flow rate is

$$\dot{m}_{\text{error},2} = \dot{m}_\text{p} - \dot{m}_\text{a} = 5{,}3 - 0{,}0 = 5{,}13 \qquad \text{(B.70)}$$

10) Interpolate between the two calculations to get a new estimate of interface height as:

$$z_3 = z_1 - \frac{\dot{m}_{\text{error},1}}{\dot{m}_{\text{error},2} - \dot{m}_{\text{error},1}}(z_2 - z_1) = 2{,}67 - \frac{-15{,}3}{5{,}13 - (-15{,}3)} \times (4{,}33 - 2{,}67) = 3{,}92 \qquad \text{(B.71)}$$

NOTE This procedure is shown in Figure B.6 by broken lines.

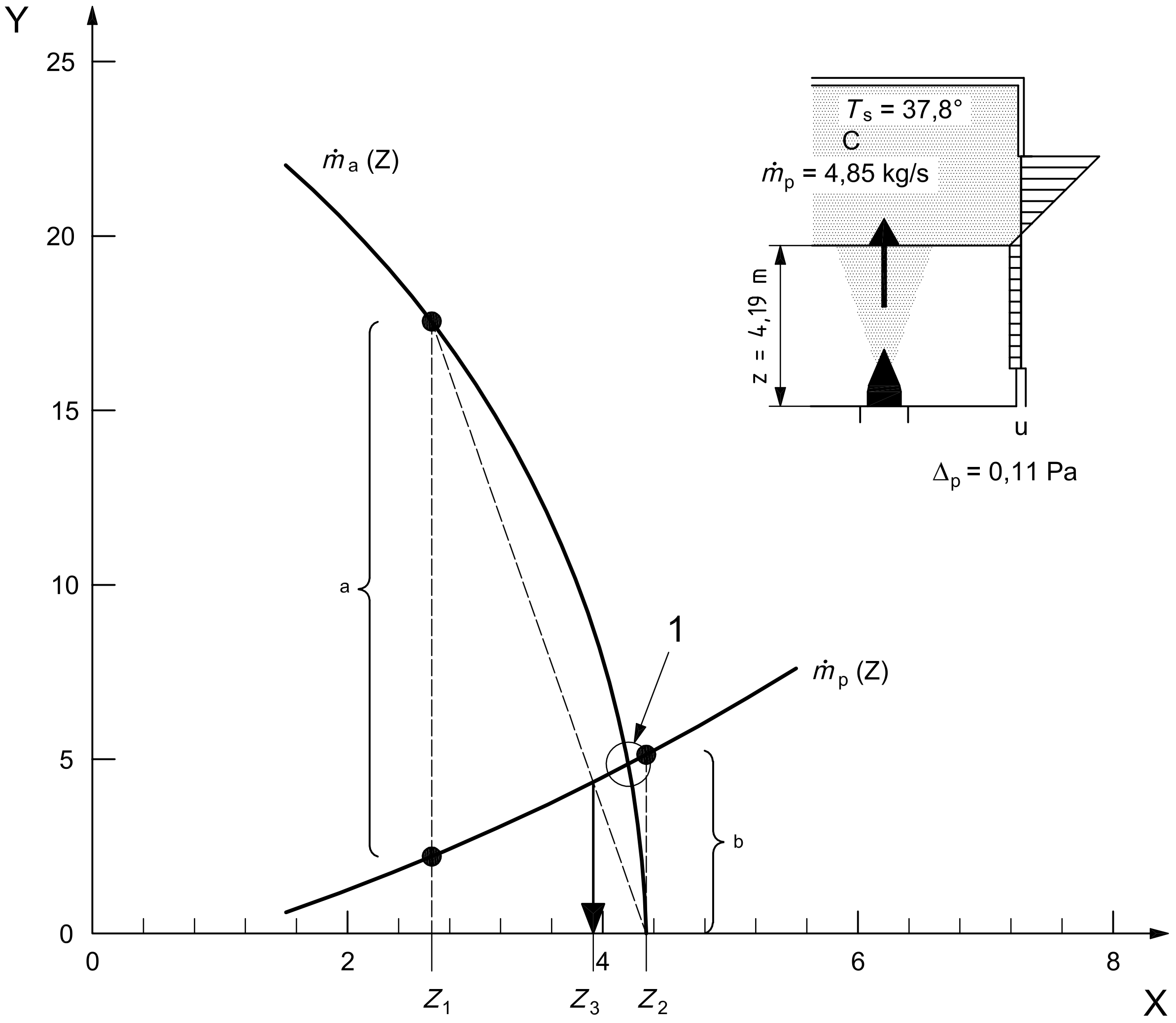
11) Repeat procedures 2) to 8) to calculate error in mass flow rate for z_3:

$$\dot{m}_{\text{error},3} = -1{,}61 \qquad \text{(B.72)}$$

12) As $\dot{m}_{\text{error},3}$ is negative, replace z_1 by z_3. Repeat procedures 2) to 11) until $\dot{m}_\text{error}$ is sufficiently small. During iteration, replace z_2 by z_3 if $\dot{m}_{\text{error},3}$ is positive. In this particular example, seven iterative calculations were needed to reach convergence, as follows:

$$z = 4{,}19 \text{ m}, \; T_s = 37{,}8 \text{ °C}, \; \dot{m}_\text{e} = \dot{m}_\text{p} = \dot{m}_\text{a} = 4{,}85 \text{ kg/s} \qquad \text{(B.73),(B.74),(B.75)}$$

NOTE The final solution is given by a crossing point of $\dot{m}_\text{p}(z)$ and $\dot{m}_\text{a}(z)$ as shown in Figure B.6 by open circle.



Key

X interface height z (m)

Y mass flow rate (kg/s)

1 solution

a $\dot{m}_{\text{error},1}$

b $\dot{m}_{\text{error},2}$

Figure B.6 — Graphical presentation of solution for smoke control by vertical vent

13) To make use of the plume Equation (B.3), flame height must be below the interface height. In this particular case, mean flame height is 1,28 m as in section B.3.3.7.

14) Calculate species concentration using the mass flow rate obtained in 12) above in Equation (B.24):

$$Y = \frac{\eta \dot{Q}}{\dot{m}_e} + Y_0 = \frac{(7{,}61 \times 10^{-5}) \times 300}{4{,}85} + 0{,}000\,3 = 0{,}005\,0 \qquad \text{(B.76)}$$

B.4 Scientific basis for the equation-set

The equation set is based on general heat and mass conservation relations given in Annex A. The research on smoke filling dates back to the basic study of fluid dynamics of Turner *et al.*[5] on formation of sharp density interface in an enclosure. Zukoski[6],[7] developed similar equations 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.*[8] to verify the assumptions of small density change. Experimental work by Tanaka *et al.*[2] found that measurement data are well reproduced if the small density change is taken into account. Efforts have been devoted to extend the analytical equations to include the effect of volume expansion (Delichatsios [3],[4]).

B.5 Equation-set limitations

B.5.1 Fire plume

The mass flow rate equation in the equation set assumes compatibility with equation-set limitations described in ISO 16734, with respect to the fire source, flame dimensions, proximity to boundaries, aerodynamic disturbances, etc.

B.5.2 Uniformity of smoke layer

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

B.6 Output parameters

The outputs of equation set are interface position, smoke layer temperature and species concentration. In addition, the equation set gives information on the mass flow rate of the fire plume and vent flows.

B.7 Equation-set input parameters

B.7.1 Fire heat release rate

The parameter $\dot{Q}$ is the rate of heat actually released by a fire under specific environmental conditions, as measured by a calorimeter that is based on product gas collection to determine O_2, CO_2 and CO generation rates, or as otherwise specified. This parameter is normally obtained from the design fire scenario.

B.7.2 Radiative fraction of heat release

The parameter χ depends on the type of fuel that is burning. Typical values are in the range of 0,3 to 0,4. For more information, refer to A.7.2, convective fraction, in ISO 16734:2006.

B.7.3 Fraction of heat absorbed by enclosure boundary during initial stage

The parameter λ is required for the calculation of the initial smoke filling process. For the calculation of steady state smoke control (mechanical, roof or side vent), heat absorption by the enclosure can be calculated in different ways. The parameter value depends mainly on 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 may be significant. However, to calculate accurate values, details of thermal radiation transfer within the enclosure are needed. For practical applications, setting $\lambda = 0$ is recommended.

B.7.4 Effectiveness of mechanical smoke venting

In the equation set B.3.3, it is assumed that the mechanical venting system extracts smoke only. However, if the smoke layer is not sufficiently thick, the lower air layer is entrained into mechanical smoke exhaust (see bibliographic reference [9]. In such cases, volume exhaust rate shall be reduced by using air entrainment ratio (see bibliographic reference [10]).

B.7.5 Species yield

The parameter η depends on the type of fuel and fuel/air ratio of burning. As this equation set assumes small fires in comparison with enclosure size, values for well-ventilated fires can be used (see bibliographic reference [11]).

B.8 Equation-set domain of applicability

The equation set has been compared with a series of experiments in a large scale atrium at Building Research Institute of Japan by Tanaka and Yamana [2]. The room floor area was 720 m^2, ceiling height was 26,3 m and the heat release rate was approximately 1 300 kW. Another comparison was made by Karlsson *et al*, [12], who compared the equation set for smoke filling with an experiment by Hägglund *et al*. [13]. Room dimensions were 5,62 m × 5,62 m, the ceiling height was 6,15 m (effective height was 5,95 m) and the fire source was kerosene burning in a pan. The heat release rate was 186 kW. In both comparisons, the equation set provides reasonable accuracy. For multiroom smoke spread, a similar set of equations is solved numerically (see bibliographic references [14],[15],[16]).

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