INTERNATIONAL STANDARD

ISO 24678-5

First edition
2023-06

Fire safety engineering — Requirements governing algebraic formulae —

Part 5: Vent flows

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

Partie 5: Ecoulements au travers d'une ouverture

Reference number
ISO 24678-5:2023(E)

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).

ISO draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). ISO takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, ISO had not received notice of (a) patent(s) which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at www.iso.org/patents. ISO shall not be held responsible for identifying any or all such patent rights.

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

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

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

This first edition cancels and replaces ISO 16737:2012, 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 former Annexes A and B have been merged into a new Annex A;

— comparisons with experimental data have been added in Annex A;

— a new Annex B has been added to describe the examples of flow coefficient values.

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

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

Introduction

The ISO 24678 series is intended to be used by fire safety practitioners involved with fire safety engineering calculation methods. It is expected that the users of this document are appropriately qualified and competent in the field of fire safety engineering. It is particularly important that users understand the parameters within which particular methodologies may be used.

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

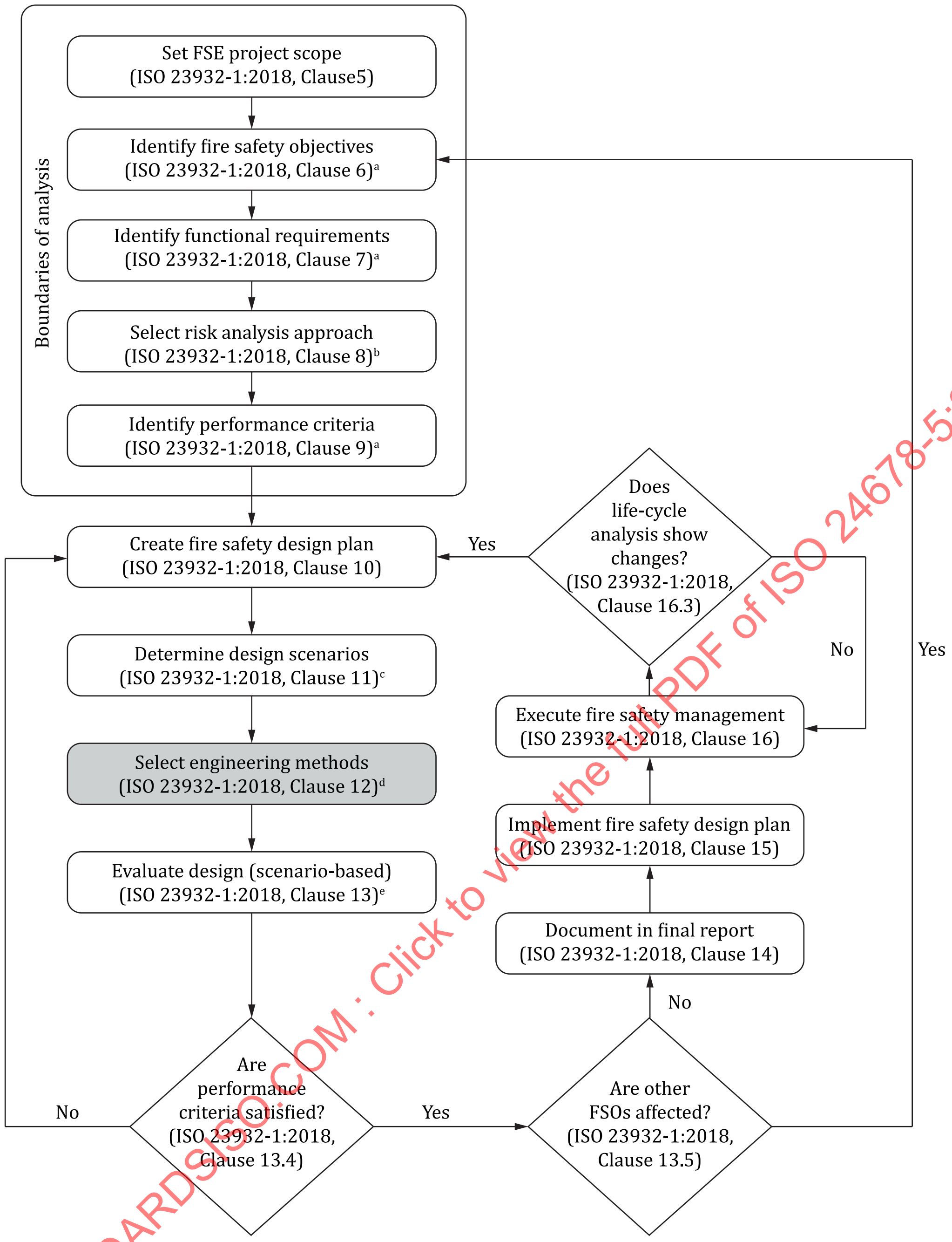
The subjects of engineering calculations include the fire-safe design of entirely new built environments, such as buildings, ships or vehicles, as well as the assessment of the fire safety of existing built environments.

The algebraic formulae discussed in this document can be useful for estimating the consequences of design fire scenarios. Such formulae are valuable for allowing the practitioner to quickly determine how a proposed fire safety design needs to be modified to meet performance criteria and to compare among multiple trial designs. Detailed numerical calculations can be carried out up until the final design documentation. Examples of areas where algebraic formulae have been applicable include determination of convective and radiative heat transfer from fire plumes, prediction of ceiling jet flow properties governing detector response times, calculation of smoke transport through vent openings, and analysis of compartment fire hazards such as smoke filling and flashover. However, the simple models often have stringent limitations and are less likely to include the effects of multiple phenomena occurring in the design scenarios.

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

ISO 23932-1 is supported by a set of fire safety engineering documents on the methods and data needed for all the steps in a fire safety engineering design as summarized in Figure 1 (taken from ISO 23932-1:2018, Clause 4). This set of documents is referred to as the Global fire safety engineering analysis and information system. This global approach and system of standards provides an awareness of the interrelationships between fire evaluations when using the set of fire safety engineering documents. The set of documents includes ISO/TS 13447, ISO 16730-1, ISO 16732-1, ISO 16733-1, ISO/TS 16733-2, ISO/TR 16738, ISO 24678-1, ISO 24679-1, ISO/TS 29761 and other supporting Technical Reports that provide examples of and information 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, ISO 24678-5 (this document), 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 5: Vent flows

1 Scope

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

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 13943, *Fire safety — Vocabulary*

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

3 Terms and definitions

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

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

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
boundary
surface that defines the extent of an enclosure

3.2
datum
elevation used as the reference elevation for evaluation of hydrostatic pressure profiles

Note 1 to entry: This is typically the lowest boundary of the enclosure.

3.3
effective flow area
flow area effective to air and smoke movement

3.4
flow coefficient
fraction of effective flow area over total area of a vent

3.5
hydrostatic pressure
atmospheric pressure profile associated with height

3.6
neutral plane height
elevation at which the pressure inside an enclosure is the same as the pressure outside the enclosure

3.7
pressure difference
difference between the pressure inside an enclosure and outside the enclosure at a specified elevation

3.8
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

3.9
smoke layer height
interface position
interface height
elevation of the smoke layer interface relative to a reference elevation

3.10
vent
opening in an enclosure boundary through which air and smoke can flow as a result of naturally- or mechanically-induced forces

3.11
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 flow through a vent is a complex thermo-physical phenomenon that can be highly transient or nearly steady-state. Vent flows may contain regions involved in flaming combustion and regions where there is no combustion taking place. In addition to buoyancy, vent flows can be influenced by dynamic forces due to external wind or mechanical fans.

4.3 Physical phenomena (e.g. natural vent flow, mechanical smoke exhaust, pressurization smoke control) to which specific formulae apply shall be clearly identified.

5 Requirements governing the calculation process

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

6 Requirements governing limitations

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

7 Requirements governing input parameters

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

8 Requirements governing the domain of applicability

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

9 Example of documentation

An example of documentation meeting the requirements in Clauses 4 to 8 is provided in Annex A. Annex B contains examples of flow coefficient values to be used as input to calculations of vent flow.

Annex A
(informative)

Formulae for vent flows

A.1 Scope

This annex is intended to document the methods to calculate mass flow rate through vents. The formula set covers the flow through vents connecting two enclosures with the same temperature, with uniform but different temperatures, or with two-layered temperature profiles.

A.2 Symbols and abbreviated terms used in this annex

A_{eq}	equivalent area of multiple seral vents (m^2)
A_{ij}	area of vent connecting enclosures i and j (m^2)
B	width of a vent (m)
B_{eq}	equivalent width of multiple seral vents (m)
B_{ij}	width of vent connecting enclosures i and j (m)
c_p	specific heat of air and smoke (kJ/kg·K)
C_D	flow coefficient (-)
g	gravity acceleration (m/s^2)
h	height above the datum (m)
h_{ij}	height of vent connecting enclosures i and j (m)
h_l	height of lower edge of vent above the datum (m)
h_m	height of the bottom of middle segment above the datum (m)
h_n	neutral plane height above the datum (m)
h_t	height of the bottom of top segment above the datum (m)
h_u	height of upper edge of vent above the datum (m)
$\dot{H}_{ij}$	enthalpy flux from enclosure i to enclosure j (kW)
$\max(x_1,x_2)$	maximum of x_1 and x_2
$\min(x_1, x_2)$	minimum of x_1 and x_2
$p_i(h)$	pressure in enclosure i at height h above the datum (Pa)
$p_j(h)$	pressure in enclosure j at height h above the datum (Pa)
$q_{m,ij}$	mass flow rate of smoke or air from enclosure i to j (kg/s)

$q_{m,ij,b}$ mass flow rate of smoke or air from enclosure i to j through bottom segment (kg/s)

$q_{m,ij,m}$ mass flow rate of smoke or air from enclosure i to j through middle segment (kg/s)

$q_{m,ij,t}$ mass flow rate of smoke or air from enclosure i to j through top segment (kg/s)

$q_{w,ij}$ mass flux of chemical species from enclosure i to enclosure j (kg/s)

$T_{a,i}$ air layer temperature in enclosure i (K)

T_i temperature of enclosure i (K)

T_j temperature of enclosure j or outside (K)

$T_{s,i}$ smoke layer temperature in enclosure i (K)

T_0 reference temperature, typically the outside temperature (K)

u_{ij} flow velocity from enclosure i to enclosure j (m/s)

Y_i mass fraction of chemical species in enclosure i (kg/kg)

z_i smoke layer height in enclosure i (m)

$\rho_{a,i}$ gas density of air layer in enclosure i (kg/m)

ρ_i gas density of smoke (or air) in enclosure i (kg/m^3)

ρ_j gas density of smoke (or air) in enclosure j (kg/m^3)

$\rho_{s,i}$ gas density of smoke layer in enclosure i (kg/m^3)

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

$\Delta p_{ij}(h)$ pressure difference between enclosure i and j at height h; that is, $p_i(h)$-$p_j(h)$ (Pa)

Δp_{flood} minimum pressure difference to cause uni-directional flow (Pa)

ζ height used as an integration variable (m)

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

The methods permit calculation of flows through vents in enclosure boundaries arising from pressure differences that develop between an enclosure and adjacent spaces as a result of temperature differences. Pressure differences may also result from fire gas expansion, mechanical ventilation, wind or other forces acting on the enclosure boundaries and vents, but these forces are not addressed in this document. Given a pressure difference across a vent and the temperatures of the enclosures that the vent connects, mass flow rate is calculated by using orifice flow theory.

The properties of an enclosure, such as smoke layer height, temperature, and other properties are calculated by the principle of heat and mass conservation for the smoke layer as described in ISO 24678-4.

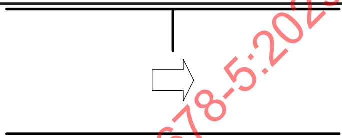
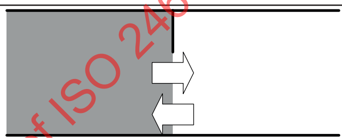
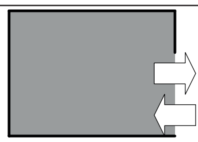
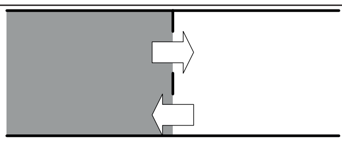
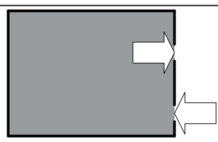
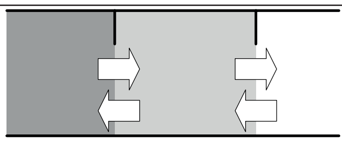
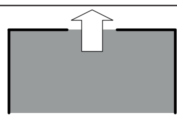
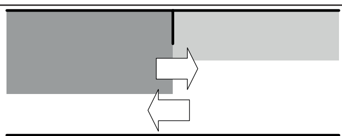
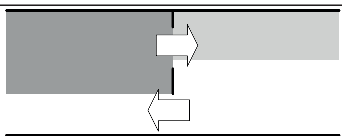
A.3.1.2 Vent flow properties to be calculated

The formula set provides the mass, enthalpy and chemical species flow rates.

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

The set of formulae is applicable to quasi-steady state vent flows driven by buoyancy caused by fire. Dynamic pressure effects, such as wind, are not considered. Methods to calculate vent flow conditions are developed for two types of temperature profiles: one is a uniform temperature profile while the other is a two-layered profile as calculated by ISO 24678-4. The calculation conditions are summarized in Table A.1.

Table A.1 — Summary of calculation conditions of vent flows

Temperature profile	Arrangement of vent(s)	flow patterns
Uniform	a) Single vent	
Single layer	b) Single vertical vent (general case, flow may be either uni-directional or bi-directional)	
	c) Single vertical vent (special case, flow is bi-directional)	
	d) Multiple vertical vents (general case, flow may be either uni-directional or bi-directional)	
	e) Multiple vertical vents (special case of two small vents in one enclosure, flow is bi-directional)	
	f) Multiple serial vertical vents (combination of multiple serial vents into equivalent single vent)	
	g) Single horizontal vent (stable uni-directional flow only)	
Two layers	h) Single vertical vent (general case, flow may be either uni-directional or bi-directional)	
	i) Multiple vertical vents (general case, flow may be either uni-directional or bi-directional)	

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 Standards and other documents where the formula set is used

ISO 24678-4 uses vent flow formulae to calculate smoke layer properties.

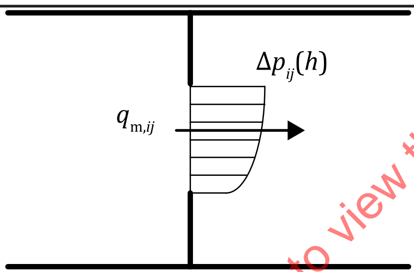
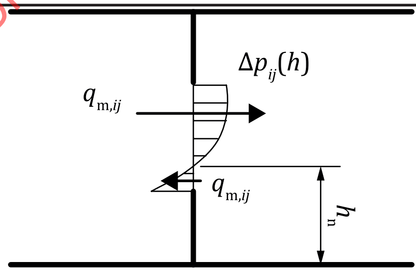
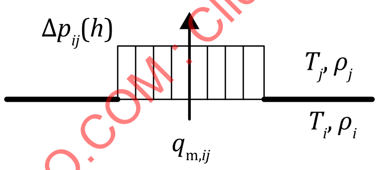
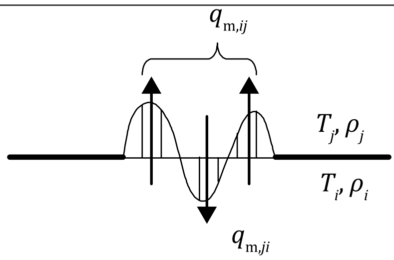
A.4 Formula-set documentation of calculation procedure

A.4.1 General aspects of vent flow

A.4.1.1 Classifications of vent flows

The velocity of flow through a vent is calculated according to the orifice flow theory based on application of Bernoulli's theory. Methods to calculate vent flows are developed for the conditions shown in Table A.2. For the case of vertical and horizontal vents, flow may be uni-directional or bi-directional. Explicit formulae presented in this annex are applicable to bi-directional and uni-directional flows through vertical vents and uni-directional flow through horizontal vents. For horizontal vents, bi-directional flow takes place when the pressure difference is small. No general formula is available in this annex because the flow is unstable.

Table A.2 — Classifications of vent flows

	Uni-directional flows	Bi-directional flows
Vertical vent		
Horizontal vent		

A.4.1.2 Orifice flow formula — uniform pressure difference over vent area

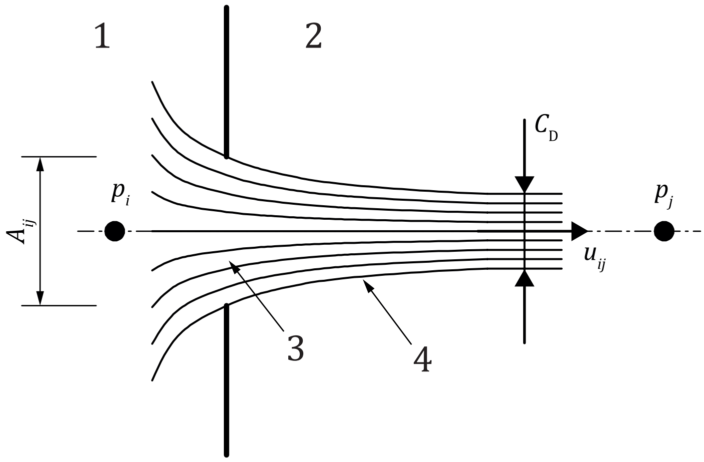
When uniform pressure difference is created by actions such as mechanical fans, the mass flow rate through the vent is given by Formula (A.1):

$$q_{m,ij} = C_D A_{ij} u_{ij} = C_D A_{ij} \sqrt{2\rho_i \Delta p_{ij}} \tag{A.1}$$

where Δp_{ij} is calculated using Formula (A.2):

$$\Delta p_{ij} = p_i - p_j \tag{A.2}$$

It is assumed that the pressure difference across the vent is uniform over the entire vent area as shown in Figure A.1.



Key

1 enclosure *i*

2 enclosure *j*

3 vent

4 stream lines

Figure A.1 — Streamlines and flow coefficient for isothermal orifice flow

A.4.1.3 General flow formula – non-uniform pressure difference over vent area

When a vertical temperature profile $T_i(h)$ exists in enclosure *i* as shown in Figure A.2, the gas density, ρ_i, at height *h* above the datum is calculated by Formula (A.3):

$$\rho_i(h) = \frac{\rho_0 T_0}{T_i(h)} \approx \frac{353}{T_i(h)} \tag{A.3}$$

NOTE Smoke is approximated by an ideal gas whose property is identical to air at normal atmospheric pressure.

The hydrostatic pressure in enclosure i is calculated by integrating gas density over height, using Formula (A.4):

$$p_i(h) = p_i(0) - \int_0^h \rho_i(\zeta) g \,\mathrm{d}\zeta \tag{A.4}$$

Hydrostatic pressure difference between enclosures i and j at height h is calculated using Formula (A.5):

$$\begin{aligned} \Delta p_{ij}(h) &= p_i(h) - p_j(h) \\ &= \{p_i(0) - p_j(0)\} - \int_0^h \{\rho_i(\zeta) - \rho_j(\zeta)\} g \,\mathrm{d}\zeta \\ &= \Delta p_{ij}(0) - \int_0^h \{\rho_i(\zeta) - \rho_j(\zeta)\} g \,\mathrm{d}\zeta \end{aligned} \tag{A.5}$$

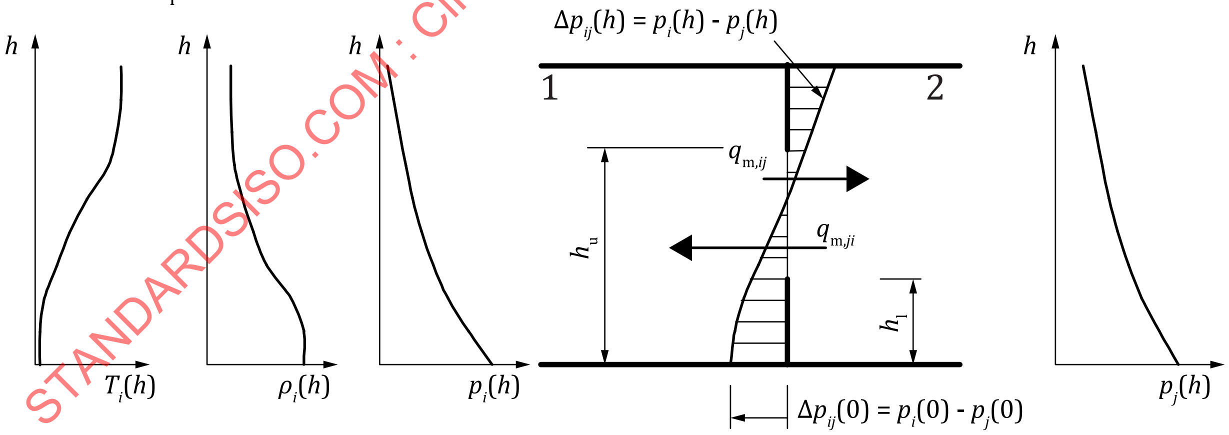
where the pressure difference at the datum is determined by Formula (A.6):

$$\Delta p_{ij}(0) = p_i(0) - p_j(0) \tag{A.6}$$

Flow through a vertical vent is calculated by applying the orifice flow theory to each vertical segment of the vent. Given the hydrostatic pressure difference calculated using Formula (A.5), mass flow rates between enclosures are calculated using Formulae (A.7) and (A.8):

$$q_{\mathrm{m},ij} = C_\mathrm{D} B \int_{h_\mathrm{l}}^{h_\mathrm{u}} \sqrt{2\rho_i(\varsigma) \max(\Delta p_{ij}(\varsigma), 0)} \,\mathrm{d}\varsigma \tag{A.7}$$

$$q_{\mathrm{m},ji} = C_\mathrm{D} B \int_{h_\mathrm{l}}^{h_\mathrm{u}} \sqrt{2\rho_\mathrm{j}(\zeta) \max(-\Delta p_{ij}(\zeta), 0)} \,\mathrm{d}\zeta \tag{A.8}$$



Key

1 enclosure i

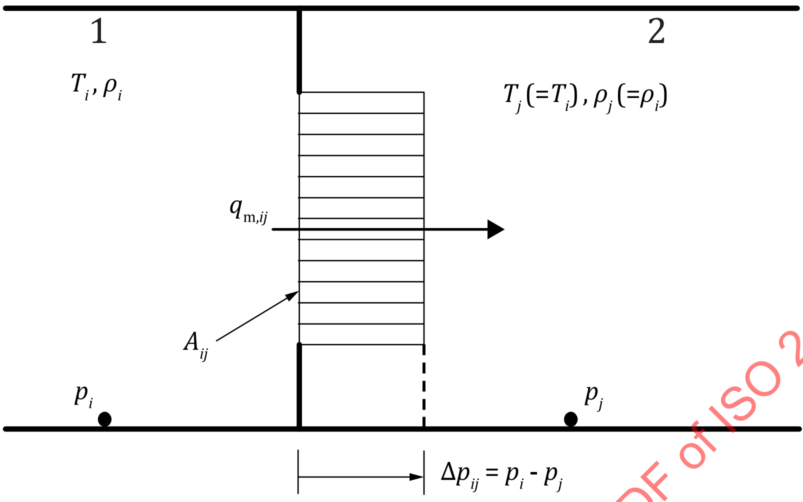
2 enclosure j

Figure A.2 — Hydrostatic pressure difference between two adjacent enclosures

A.4.2 Flow through a vent connecting two enclosures of uniform, identical temperature

A.4.2.1 Scenario element

A vent is connecting two enclosures *i* and *j*. The temperatures of both enclosures are uniform and identical. Pressure difference, Δp_{ij}, is created across the vent as shown in Figure A.3.



Key

1 enclosure *i*

2 enclosure *j*

Figure A.3 — Pressure difference across vertical vent and corresponding flow in case of uniform, identical temperature

A.4.2.2 Mass flow rate through a vent

When a pressure difference is imposed across a vent with a uniform temperature profile, the mass flow rate is calculated using Formula (A.9):

$$q_{m,ij} = C_D A_{ij} \sqrt{2 \rho_i \Delta p_{ij}} \quad \text{(A.9)}$$

where Formulae (A.10) and (A.11) apply:

$$\Delta p_{ij} = p_i - p_j \quad \text{(A.10)}$$

$$\rho_i = \frac{353}{T_i} \quad \text{(A.11)}$$

A.4.2.3 Enthalpy flow rate through a vent

Enthalpy flow rate is calculated using the mass flow rate as shown in Formula (A.12):

$$\dot{H}_{ij} = c_p (T_i - T_0) q_{m,ij} \quad \text{(A.12)}$$

NOTE Formula (A.12) is not repeated in the following subclauses but it is applicable to all cases in this annex.

A.4.2.4 Flow of chemical species through a vent

The flow rate of chemical species through a vent is calculated using the mass flow rate as shown in Formula (A.13):

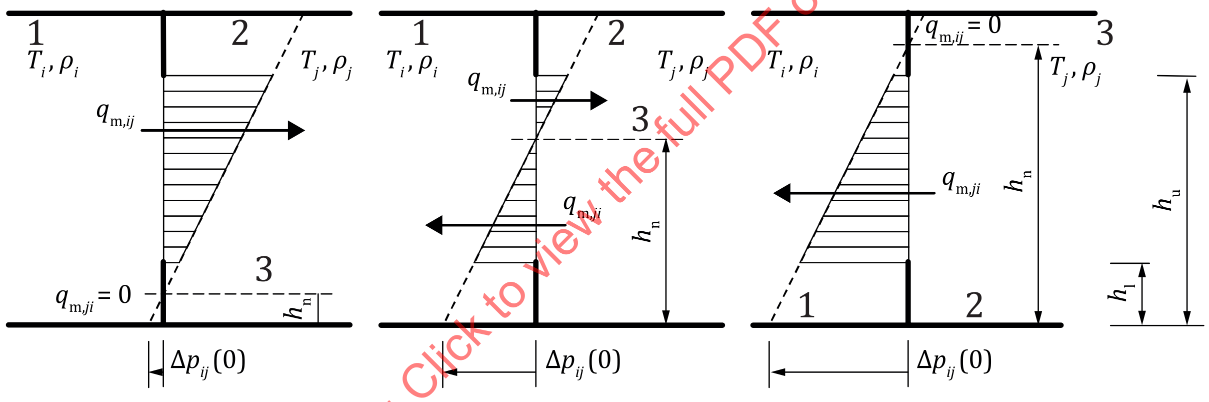
$$q_{w,ij} = Y_i q_{m,ij} \tag{A.13}$$

NOTE Formula (A.13) is not repeated in the following subclauses but it is applicable to all cases in this annex.

A.4.3 Flow through single vertical vent connecting two enclosures of uniform but different temperatures — General case

A.4.3.1 Scenario element

As shown in Figure A.4, flow patterns are classified in accordance with the neutral plane height. When the neutral plane locates below the lower edge of the vent ($h_n < h_l$), flow is unidirectional from enclosure *i* to enclosure *j*. When the neutral plane locates within the range of vent ($h_l < h_n < h_u$), flow is bi-directional. When the neutral plane locates above the upper edge of the vent ($h_u < h_n$), flow is uni-directional from enclosure *j* to enclosure *i*.[28],[29]



Key

1 enclosure *i*

2 enclosure *j*

3 neutral plane

Figure A.4 — Pressure difference across a vertical vent and corresponding flow directions in case of $T_i > T_j$, ($\rho_i < \rho_j$)

A.4.3.2 Gas densities of enclosures

The gas densities of enclosures are calculated using Formulae (A.14) and (A.15):

$$\rho_i = \frac{353}{T_i} \tag{A.14}$$

$$\rho_j = \frac{353}{T_j} \tag{A.15}$$

A.4.3.3 Neutral plane height above the datum

The neutral plane height above the datum is calculated using Formula (A.16):

$$h_{\mathrm{n}} = \frac{\Delta p_{ij}(0)}{(\rho_i - \rho_{\mathrm{j}})g} \tag{A.16}$$

A.4.3.4 Mass flow rates

The mass flow rates are calculated by the following formulae according to temperature difference. In case of $T_i > T_j$, ($\rho_i < \rho_j$), see Formulae (A.17) and (A.18):

$$q_{\mathrm{m},ij} = \begin{cases} \frac{2}{3} C_{\mathrm{D}} B_{ij} \sqrt{2\rho_i(\rho_j - \rho_i)g}\{(h_{\mathrm{u}} - h_{\mathrm{n}})^{3/2} - (h_{\mathrm{l}} - h_{\mathrm{n}})^{3/2}\} & (h_{\mathrm{n}} < h_{\mathrm{l}}) \\ \frac{2}{3} C_{\mathrm{D}} B_{ij} \sqrt{2\rho_i(\rho_j - \rho_i)g}(h_{\mathrm{u}} - h_{\mathrm{n}})^{3/2} & (h_{\mathrm{l}} \le h_{\mathrm{n}} < h_{\mathrm{u}}) \\ 0 & (h_{\mathrm{u}} \le h_{\mathrm{n}}) \end{cases} \tag{A.17}$$

$$q_{\mathrm{m},ji} = \begin{cases} 0 & (h_{\mathrm{n}} < h_{\mathrm{l}}) \\ \frac{2}{3} C_{\mathrm{D}} B_{ij} \sqrt{2\rho_j(\rho_j - \rho_i)g}(h_{\mathrm{n}} - h_{\mathrm{l}})^{3/2} & (h_{\mathrm{l}} \le h_{\mathrm{n}} < h_{\mathrm{u}}) \\ \frac{2}{3} C_{\mathrm{D}} B_{ij} \sqrt{2\rho_j(\rho_j - \rho_i)g}\{(h_{\mathrm{n}} - h_{\mathrm{l}})^{3/2} - (h_{\mathrm{n}} - h_{\mathrm{u}})^{3/2}\} & (h_{\mathrm{u}} \le h_{\mathrm{n}}) \end{cases} \tag{A.18}$$

and in case of $T_i < T_j$ ($\rho_i > \rho_j$), see Formulae (A.19) and (A.20):

$$q_{\mathrm{m},ij} = \begin{cases} 0 & (h_{\mathrm{n}} < h_{\mathrm{l}}) \\ \frac{2}{3} C_{\mathrm{D}} B_{ij} \sqrt{2\rho_i(\rho_i - \rho_j)g}(h_{\mathrm{n}} - h_{\mathrm{l}})^{3/2} & (h_{\mathrm{l}} \le h_{\mathrm{n}} < h_{\mathrm{u}}) \\ \frac{2}{3} C_{\mathrm{D}} B_{ij} \sqrt{2\rho_i(\rho_i - \rho_j)g}\{(h_{\mathrm{n}} - h_{\mathrm{l}})^{3/2} - (h_{\mathrm{n}} - h_{\mathrm{u}})^{3/2}\} & (h_{\mathrm{u}} \le h_{\mathrm{n}}) \end{cases} \tag{A.19}$$

$$q_{\mathrm{m},ji} = \begin{cases} \frac{2}{3} C_{\mathrm{D}} B_{ij} \sqrt{2\rho_j(\rho_i - \rho_j)g}\{(h_{\mathrm{u}} - h_{\mathrm{n}})^{3/2} - (h_{\mathrm{l}} - h_{\mathrm{n}})^{3/2}\} & (h_{\mathrm{n}} < h_{\mathrm{l}}) \\ \frac{2}{3} C_{\mathrm{D}} B_{ij} \sqrt{2\rho_j(\rho_i - \rho_j)g}(h_{\mathrm{u}} - h_{\mathrm{n}})^{3/2} & (h_{\mathrm{l}} \le h_{\mathrm{n}} < h_{\mathrm{u}}) \\ 0 & (h_{\mathrm{u}} \le h_{\mathrm{n}}) \end{cases} \tag{A.20}$$

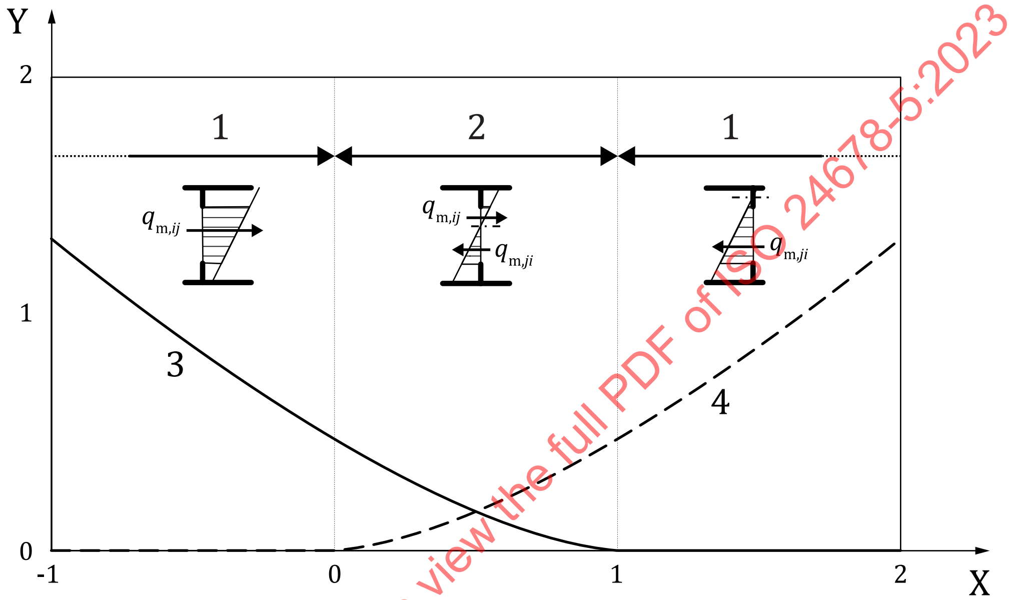
In non-dimensional form, the mass flow rates can be expressed using Formulae (A.21) and (A.22):

$$q_{\mathrm{m},ij}^{*} = \frac{q_{\mathrm{m},ij}}{\sqrt{2\rho_i(\rho_j - \rho_i)}B_{ij}(h_{\mathrm{u}} - h_{\mathrm{l}})^{3/2}} \tag{A.21}$$

$$q^*_{m,ji} = \frac{q_{m,ji}}{\sqrt{2\rho_j(\rho_j - \rho_i)}B_{ij}(h_u - h_l)^{3/2}} \tag{A.22}$$

Formulae (A.21) and (A.22) are plotted in Figure A.5 against non-dimensional neutral plane height; see Formula (A.23):

$$h^*_n = \frac{h_n - h_l}{h_u - h_l} \tag{A.23}$$



Key

X non-dimensional neutral plane height, h^*_n

Y non-dimensional mass flow rates, q^*_m

1 uni-directional flow

2 bi-directional flow

——— non-dimensional mass flow rate from enclosure i to enclosure j, $q^*_{m,ij}$

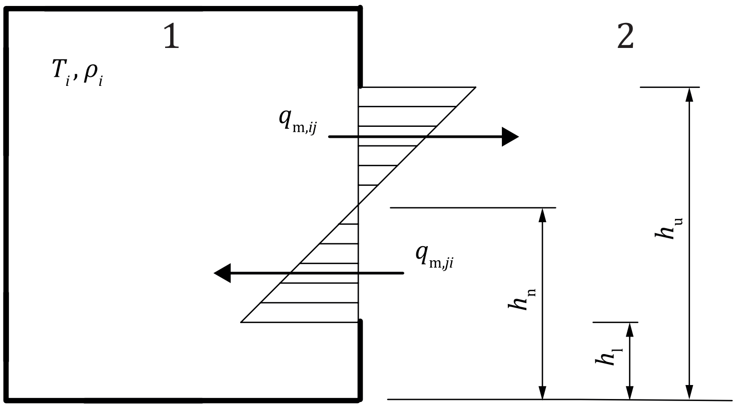
– – – non-dimensional mass flow rate from enclosure j to enclosure i, $q^*_{m,ji}$

Figure A.5 — Non-dimensional mass flow rates through a vertical vent in case of $T_i > T_j$ ($\rho_i < \rho_j$)

A.4.4 Flow through single vertical vent connecting two enclosures of uniform but different temperatures — Special case of single vent in one enclosure

A.4.4.1 Scenario element

In case of an enclosure with a single vent as shown in Figure A.6, the mass flow rate out of the enclosure, $q_{m,ij}$, is equal to the incoming mass flow rate, $q_{m,ji}$.



Key

1 enclosure *i*

2 enclosure *j* (outside)

Figure A.6 — Pressure difference across single vertical vent and corresponding flow rates in case of $T_i > T_j$, $(\rho_i < \rho_j)$

A.4.4.2 Gas densities of enclosure and outside space

The gas densities ρ_i and ρ_j are calculated using Formulae (A.14) and (A.15).

A.4.4.3 Neutral plane height above the datum

The neutral plane height, h_n, is located so that the mass balance, $q_{m,ij} = q_{m,ji}$, is satisfied as shown in Formula (A.24):

$$h_n = \frac{h_u - h_l}{1 + (\rho_j / \rho_i)^{1/3}} + h_l \tag{A.24}$$

A.4.4.4 Mass flow rates

The mass flow rates are calculated by the following Formulae (A.25) and (A.26):

$$q_{m,ij} = \frac{2}{3} C_D \sqrt{2\rho_i(\rho_j - \rho_i)g} \left(\frac{(\rho_j / \rho_i)^{1/3}}{1 + (\rho_j / \rho_i)^{1/3}} \right)^{3/2} B_{ij} (h_u - h_l)^{3/2} \tag{A.25}$$

$$q_{m,ji} = \frac{2}{3} C_D \sqrt{2\rho_j(\rho_j - \rho_i)g} \left(\frac{1}{1 + (\rho_j / \rho_i)^{1/3}} \right)^{3/2} B_{ij} (h_u - h_l)^{3/2} \tag{A.26}$$

NOTE Calculation by either Formula (A.25) or Formula (A.26) is sufficient because both mass flow rates are equal.

A.4.4.5 Mass flow rates through vents in an enclosure with sufficiently high temperature

If the temperature of enclosure *i*, T_i, is higher than 300 °C, and if the temperature of enclosure *j* is close to ambient temperature, $T_j = T_0$, the coefficients in Formulae (A.25) and (A.26) are fairly constant. As a result, the following useful relationship applies:[30]

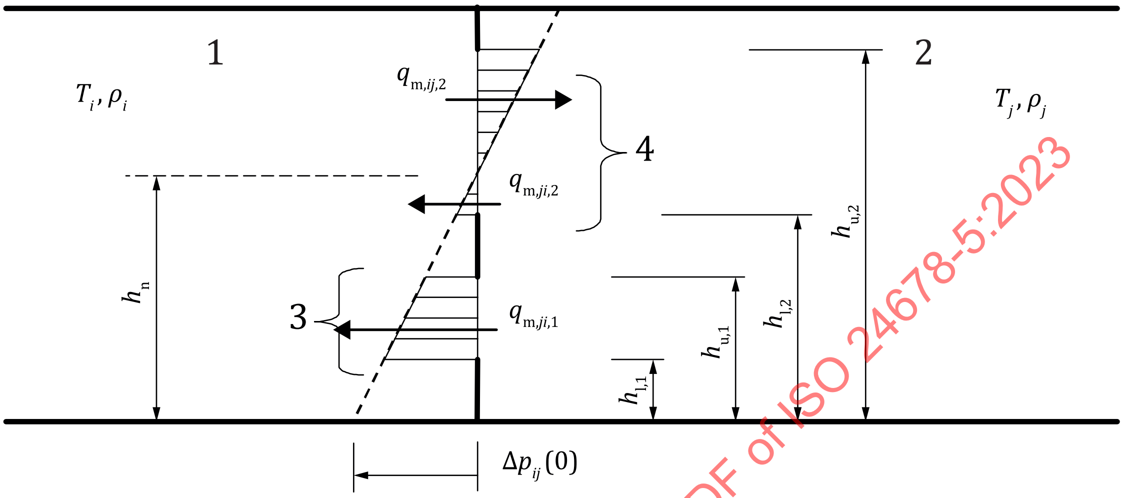
$$q_{m,ij} = q_{m,ji} \approx 0{,}52 B_{ij} (h_u - h_l)^{3/2} \tag{A.27}$$

The term $B_{ij}(h_u - h_l)^{3/2}$ is called the opening factor or ventilation parameter ($m^{5/2}$).

A.4.5 Flow through multiple vertical vents connecting two enclosures of uniform but different temperatures

A.4.5.1 Scenario element

In practical situations, an enclosure may have several vents as shown in Figure A.7.



Key

1 enclosure *i*

2 enclosure *j*

3 vent flow 1

4 vent flow 2

Figure A.7 — Pressure difference across vertical two vents and corresponding flow directions in case of $T_i > T_j$, ($\rho_i < \rho_j$)

A.4.5.2 Gas densities of enclosures

The gas densities of the two enclosures are calculated using Formulae (A.14) and (A.15).

A.4.5.3 Neutral plane height above the datum

The neutral plane height is calculated using Formula (A.16).

A.4.5.4 Mass flow rates

Mass flow rates are calculated in a similar way to that described in A.4.3. Formulae (A.17) to (A.20) are applied to each vent.

A.4.6 Flow through multiple vertical vents connecting two enclosures of uniform but different temperatures — Special case of two small vents in an enclosure

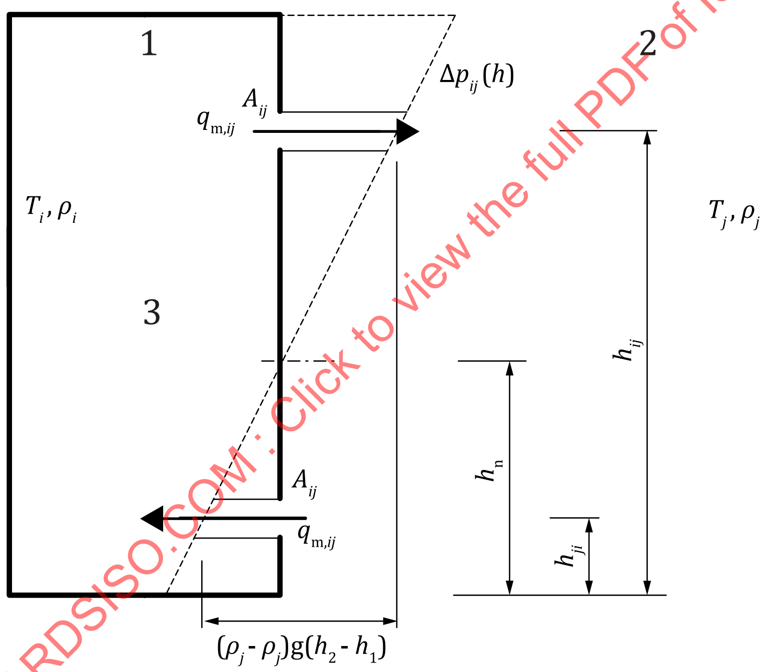
A.4.6.1 Scenario element

An enclosure has two small vents at different heights as shown in Figure A.8. The enclosure temperature is T_i, while the outside temperature is T_j. In this case, the pressure difference between the enclosure and the outside space is given by Formula (A.28):

$$\Delta p_{ij}(h)=(\rho_i-\rho_j)g(h_\mathrm{n}-h) \tag{A.28}$$

At steady state, the neutral plane is located so that incoming and outgoing mass flow rates are balanced; see Formula (A.29):

$$h_\mathrm{n} = \frac{1}{1+\frac{\rho_j}{\rho_i}\left(\frac{A_{ji}}{A_{ij}}\right)^2}(h_{ij}-h_{ji})+h_{ji} \tag{A.29}$$



Key

1 enclosure i (shaft)

2 enclosure j (outside)

3 neutral plane

Figure A.8 — Pressure difference and flow pattern across an enclosure with two small vents in case of $T_i > T_j$, ($\rho_i < \rho_j$)

A.4.6.2 Gas densities of the enclosure and outside space

The gas densities of the enclosure and outside space are calculated by Formulae (A.14) and (A.15).

A.4.6.3 Equivalent vent area

The equivalent vent area is calculated to account for total flow resistance of the two vents using Formula (A.30):

$$A_{eq} = \frac{1}{\sqrt{(\frac{1}{A_{ji}})^2 + \frac{\rho_j}{\rho_i}(\frac{1}{A_{ij}})^2}} \quad (A.30)$$

A.4.6.4 Mass flow rate

Using the equivalent vent area, incoming and outgoing mass flow rates are calculated using Formula (A.31):

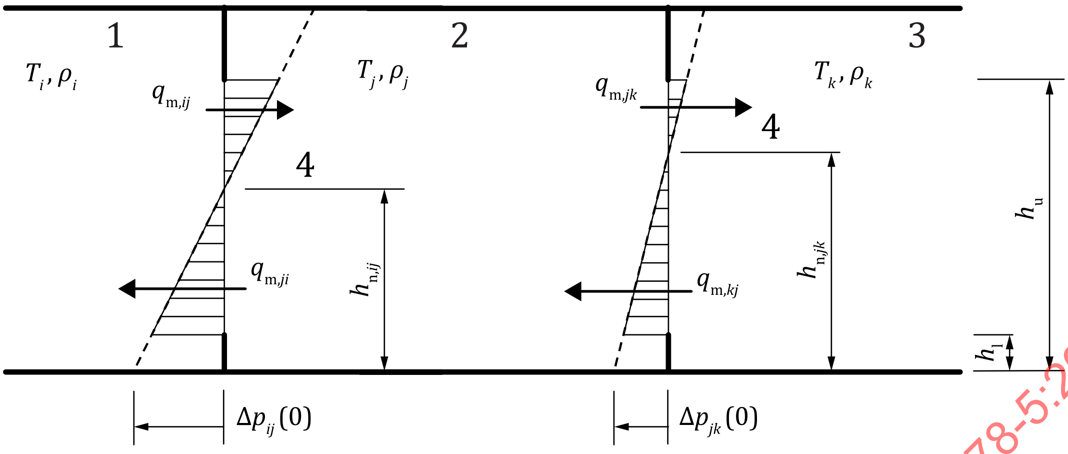
$$q_{m,ij} = q_{m,ji} = C_D A_{eq} \sqrt{2\rho_j(\rho_j - \rho_i)g(h_{ij} - h_{ji})} \quad (A.31)$$

A.4.7 Flow through multiple serial vents

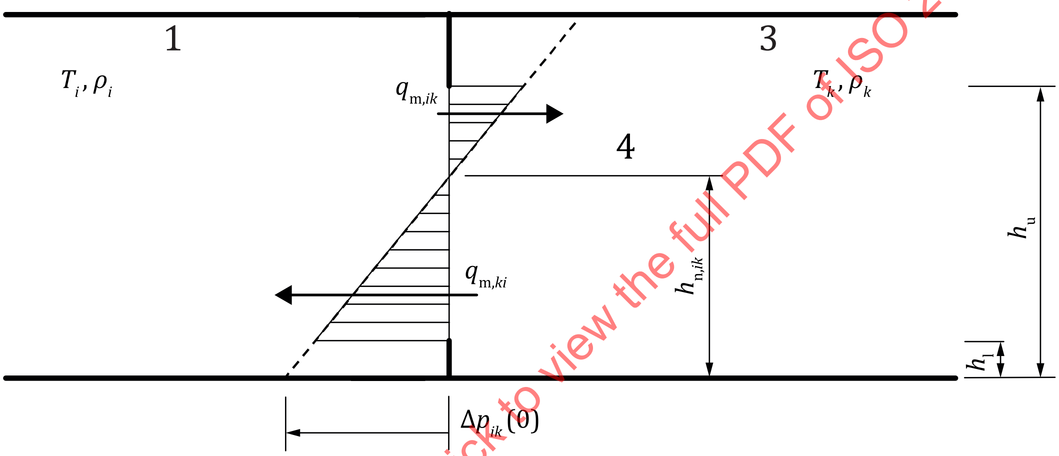
A.4.7.1 Scenario element

In practical smoke control design, multiple vents are combined into an equivalent single vent to yield the same mass flow rate under a specific pressure difference. This approximation is useful in calculations in realistic built environments that can potentially have many vents.

As shown in Figure A.9 a), three enclosures are connected in series. The pressures of enclosures *i* and *k* are given. The lower and upper heights of the vents are common to both vents, while the width of vents can be different. Temperatures of enclosures *i* and *k* are uniform but can be different. The temperature in enclosure *j* is not needed, as it does not influence the final calculation results. To calculate the mass flow rate, the two serial vents are combined into an equivalent vent as shown in Figure A.9 b).



a) Original configuration



b) Approximation to single vent by equivalent vent width

Key

1 enclosure *i*

2 enclosure *j*

3 enclosure *k*

4 neutral plane

NOTE Lower and upper heights, h_u and h_l, are common to all vents. Vent widths B_{ij} and B_{jk} can be different.

Figure A.9 — Pressure difference across serial two vents and equivalent single vent in case of $T_i > T_j > T_k$, ($\rho_i < \rho_j < \rho_k$)

A.4.7.2 Gas densities of two enclosures

The gas densities of enclosures are calculated using Formulae (A.32) and (A.33):

$$\rho_i = \frac{353}{T_i} \tag{A.32}$$

$$\rho_k = \frac{353}{T_k} \tag{A.33}$$

A.4.7.3 Equivalent vent width

The equivalent vent width is calculated using Formula (A.34):

$$B_{eq} = \frac{1}{\sqrt{\left(\frac{1}{B_{ij}}\right)^2 + \left(\frac{1}{B_{jk}}\right)^2}} \tag{A.34}$$

To combine more than two vents in series, Formula (A.34) may be applied recursively; see Formula (A.35):

$$B_{eq} = \frac{1}{\sqrt{\left(\frac{1}{B_{ij}}\right)^2 + \left(\frac{1}{B_{jk}}\right)^2 + \cdots + \left(\frac{1}{B_{mn}}\right)^2}} \tag{A.35}$$

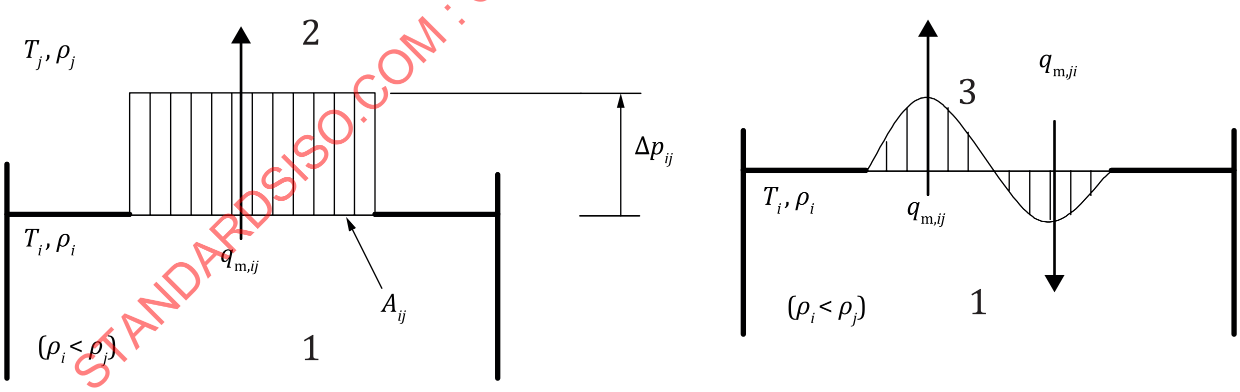
A.4.7.4 Mass Flow Rate

The mass flow rates between enclosures i and k are calculated by the Formula (A.17) to (A.20) by replacing vent width B_{ij} with the equivalent width B_{eq}, and the gas density of enclosure j, ρ_j, with that of enclosure k, ρ_k.

A.4.8 Flow through horizontal vent connecting two enclosures of uniform but different temperatures

A.4.8.1 Scenario element

For a flow through horizontal vents such as in roofs, the mass flow rates can be calculated in a similar way to vertical vents as shown in Figure A.10 a). However, if the pressure difference is small, bi-directional flow can arise as shown in Figure A.10 b). The minimum pressure difference, Δp_{flood}, for uni-directional flow is still under investigation. Examples of formulae are those developed by Yamada *et al.*[31] and Cooper.[32] An example of an explicit formula for flow rate under the bi-directional flow is proposed for a small vent,[33] but a general formula is not available yet. In this subclause, only a simple formula for uni-directional flow is given.



a) uni-directional flow, $\Delta p_{flood} \le \Delta p_{ij}$ **b) bi-directional flow, $\Delta p_{ij} < \Delta p_{flood}$**

Key

1 enclosure *i*

2 enclosure *j*

3 velocity profile

Figure A.10 — Pressure difference across a vertical vent and corresponding flow directions in case of $T_i > T_j$, ($\rho_i < \rho_j$)

A.4.8.2 Gas density of an enclosure

The gas density of enclosure i is calculated by Formula (A.14).

A.4.8.3 Mass Flow Rate

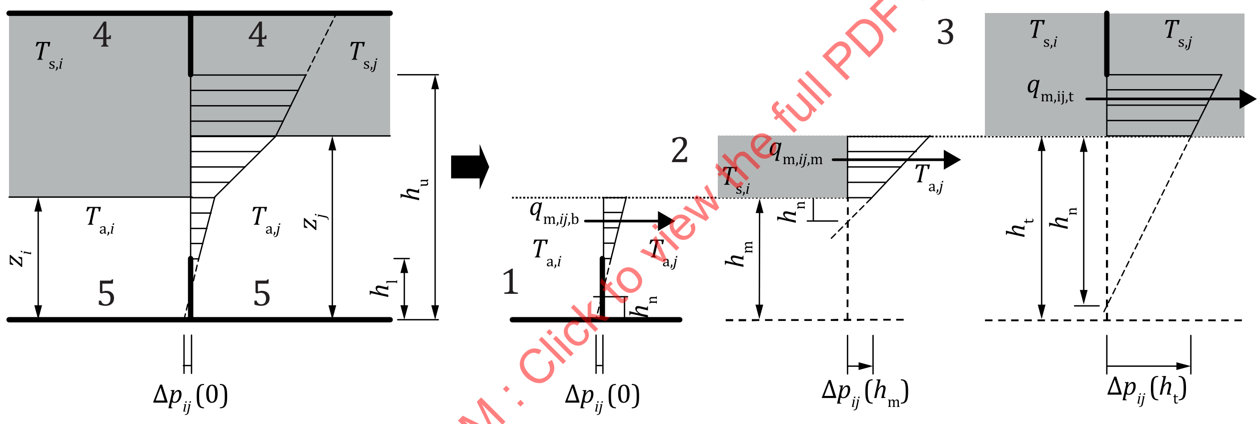
Flow through a horizontal vent can be calculated by the orifice flow Formula (A.1). If the pressure difference is sufficiently large to cause uni-directional flow, $\Delta p_{ij} > \Delta p_{\text{flood}}$, Formula (A.36) applies:

$$q_{\text{m},ij} = C_\text{D} A_{ij} \sqrt{2\rho_i \Delta p_{ij}} \quad \text{(A.36)}$$

A.4.9 Two-layered environment — Flow through single vertical vent connecting two enclosures

A.4.9.1 Scenario element

In a two-layered environment, the flow through a vent is complicated. As shown in Figure A.11, flow through a vent is calculated in three segments. The bottom segment is in contact with the air layers on both sides. The middle segment is in contact with the smoke and air layers on either side. The top segment is in contact with the smoke layers on both sides.



Key

1 bottom segment
2 middle segment
3 top segment
4 smoke layer
5 air layer

Figure A.11 — Pressure difference and mass flow profile in two-layered environment in case of $T_{s,i} > T_{s,j}$, $(\rho_{s,i} < \rho_{s,j})$ and $T_{a,i} > T_{a,j}$, $(\rho_{a,i} < \rho_{a,j})$

A.4.9.2 Heights of the bottom of each segment

The heights of the bottom of middle and top segments are determined by Formulae (A.37) and (A.38):

$$h_\text{m} = \min(z_i, z_j) \quad \text{(A.37)}$$

$$h_\text{t} = \max(z_i, z_j) \quad \text{(A.38)}$$

A.4.9.3 Gas densities of layers

The densities of smoke and air layers are calculated by Formulae (A.39), (A.40), (A.41) and (A.42):

$$\rho_{a,i} = \frac{353}{T_{a,i}} \tag{A.39}$$

$$\rho_{a,j} = \frac{353}{\mathrm{T}_{a,j}} \tag{A.40}$$

$$\rho_{s,i} = \frac{353}{T_{s,i}} \tag{A.41}$$

$$\rho_{s,j} = \frac{353}{T_{s,j}} \tag{A.42}$$

A.4.9.4 Mass flow rates in the bottom segment

Mass flow rates in the bottom segment ($h < h_m$) are calculated by the Formulae (A.17) to (A.20) in A.4.3 for a vertical vent connecting two enclosures of uniform but different temperatures. The following substitutions [Formulae (A.43) to (A.45)] are necessary to apply Formulae (A.17) to (A.20):

$$T_i = T_{a,i} \tag{A.43}$$

$$T_j = T_{a,j} \tag{A.44}$$

$$h_u = \min(h_u, h_m) \tag{A.45}$$

The neutral plane height above the datum is calculated by Formula (A.46):

$$h_n = \frac{\Delta p_{ij}(0)}{(\rho_{a,i} - \rho_{a,j})g} \tag{A.46}$$

A.4.9.5 Mass flow rates in the middle segment

Mass flow rates in the middle segment ($h_m < h < h_u$) are calculated using Formulae (A.17) to (A.20) with substitutions as shown in Formulae (A.47) to (A.50):

$$T_i = \begin{cases} T_{s,i} & (z_i \le z_j) \\ T_{a,i} & (z_i > z_j) \end{cases} \tag{A.47}$$

$$T_j = \begin{cases} T_{a,j} & (z_i \le z_j) \\ T_{s,j} & (z_i > z_j) \end{cases} \tag{A.48}$$

$$h_l = \max(h_l - h_m, 0) \tag{A.49}$$

$$h_{\mathrm{u}} = \min(h_{\mathrm{t}} - h_{\mathrm{m}}, h_{\mathrm{u}} - h_{\mathrm{m}}) \quad \text{(A.50)}$$

The neutral plane height above the bottom of the middle segment is calculated using Formula (A.51):

$$h_{\mathrm{n}} = \begin{cases} \dfrac{\Delta p_{ij}(h_{\mathrm{m}})}{(\rho_{\mathrm{s},i} - \rho_{\mathrm{a},j})g} & (z_i \leq z_j) \\ \dfrac{\Delta p_{ij}(h_{\mathrm{m}})}{(\rho_{\mathrm{a},i} - \rho_{\mathrm{s},j})g} & (z_i > z_j) \end{cases} \quad \text{(A.51)}$$

where the pressure difference at the bottom of the middle segment is calculated using Formula (A.52):

$$\Delta p_{ij}(h_{\mathrm{m}}) = \Delta p_{ij}(0) - (\rho_{\mathrm{a},i} - \rho_{\mathrm{a},j})g h_{\mathrm{m}} \quad \text{(A.52)}$$

A.4.9.6 Mass flow rates in the top segment

Similarly to the previous two segments, mass flow rates in the top segment ($h_{\mathrm{t}} < h$) are calculated using Formulae (A.17) to (A.20) with substitutions as shown in Formulae (A.53) to (A.56):

$$T_i = T_{\mathrm{s},i} \quad \text{(A.53)}$$

$$T_j = T_{\mathrm{s},j} \quad \text{(A.54)}$$

$$h_{\mathrm{l}} = \max(h_{\mathrm{l}} - h_{\mathrm{t}}, 0) \quad \text{(A.55)}$$

$$h_{\mathrm{u}} = h_{\mathrm{u}} - h_{\mathrm{t}} \quad \text{(A.56)}$$

The neutral plane height above the bottom of the top segment is calculated using Formula (A.57):

$$h_{\mathrm{n}} = \frac{\Delta p_{ij}(h_{\mathrm{t}})}{(\rho_{\mathrm{s},i} - \rho_{\mathrm{s},j})g} \quad \text{(A.57)}$$

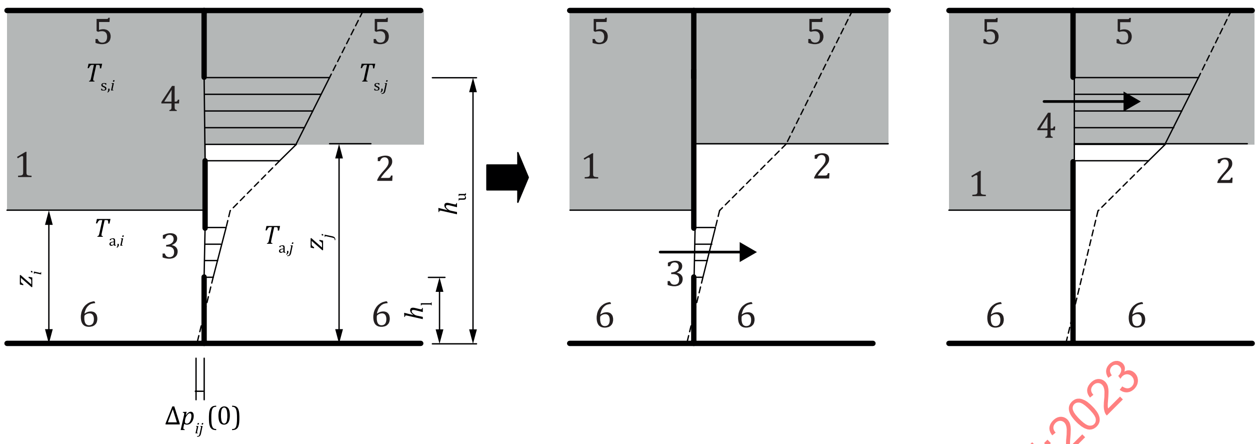
where the pressure difference at the bottom of the top segment is calculated using Formula (A.58):

$$\Delta p_{ij}(h_{\mathrm{t}}) = \Delta p_{ij}(h_{\mathrm{m}}) - \begin{cases} (\rho_{\mathrm{s},i} - \rho_{\mathrm{a},j})g(h_{\mathrm{t}} - h_{\mathrm{m}}), & (z_i < z_j) \\ (\rho_{\mathrm{a},i} - \rho_{\mathrm{s},j})g(h_{\mathrm{t}} - h_{\mathrm{m}}), & (z_i \geq z_j) \end{cases} \quad \text{(A.58)}$$

A.4.10 Two-layered environment — Flow through multiple vertical vents connecting two enclosures

A.4.10.1 Scenario element

In case of multiple vents in a two-layered environment, as shown in Figure A.12, the same Formulae (A.37) to (A.58) as given in A.4.9 are applied to each vent independently.



Key

1 enclosure *i*
2 enclosure *j*
3 vent 1
4 vent 2
5 smoke layer
6 air layer

Figure A.12 — Calculation in case of multiple vents in two-layered environment

A.4.10.2 Heights of the bottom of each segment

The heights of the bottom of each segment are calculated using Formulae (A.37) and (A.38).

A.4.10.3 Gas densities of layers

The gas densities of smoke and air layers are calculated using Formulae (A.39) to (A.42).

A.4.10.4 Mass flow rates in bottom segment

The substitutions of Formulae (A.43) to (A.45) for Formulae (A.17) to (A.20) are made to calculate the mass flow rates in the bottom segment.

A.4.10.5 Mass flow rates in middle segment

The substitutions of Formulae (A.47) to (A.50) for Formulae (A.17) to (A.20) are made to calculate the mass flow rates in the middle segment.

A.4.10.6 Mass flow rates in top segment

The substitutions of Formulae (A.53) to (A.56) for Formulae (A.17) to (A.20) are made to calculate the mass flow rates in the top segment.

A.5 Scientific basis for the formula set

Vent flow has been analysed in relation to quantitative prediction of enclosure fires. Early studies include the prediction of fully developed fire temperatures by Kawagoe[30] based on the suggestions of Sekine. Extensions were made to a two-layered environment by Prahl *et al.*[34] and Rockett.[35] For these early studies, flow formulae were derived by fundamental flow theory. Direct full scale measurements were carried out in the 1980s by Steckler *et al.*[36][37][38] and Nakaya *et al.*[39] These measurements determined that the flow coefficient is in the range of 0,68 to 0,73, and typically 0,7. Further historical aspects are reviewed by Beyler.[40]

A.6 Formula set limitations

A.6.1 Uniformity of smoke layer

The formula set assumes uniform or a two-layered profile of enclosure temperatures adjacent to the vent. When this assumption is not valid, direct use of the integral by Formulae (A.7) and (A.8) is recommended.

A.6.2 Dynamic pressure

The effect of dynamic pressure caused by external wind or mechanical fans is not considered. In such cases, the dynamic pressure distribution should be carefully considered.

A.7 Formula set input parameters

A.7.1 Pressure difference across vents

The parameter, $\Delta p_{ij}(0)$, is defined as the pressure difference at the datum, which is normally taken at the lowest boundary elevation.

A.7.2 Enclosure temperature profile adjacent to vents

The temperature profile adjacent to vents needs to be either uniform or two-layered. In case of uniform profile, the temperature of each enclosure shall be specified. In a two-layered case, smoke layer height, smoke layer temperatures and air layer temperatures shall all be specified.

A.7.3 Flow coefficient of vents

The flow coefficient C_D is typically 0,7 for simple vents. For various vents, example values are collected in Annex B.

A.8 Formula set domain of applicability

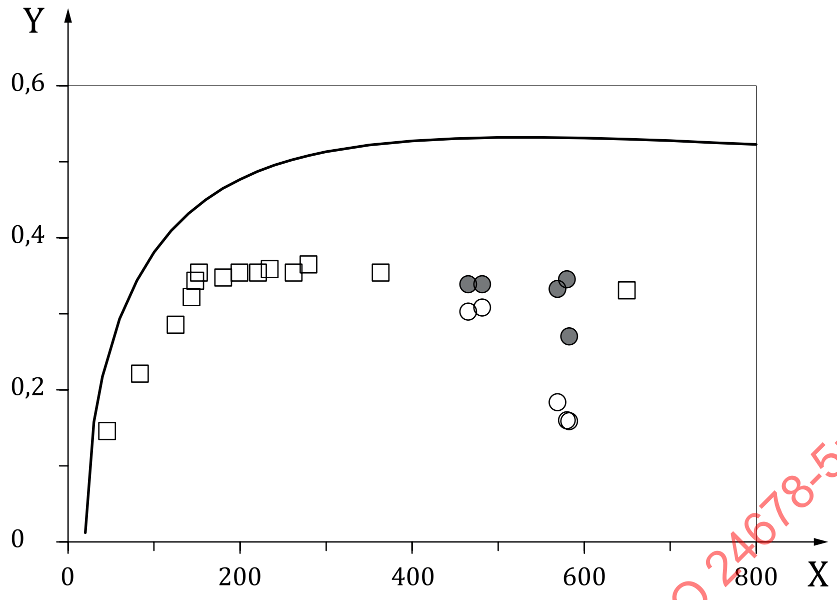
A.8.1 General

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

A.8.2 Comparison with experiments

A.8.2.1 Flow through single vertical vent connecting two enclosures of uniform but different temperatures — Special case of single vent in one enclosure

Kawagoe[41] carried out full-scale fire experiments of a concrete block structure. The room dimension was approximately 3 m × 3 m. Ceiling height was 2,4 m. A single vent was equipped in one of the walls. The size was 1,05 m × 1,8 m. The velocity profile at the vent was measured by Pitot tubes. During the post flashover period, the vertical temperature profile of the fire room and the velocity profile at a vent were measured. Similarly, Harmathy carried out experiments under uniform fire room temperature[42] as reviewed by Prahl and Emmons[34]. Figure A.13 shows the results of measurements compared with calculations using Formulae (A.25) and (A.26). Using the data, a comparison was made for normalized mass flow rate, $q_{m,ij}/B_{ij}(h_u\text{-}h_l)^{1/2}$. Both data are consistent, but smaller than calculated results.



Key

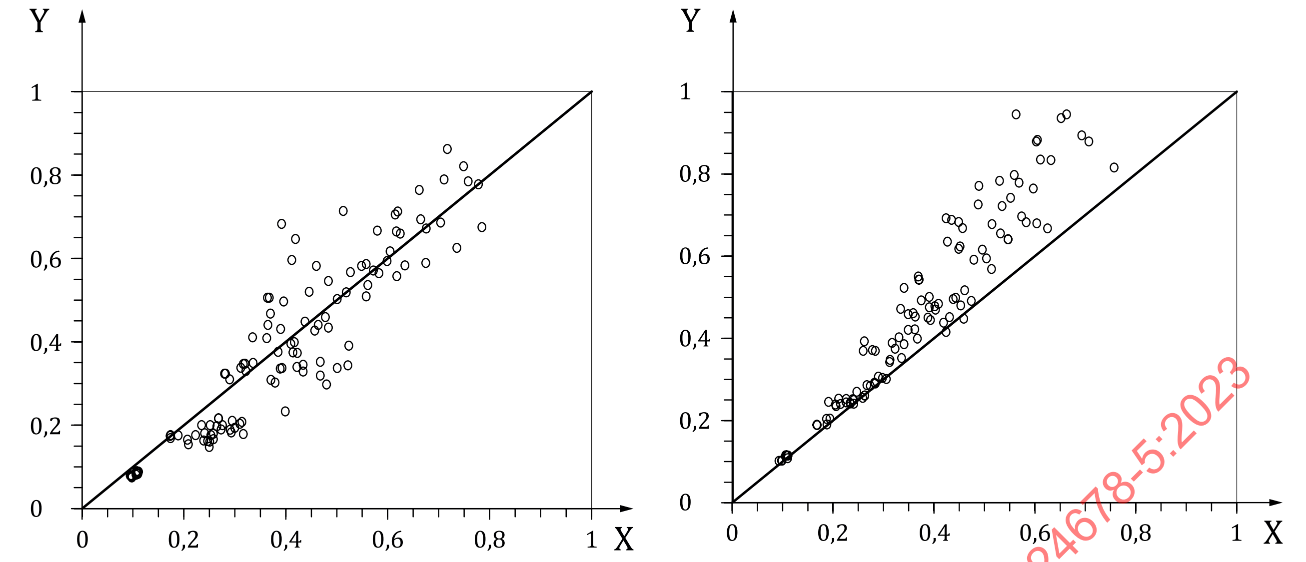
X	enclosure temperature (ºC)
Y	normalized mass flow rate (-)
○	measured by Kawagoe, inflow to enclosure (kg/s)
●	measured by Kawagoe, outflow from enclosure (kg/s)
□	measured by Harmathy (kg/s)
———	calculated using Formula (A.25)

Figure A.13 — Comparison of calculation results with experiments by Kawagoe[41] and by Harmathy[42]

A.8.2.2 Two-layered environment — Flow through a single vertical vent in single room experiments by Quintiere *et al.*

Single room experiments were conducted by Quintiere *et al.*[43] The room dimension was 2,8 m × 2,8 m × 2,18 m (height). A single vent was equipped on a wall. A line burner with methane gas was used. The heat release rate was in the range of 30 kW to 120 kW. A smoke layer was developed in the room. In case of a doorway vent, height was fixed to 1,83 m. Widths were varied in the range of 0,24 m to 0,99 m. In case of a window vent, the width was fixed to 0,74 m. Heights were varied to 0,46 m, 0,92 m and 1,38 m. Mass flow rates, smoke layer height, neutral plane height, smoke layer temperature and lower layer temperature were measured.

Using the measured smoke layer height, neutral plane height, smoke layer temperature and lower layer temperature, mass flow rates were calculated using Formulae (A.17) to (A.20). The results are shown in Figure A.14 in comparison with experimental data. In case of inflow air, calculated results scatter along the median value of measurements. In case of outflow smoke, calculated values are slightly larger than measurements.



a) Mass flow rates of air into the enclosure

b) Mass flow rates of smoke out from the enclosure

Key

X measured mass flow rates of air into enclosure (kg/s)

Y calculated mass flow rates of air into enclosure (kg/s)

Key

X measured mass flow rates of smoke out from enclosure (kg/s)

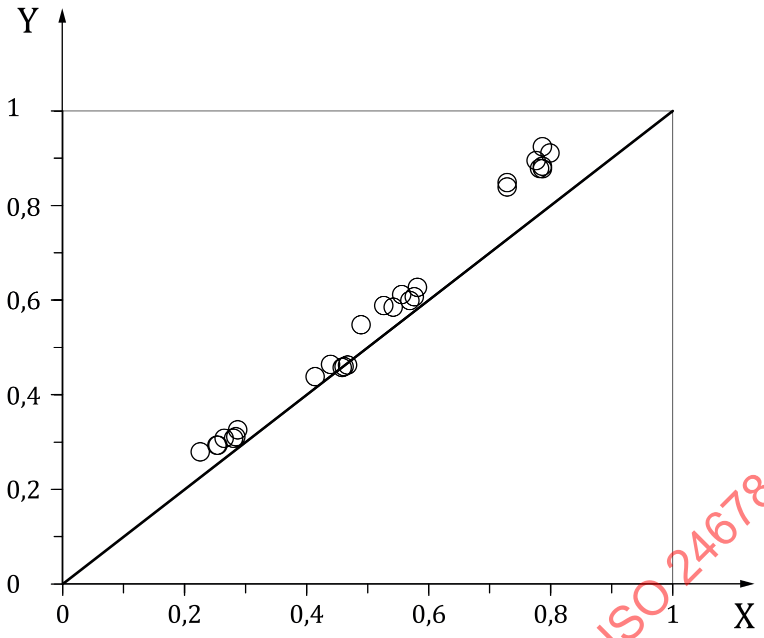
Y calculated mass flow rates of smoke out from enclosure (kg/s)

Figure A.14 — Comparisons of calculation results with experiments by Quintiere *et al.*[43]

A.8.2.3 Two Rooms experiments by Nakaya et al.

Nakaya *et al.* carried out two-rooms experiments.[39] The size of the burn room was 3,45 m (width) × 3,45 m (depth) × 2,12 m (height). The adjacent room size was 3,45 m (width) × 3,45 m (depth) × 2,17 m (height). Single vent was equipped between burn room and adjacent room. The size of the vent was varied. Another vent was equipped between adjacent room and outside. The size was 1,8 m (width) × 1,8 m (height).

Fire source was a propane gas burner of 0,6 m × 0,6 m. The burner strength was varied in the range of 100 to 600 kW. Temperature of the burn room was almost uniform, while the temperature of the adjacent room was two-layered. The mass flow rate through the vent was measured but assumed that inflow and outflow rates are identical. The incoming mass flow rates were calculated using Formula (A.18). The comparison results are shown in Figure A.15. The calculated results are slightly larger than the experimental values.



Key

X measured mass flow rate of air into burn room(kg/s)

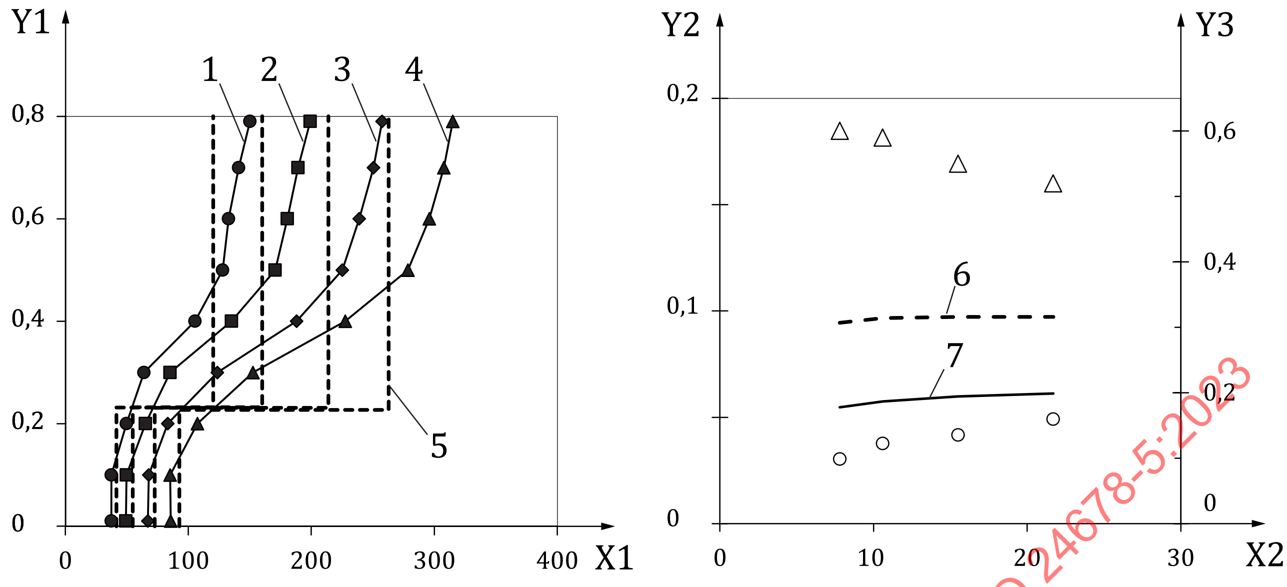
Y calculated mass flow rate of air into burn room (kg/s)

Figure A.15 — Comparison of calculation results with experiments by Nakaya *et al.*[39]

A.8.2.4 Model scale experiments by Koched *et al.*

Formulae (A.43) to (A.58) in A.4.9 are compared with a series of model scale experiments by Koched *et al.*[44] The model box was 1,0 m × 1,3 m. The ceiling height was 0,8 m. A doorway opening of 0,26 m (width) × 0,65 m (height) was equipped. A propane gas burner was set in the box. Heat release rates were varied in the range of 7,5 kW to 21,7 kW. Using a particle image velocimetry (PIV) system, the velocity profile at the doorway opening was measured. The mass flow rates and neutral plane heights were determined from the measured velocity profile. The vertical temperature profile was measured as shown in Figure A.16 a). Two-layered profiles are fitted to measured temperature profiles in order to apply Formulae (A.37) to (A.58). The pressure difference at floor level was calculated so that the inflow and outflow mass flow rates are balanced.

The calculated results are shown in Figure A.16 b) in comparison with measured data. Mass flow rates are calculated as being slightly larger than in experiments. Neutral plane heights are calculated as being lower than in experiments.



a) Vertical temperature profile **b) Mass flow rates and neutral plane heights**

Key

X	temperature (ºC)
Y1	height above floor (m)
—○—	Q = 7,8 kW
—□—	Q = 10,6 kW
—◇—	Q = 15,5 kW
—△—	Q = 21,7 kW
- - - -	approximation by two-layered profile

Key

X	heat release rate (kW)
Y2	incoming mass flow rate (kg/s)
Y3	neutral plane height (m)
○	measured incoming mass flow rate (kg/s)
——	calculated incoming mass flow rate (kg/s)
△	measured neutral plane height (m)
- - - -	calculated neutral plane height (m)

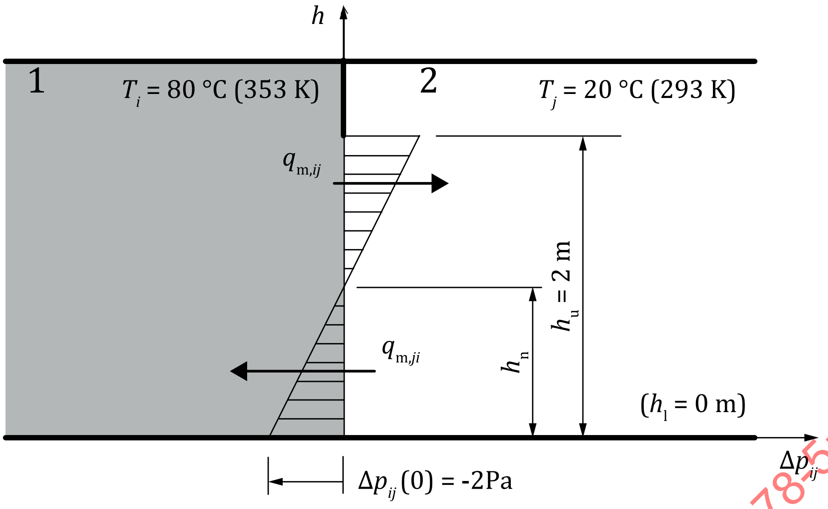
Figure A.16 — Comparison of calculation results with experiments by Koched *et al.*[44]

A.9 Calculation examples

A.9.1 Flow through single vertical vent connecting two enclosures of uniform but different temperatures — General case

A.9.1.1 Calculation conditions

As an example for A.4.3, the flow rate through a doorway (0,9 m wide, 2,0 m high) is calculated. It is assumed that T_i is 80 °C (353 K) and T_j is 20 °C (293 K). Pressure in enclosure j is higher than that in enclosure i at the floor level by 2 Pa ($\Delta p_{ij}(0)$ = −2 Pa) as shown in Figure A.17.



Key

1 enclosure *i*

2 enclosure *j*

Figure A.17 — Calculation example of mass flow rates in uniform temperatures

A.9.1.2 Gas densities of enclosures

The gas densities of the two enclosures are calculated by Formulae (A.59) and (A.60) [based on Formulae (A.14) and (A.15)]:

$$\rho_i = \frac{353}{T_i} = \frac{353}{353} = 1{,}000 \quad \text{(A.59)}$$

$$\rho_j = \frac{353}{T_j} = \frac{353}{293} = 1{,}205 \quad \text{(A.60)}$$

where ρ_i and ρ_j are expressed in kg/m^3.

A.9.1.3 Neutral plane height above the datum

The neutral plane height above the datum is calculated by Formulae (A.61) [based on Formula (A.16)]:

$$h_n = \frac{\Delta p_{ij}(0)}{(\rho_i - \rho_j)g} = \frac{-2}{(1{,}0 - 1{,}205) \times 9{,}8} = 0{,}997 \quad \text{(A.61)}$$

where h_n is expressed in m.

A.9.1.4 Mass flow rates

As the neutral plane height, h_n, is between h_u and h_l, flow is bi-directional. Based on Formulae (A.17) and (A.18), mass flow rates to and from enclosure *j* are calculated using Formulae (A.62) and (A.63):

$$q_{m,ij} = \frac{2}{3} C_D B_{ij} \sqrt{2\rho_i (\rho_j - \rho_i) g} (h_u - h_n)^{3/2}$$

$$= \frac{2}{3} \times 0{,}7 \times 0{,}9 \sqrt{2 \times 1{,}00 \times (1{,}205 - 1{,}0) \times 9{,}8} \times (2{,}0 - 0{,}997)^{3/2} \quad \text{(A.62)}$$

$$= 0{,}846$$

$$q_{m,ji} = \frac{2}{3} C_D B_{ij} \sqrt{2\rho_j(\rho_j - \rho_i)g} (h_n - h_l)^{3/2}$$
$$= \frac{2}{3} \times 0,7 \times 0,9 \sqrt{2 \times 1,205 \times (1,205 - 1,00) \times 9,8} \times (0,997 - 0,0)^{3/2} \quad (A.63)$$
$$= 0,919$$

where $q_{m,ij}$ and $q_{m,ji}$ are expressed in kg/s.

A.9.2 Flow through multiple vertical vents connecting two enclosures of uniform but different temperatures

A.9.2.1 Calculation conditions

As an example for A.4.5, flow through multiple vertical vents connecting two enclosures is calculated. Consider two vents connecting enclosures i and j as shown in Figure A.7. Dimensions of vent 1 are $B_{ij,1}$=0,9 m (width), $h_{l,1}$=0,7 m (lower height), and $h_{u,1}$=1,2 m (upper height). Dimensions of vent 2 are $B_{ij,2}$=2,0 m (width), $h_{l,2}$=1,8 m (lower height) and $h_{u,2}$=4,0 m (upper height). It is assumed that T_i is 80 °C (353 K) and T_j is 20 °C (293 K). Pressure in enclosure j is higher than that in enclosure i at the floor level by 5 Pa: $\Delta p_{ij}(0)$= −5 Pa.

A.9.2.2 Gas densities of enclosures

The gas densities of the two enclosures are calculated by Formulae (A.64) and (A.65) [based on Formulae (A.14) and (A.15)]:

$$\rho_i = \frac{353}{T_i} = \frac{353}{353} = 1,000 \quad (A.64)$$

$$\rho_j = \frac{353}{T_j} = \frac{353}{293} = 1,205 \quad (A.65)$$

where ρ_i and ρ_j are expressed in kg/m^3.

A.9.2.3 Neutral plane height above the datum

The neutral plane height above the datum is calculated using Formula (A.66) [based on Formula (A.16)]:

$$h_n = \frac{\Delta p_{ij}(0)}{(\rho_i - \rho_j)g} = \frac{-5}{(1,000 - 1,205) \times 9,8} = 2,491 \quad (A.66)$$

where h_n is expressed in m.

A.9.2.4 Mass flow rates

Mass flow rates are calculated for each vent. For vent 1, the neutral plane is located above the upper height of vent. Thus, the flow is uni-directional from enclosure j to enclosure i. Applying the last line in Formula (A.18), the mass flow rate is calculated using Formula (A.67):

$$q_{m,ji,1} = \frac{2}{3} C_D B_{ij,1} \sqrt{2\rho_j(\rho_j - \rho_i)g} \{(h_n - h_{l,1})^{3/2} - (h_n - h_{u,1})^{3/2}\}$$
$$= \frac{2}{3} \times 0,7 \times 0,9 \sqrt{2 \times 1,205 \times (1,205 - 1,00) \times 9,8} \times \{(2,491 - 0,7)^{3/2} - (2,491 - 1,2)^{3/2}\} \quad (A.67)$$
$$= 0,859$$

where $q_{m,ji,1}$ is expressed in kg/s.

For vent 2, the neutral plane is located within the vent. Thus, the flow is bi-directional. Applying the second line in Formula (A.17), the mass flow rate from enclosure *i* to *j* is calculated using Formula (A.68):

$$q_{m,ij,2} = \frac{2}{3} C_D B_{ij,2} \sqrt{2\rho_i (\rho_j - \rho_i) g} (h_{u,2} - h_n)^{3/2}$$
$$= \frac{2}{3} \times 0{,}7 \times 2{,}0 \sqrt{2 \times 1{,}000 \times (1{,}205 - 1{,}000) \times 9{,}8} \times (4{,}0 - 2{,}491)^{3/2} \quad \text{(A.68)}$$
$$= 3{,}46$$

where $q_{m,ij,2}$ is expressed in kg/s.

Applying the second line in Formula (A.18), the mass flow rate from enclosure *j* to *i* is calculated using Formula (A.69):

$$q_{m,ji,2} = \frac{2}{3} C_D B_{ij,2} \sqrt{2\rho_j (\rho_j - \rho_i) g} (h_n - h_{l,2})^{3/2}$$
$$= \frac{2}{3} \times 0{,}7 \times 2{,}0 \sqrt{2 \times 1{,}205 \times (1{,}205 - 1{,}000) \times 9{,}8} \times (2{,}491 - 1{,}8)^{3/2} \quad \text{(A.69)}$$
$$= 1{,}18$$

where $q_{m,ji,2}$ is expressed in kg/s.

A.9.3 Flow through multiple vertical vents connecting two enclosures of uniform but different temperatures — Special case of two small vents

A.9.3.1 Calculation condition

As an example for A.4.6, flow through two small vents is calculated. Consider a shaft as shown in Figure A.8. The upper and lower vent areas are A_{ij} = 1,0 m² and A_{ji} = 2,0 m². The upper vent is located 20 m above the lower vent. The shaft temperature is 80 °C (353 K) and the outside air temperature is 20 °C (293 K).

A.9.3.2 Gas densities of enclosures

The gas densities of the two enclosures are calculated using Formulae (A.70) and (A.71), [based on Formulae (A.14) and (A.15)]:

$$\rho_i = \frac{353}{T_i} = \frac{353}{353} = 1{,}000 \quad \text{(A.70)}$$

$$\rho_j = \frac{353}{T_j} = \frac{353}{293} = 1{,}205 \quad \text{(A.71)}$$

where ρ_i and ρ_j are expressed in kg/m³.

A.9.3.3 Equivalent flow area

The equivalent flow area is calculated using Formula (A.72) [based on Formula (A.30)] as:

$$A_{eq} = \frac{1}{\sqrt{(\frac{1}{A_{ji}})^2 + \frac{\rho_j}{\rho_i}(\frac{1}{A_{ji}})^2}} = \frac{1}{\sqrt{(\frac{1}{1{,}0})^2 + \frac{1{,}205}{1{,}000}(\frac{1}{2{,}0})^2}} = 0{,}877 \quad \text{(A.72)}$$

where A_{eq} is expressed in m².

For practical calculations, the density fraction, ρ_j/ρ_i, in Formula (A.72) is negligible. This is shown in Formula (A.73) for this example:

$$A_{eq} \approx \frac{1}{\sqrt{(\frac{1}{A_{ij}})^2 + (\frac{1}{A_{ji}})^2}} = \frac{1}{\sqrt{(\frac{1}{1,00})^2 + (\frac{1}{2,00})^2}} = 0,894 \quad \text{(A.73)}$$

where A_{eq} is expressed in m^2. The result is within 2 % of error in comparison with the exact value calculated by Formula (A.72).

A.9.3.4 Mass flow rate

The mass flow rate is calculated by Formula (A.74) [based on (A.31)] as:

$$\begin{aligned} q_{m,ij} = q_{m,ji} &= C_D A_{eq} \sqrt{2\rho_j(\rho_j - \rho_i) g (h_{ij} - h_{ji})} \\ &= 0,7 \times 0,877 \sqrt{2 \times 1,205 \times (1,205 - 1,00) \times 9,8 \times 20} = 6,04 \end{aligned} \quad \text{(A.74)}$$

where $q_{m,ij}$ and $q_{m,ji}$ are expressed in kg/s.

A.9.4 Flow through multiple serial vents

A.9.4.1 calculation condition

As an example for A.4.7, flow through multiple serial vents is calculated. In this example, enclosures i, j and k are connected by two vents in series as shown in Figure A.9. The vent height is h_u=2,1 m, h_l=0 m. The vent widths are B_{ij}=B_{jk}=1 m. The temperatures of enclosures are T_i = 200 °C (473 K), T_k = 20 °C (293 K). The pressure difference between enclosures i and k is $\Delta p_{ik}(0)$ = −6 Pa at the floor level.

A.9.4.2 Gas densities in enclosures

The gas densities of the two enclosures are calculated using Formulae (A.75) and (A.76) [based on Formulae (A.32) and (A.33)]:

$$\rho_i = \frac{353}{T_i} = \frac{353}{473} = 0,746 \quad \text{(A.75)}$$

$$\rho_k = \frac{353}{T_k} = \frac{353}{293} = 1,205 \quad \text{(A.76)}$$

where ρ_i and ρ_k are expressed in kg/m^3.

A.9.4.3 Equivalent vent width

The equivalent vent width is calculated using Formula (A.77) [based on Formula (A.34)]:

$$B_{eq} = \frac{1}{\sqrt{(\frac{1}{B_{ij}})^2 + (\frac{1}{B_{jk}})^2}} = \frac{1}{\sqrt{(\frac{1}{1,0})^2 + (\frac{1}{1,0})^2}} = 0,707 \quad \text{(A.77)}$$

where B_{eq} is expressed in m.

A.9.4.4 Neutral plane height

The neutral plane height is calculated using Formula (A.78) [based on Formula (A.16)]:

$$h_{\rm n} = \frac{\Delta p_{ik}(0)}{(\rho_i - \rho_k)g} = \frac{-6}{(0{,}746 - 1{,}205) \times 9{,}8} = 1{,}335 \tag{A.78}$$

where $h_{\rm n}$ is expressed in m.

A.9.4.5 Mass flow rate

The mass flow rates are calculated using Formulae (A.79) and (A.80) [based on Formulae (A.17) and (A.18)]:

$$\begin{aligned} q_{{\rm m},ik} &= \frac{2}{3} C_{\rm D} B_{\rm eq} \sqrt{2\rho_i(\rho_k - \rho_i)g} \, (h_{\rm u} - h_{\rm n})^{3/2} \\ &= \frac{2}{3} \times 0{,}7 \times 0{,}707 \sqrt{2 \times 0{,}746 \times (1{,}205 - 0{,}746) \times 9{,}8} \times (2{,}1 - 1{,}335)^{3/2} \\ &= 0{,}57 \end{aligned} \tag{A.79}$$

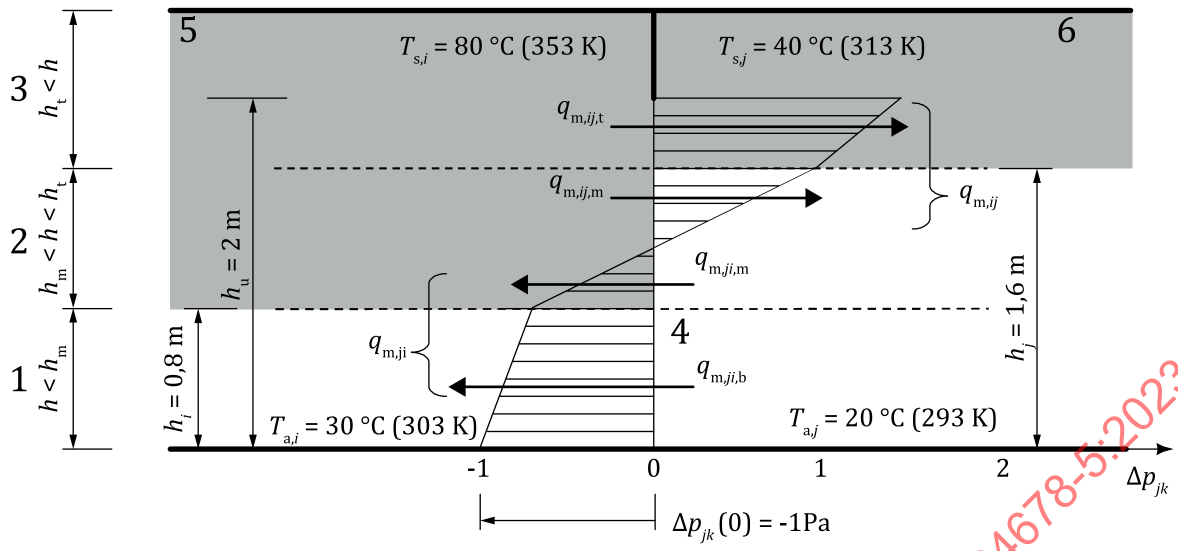
$$\begin{aligned} q_{{\rm m},ki} &= \frac{2}{3} C_{\rm D} B_{\rm eq} \sqrt{2\rho_k(\rho_k - \rho_i)g} \, (h_{\rm n} - h_{\rm l})^{3/2} \\ &= \frac{2}{3} \times 0{,}7 \times 0{,}707 \sqrt{2 \times 1{,}205 \times (1{,}205 - 0{,}746) \times 9{,}8} \times (1{,}335 - 0)^{3/2} \\ &= 1{,}68 \end{aligned} \tag{A.80}$$

where $q_{{\rm m},ik}$ and $q_{{\rm m},ki}$ are expressed in kg/s.

A.9.5 Two-layered environment — Flow through single vertical vent connecting two enclosures

A.9.5.1 Calculation condition

As an example for A.4.9, flow through a single vertical vent connecting two layered enclosures is calculated. Consider two enclosures as shown in Figure A.18. Smoke layers are formed in the upper parts of the two enclosures. The smoke layer heights are 0,8 m and 1,6 m in enclosures *i* and *j*, respectively. Smoke layer temperatures are 80 °C (353 K) and 40 °C (313 K). Lower layer temperatures are 30 °C (303 K) and 20 °C (293 K). The pressure in enclosure *j* is higher than that in enclosure *i* by 1 Pa at the datum, $\Delta p_{ij}(0)$ = −1 Pa. The vent width, B_{ij}, is 0,9 m and the vent height is 2,0 m ($h_{\rm l}$=0,0 m, $h_{\rm u}$ = 2,0 m). Mass flow rates are calculated for each segment.



Key

1 bottom segment
2 middle segment
3 top segment
4 vent
5 enclosure *i*
6 enclosure *j*

Figure A.18 — A calculation example of mass flow rates in two-layered environment

A.9.5.2 Mass flow rates in the bottom segment

The range of the bottom segment is $0 < h < h_m$ (= 0,8 m). The gas density is calculated using Formulae (A.81) and (A.82) [based on Formulae (A.39) and (A.40)] as:

$$\rho_{a,i} = \frac{353}{T_i} = \frac{353}{303} = 1{,}165 \quad \text{(A.81)}$$

$$\rho_{a,j} = \frac{353}{T_j} = \frac{353}{293} = 1{,}205 \quad \text{(A.82)}$$

where $\rho_{a,i}$ and $\rho_{a,j}$ are expressed in kg/m^3.

The neutral plane height is calculated by Formula (A.83) [based on Formula (A.46)] as:

$$h_n = \frac{\Delta p_{ij}(0)}{(\rho_{a,i} - \rho_{a,j})g} = \frac{-1}{(1{,}165 - 1{,}205) \times 9{,}8} = 2{,}566 \quad \text{(A.83)}$$

where h_n is expressed in m.

As the neutral plane height, h_n, is larger than segment height, h_m, the flow is uni-directional from enclosure j to enclosure i. Using the last line of Formula (A.18), the mass flow rate in the bottom segment is calculated as show in Formula (A.84):

$$\begin{aligned} q_{m,ji,b} &= \frac{2}{3} C_D B_{ij} \sqrt{2\rho_{a,j}\left(\rho_{a,j}-\rho_{a,i}\right) g}\,\{h_n^{3/2}-(h_n-h_m)^{3/2}\} \\ &= \frac{2}{3}\times 0{,}7\times 0{,}9\sqrt{2\times 1{,}205\times(1{,}205-1{,}165)\times 9{,}8}\times\{2{,}566^{3/2}-(2{,}566-0{,}8)^{3/2}\} \\ &= 0{,}718 \end{aligned} \qquad \text{(A.84)}$$

where $q_{m,ji,b}$ is expressed in kg/s.

A.9.5.3 Mass flow rates in the middle segment

The range of the middle segment is h_m (=0,8 m) < h < h_t (=1,6 m). The pressure difference at the bottom of the middle segment is calculated using Formula (A.85) [based on Formula (A.52)] as:

$$\begin{aligned} \Delta p_{ij}(h_m) &= \Delta p_{ij}(0)-(\rho_{a,i}-\rho_{a,j})\,g\,h_m \\ &= -1-(1{,}165-1{,}205)\times 9{,}8\times 0{,}8 \\ &= -0{,}689 \end{aligned} \qquad \text{(A.85)}$$

where $\Delta p_{ij}(h_m)$ is expressed in Pa.

The neutral plane height for this segment is calculated using Formulae (A.86) and (A.87) [based on Formulae (A.41) and (A.51)] as:

$$\rho_{s,i} = \frac{353}{T_i} = \frac{353}{353} = 1{,}000 \qquad \text{(A.86)}$$

$$h_n = \frac{\Delta p_{ij}(H_m)}{(\rho_{s,i}-\rho_{a,j})g} = \frac{-0{,}686}{(1{,}000-1{,}205)\times 9{,}8} = 0{,}343 \qquad \text{(A.87)}$$

where $\rho_{s,i}$ is expressed in kg/m^3 and h_n is expressed in m.

As 0 < h_n < $h_u - h_m$, flow is bi-directional. Using the second line in Formula (A.17) and the second line in Formula (A.20), the mass flow rates are calculated as shown in Formulae (A.88) and (A.89):

$$\begin{aligned} q_{m,ij,m} &= \frac{2}{3} C_D B_{ij} \sqrt{2\rho_{s,i}\left(\rho_{a,j}-\rho_{s,i}\right) g}\,\left\{(h_j-h_i)-h_n\right\}^{3/2} \\ &= \frac{2}{3}\times 0{,}7\times 0{,}9\times\sqrt{2\times 1{,}0\times(1{,}205-1{,}000)\times 9{,}8}\times\{(1{,}6-0{,}8)-0{,}343\}^{3/2} \\ &= 0{,}260 \end{aligned} \qquad \text{(A.88)}$$

$$\begin{aligned} q_{m,ji,m} &= \frac{2}{3} C_D B_{ij} \sqrt{2\rho_{a,j}(\rho_{a,j}-\rho_{s,i})g}\,h_n^{3/2} \\ &= \frac{2}{3}\times 0{,}7\times 0{,}9\times\sqrt{2\times 1{,}205\times(1{,}205-1{,}000)\times 9{,}8}\times 0{,}343^{3/2} \\ &= 0{,}186 \end{aligned} \qquad \text{(A.89)}$$

where $q_{m,ij,m}$ and $q_{m,ji,m}$ are expressed in kg/s.