BS ISO 16737:2012

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Fire safety engineering — Requirements governing algebraic equations — Vent flows

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National foreword

This British Standard is the UK implementation of ISO 16737:2012.

The UK participation in its preparation was entrusted to Technical Committee FSH/24, Fire safety engineering.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Contents

Foreword

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

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

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

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

ISO 16737 was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

This second edition cancels and replaces the first edition (ISO 16737:2006), which has been technically revised.

Introduction

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

Algebraic formulas 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 formulas discussed in this International Standard are very useful for quantifying the consequences of design fire scenarios. Such formulas are particularly valuable for allowing the practitioner to determine very quickly how a tentative fire safety design should be modified to meet performance criteria, without having to spend time on detailed numerical calculations until the stage of final design documentation. Examples of areas where algebraic formulas 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 enclosure fire hazards such as smoke filling and flashover.

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

Fire safety engineering — Requirements governing algebraic equations — Vent flows

1 Scope

1.1 This International Standard specifies requirements for the application of algebraic formula set for the calculation of specific characteristics of vent flows.

1.2 This International Standard is an implementation of the general high-level requirements for the case of fire dynamics calculations involving sets of algebraic formulas.

1.3 This International Standard is arranged in the form of a template, where specific information relevant to algebraic vent flow formulas 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.

NOTE Examples of sets of algebraic formulae meeting all the requirements of this International Standard will be provided in separate annexes for each different type of vent flow scenario. Currently, there are two informative annexes containing general information on vent flows and specific algebraic formulas for practical engineering calculations.

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 13943, *Fire safety — Vocabulary*

ISO 16730, *Fire safety engineering — Assessment, verification and validation of calculation methods*

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

3 Terms and definitions

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

4 Requirements governing description of physical phenomena

4.1 The buoyant flow through a vent resulting from a source fire in an enclosure having one or more openings 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.

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

4.3 Vent flow characteristics to be calculated and their useful ranges shall be clearly identified, including those characteristics inferred by association with calculated quantities.

4.4 Scenario elements (e.g. two-layer environments, uniform mixture, etc.) to which specific formulas apply shall be clearly identified.

4.5 Because different formulas describe different vent flow 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 The procedure to be followed in performing calculations shall be described through a set of algebraic formulas.

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

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

5.4 The scientific basis for the formula set shall be provided through reference to recognized handbooks, the peer-reviewed scientific literature or through derivations, as appropriate.

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

6 Requirements governing limitations

6.1 Quantitative limits on direct application of the algebraic formula 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 formula set within a more general calculation method shall be provided, which shall include checks of consistency with the other relations used in the calculation method and the numerical procedures employed.

7 Requirements governing input parameters

7.1 Input parameters for the set of algebraic formulas shall be identified clearly, such as layer temperature, pressure and geometric dimensions.

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

7.3 The valid ranges for input parameters shall be listed as specified in ISO 16730.

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 formula set. These data shall have a level of quality (e.g. repeatability, reproducibility – see ISO 5725) assessed through a documented/standardized procedure).

8.2 The domain of applicability of the algebraic formulas shall be determined through comparison with the measurement data of 8.1.

8.3 Potential sources of error that limit the set of algebraic formulas to the specific scenarios given in Clause 4 shall be identified, for example, the assumption of one or more uniform gas layers in an enclosed space.

Annex A
(informative)

General aspects of vent flows

A.1 Terms and definitions used in this annex

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

A.1.1

boundary

surface that defines the extent of an enclosure

A.1.2

datum

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

A.1.3

enclosure

room, space or volume that is bounded by surfaces

A.1.4

flow coefficient

empirical efficiency factor that accounts for the difference between the actual and the theoretical flow rate through a vent

A.1.5

hydrostatic pressure

atmospheric pressure gradient associated with height

A.1.6

interface position

smoke layer height

elevation of the smoke layer interface relative to datum, typically the elevation of the lowest boundary of the enclosure

A.1.7

neutral plane height

elevation at which the pressure inside an enclosure is the same as the pressure outside the enclosure

A.1.8

pressure difference

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

A.1.9

smoke

airborne stream of 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 stream

A.1.10

smoke layer

hot upper layer

hot gas 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

A.1.11

smoke layer interface

horizontal plane separating the smoke layer from the lower layer

A.1.12

vent

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

A.1.13

vent flow

flows of smoke or air through a vent in an enclosure boundary

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

A.2.1 Scope

This annex is intended to document the general methods that can be used to calculate mass flow rate through a vent. The formula set is based on orifice flow theory.

A.2.2 General description of calculation method

The calculation 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 between the enclosure and the adjacent spaces. 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 International Standard. 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 interface height, temperature, and other properties are calculated by the principle of heat and mass conservation for the smoke layer as described in ISO 16735.

A.2.3 Vent flow characteristics to be calculated

Formulas provide the mass flow rate, enthalpy and chemical species flow rate.

A.3 Symbols and abbreviated terms used in this annex

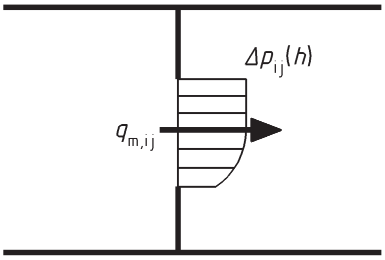
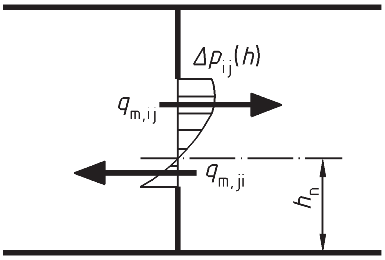
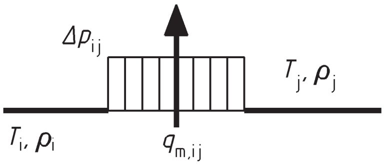
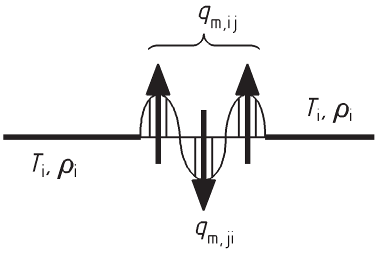
A	area of vent (m^2)
B	width of vent (m)
C_D	flow coefficient (–)
g	gravity acceleration ($m\ s^{-2}$)
h_l	height of lower edge of vent above datum (m)
h_u	height of upper edge of vent above datum (m)
$\max(x_1, x_2)$	maximum of x_1 and x_2
$q_{m,ij}$	mass flow rate flowing out from enclosure i into enclosure j ($kg\ s^{-1}$)
$q_{m,ji}$	mass flow rate flowing out from enclosure j into enclosure i ($kg\ s^{-1}$)
$p_i(h)$	pressure in enclosure i at height h above datum (Pa)
$p_j(h)$	pressure in enclosure j at height h above datum (Pa)
T	temperature (K)
T_0	reference temperature (K)
v	flow velocity ($m\ s^{-1}$)
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 ($kg\ m^{-3}$)
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)
ξ	height used as integration variable (m)

A.4 Formula-set documentation

A.4.1 List of formula sets

The velocity of flow through vents is calculated according to orifice flow theory based on application of the Bernoulli equation. Methods to calculate vent flows are developed for the conditions shown in Table A.1. For the case of vertical and horizontal vents, flow may be uni-directional or bi-directional. For horizontal vents, bi-directional flow takes place only for special cases when the pressure difference is small. Explicit formulas presented here are applicable to flow through vertical vents and uni-directional flow through horizontal vents.

Table A.1 — Conditions of vent flow calculation

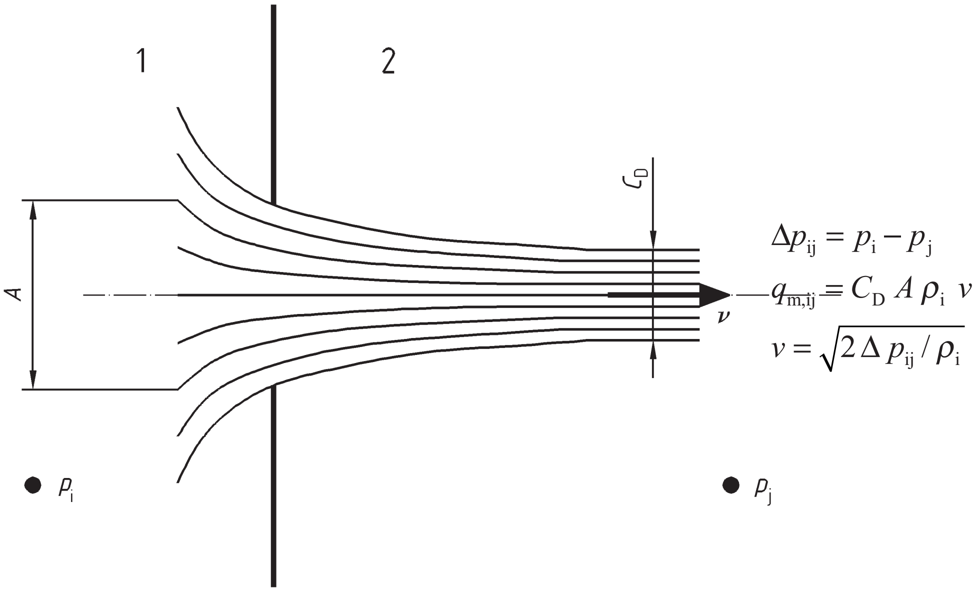
	uni-directional flow	bi-directional flow
vertical vent	 	
horizontal vent	 	 Flow is unstable. No explicit formula is available at present.

A.4.2 Orifice flow — Uniform pressure distribution over vent area

When pressure difference is created by some actions such as external wind or mechanical fans, the flow through the vent is given by:

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

where $\Delta p_{ij} = p_i - p_j$ and the assumption is made 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

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

A.4.3 Hydrostatic pressure difference

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

$$\rho_i(h) = \frac{\rho_0 T_0}{T_i(h)} \approx \frac{353}{T_i(h)} \tag{A.2}$$

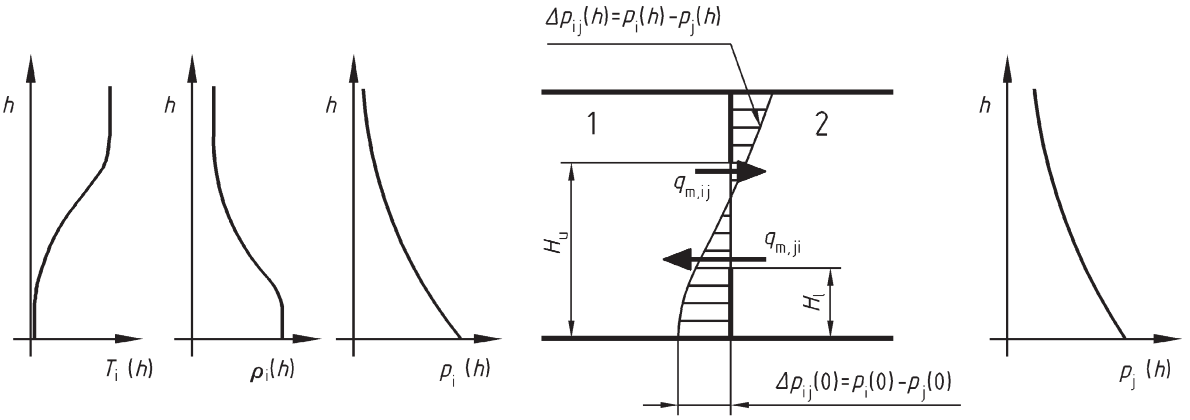
The hydrostatic pressure in enclosure is calculated by integrating gas density over height to yield

$$p_i(h) = p_i(0) - \int_0^h \rho_i(\zeta) g \,\mathrm{d}\zeta \tag{A.3}$$

Hydrostatic pressure difference between enclosures i and j at height h is

$$\begin{aligned} \Delta p_{ij}(h) &= p_i(h) - p_j(h) \\ &= \{p_i(0) - p_j(0)\} - \int_0^h \{\rho_i(\zeta) - \rho_j(\zeta)\} g \,\mathrm{d}\zeta \;. \\ &= \Delta p_{ij}(0) - \int_0^h \{\rho_i(\zeta) - \rho_j(\zeta)\} g \,\mathrm{d}\zeta \end{aligned} \tag{A.4}$$

NOTE To derive Formula (A.2), smoke gas is approximated by an ideal gas whose property is identical to air at normal atmospheric pressure.



Key

1 enclosure i
2 enclosure j

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

A.4.4 General flow equation — Flow through vertical vent with pressure difference

When the pressure difference across the vent is not uniform over the vent area, flow through the vent is calculated by applying orifice flow theory to each part of the vent, as shown in Figure A.2. Given the hydrostatic pressure difference by Formula (A.4), mass flow rates between enclosures are calculated by

$$q_{\mathrm{m,ij}} = C_{\mathrm{D}} B \int_{h_{\mathrm{l}}}^{h_{\mathrm{u}}} \sqrt{2\rho_{\mathrm{i}}(\varsigma)\max(\Delta p_{\mathrm{ij}}(\varsigma),0)}\,\mathrm{d}\varsigma \tag{A.5}$$

$$q_{\mathrm{m,ji}} = C_{\mathrm{D}} B \int_{h_{\mathrm{l}}}^{h_{\mathrm{u}}} \sqrt{2\rho_{\mathrm{j}}(\zeta)\max(-\Delta p_{\mathrm{ij}}(\zeta),0)}\,\mathrm{d}\zeta \tag{A.6}$$

Annex B
(informative)

Specific formulas for vent flows meeting requirements of Annex A

B.1 Description of physical phenomena addressed by the formula set

B.1.1 General

The formulas given in this annex permit the calculation of the mass flow rate of smoke through a vent. 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.1.2 Scenario elements to which the formula set is applicable

The set of formulas is applicable to 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 16735. The calculation conditions are summarized in Table B.1.

Table B.1 — Conditions of vent flow calculation formulas

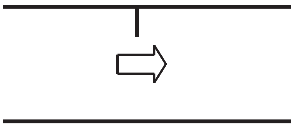
Temperature profile	Arrangement of vent(s)	Flow patterns	Clause
Uniform	Single vent		B.3.1

Table B.1 *(continued)*

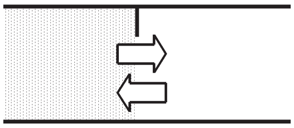
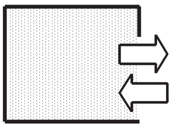
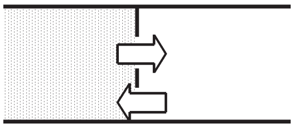
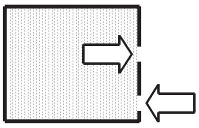
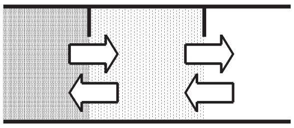
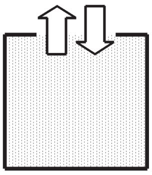
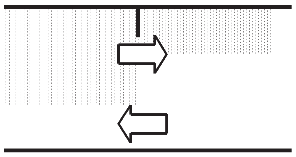
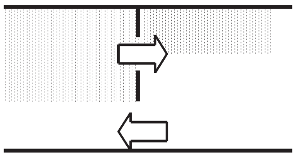
Temperature profile	Arrangement of vent(s)	Flow patterns	Clause
Single layer	Single vertical vent (general case, flow may be either uni-directional or bi-directional)		B.3.2
	Single vertical vent (special case, flow is bi-directional)		B.3.3
	Multiple vertical vents (general case, flow may be either uni-directional or bi-directional)		B.3.4
	Multiple vertical vents (special case of two small vertical vents in one enclosure, flow is bi-directional)		B.3.5
	Multiple serial vertical vents (Combination of multiple serial vents into equivalent single vent)		B.3.6
	Single horizontal vent (unsteady bi-directional flow)		B.3.7

Table B.1 *(continued)*

Temperature profile	Arrangement of vent(s)	Flow patterns	Clause
Two layers	Single vertical vent (general case, flow may be either uni-directional or bi-directional)		B.3.8
	Multiple vertical vents (general case, flow may be either uni-directional or bi-directional)		B.3.9

B.1.3 Vent flow characteristics to be calculated

Formulas provide mass flow rates of smoke and air through a vent.

B.1.4 Vent flow conditions to which formulas apply

Explicit formulas provide the flow of smoke through vertical and horizontal vents under specified conditions.

B.1.5 Self-consistency of the formula set

The formula set is developed in a self-consistent manner.

B.1.6 Standards and other documents where the formula set is used

ISO 16735:2006, *Fire safety engineering — Requirements governing algebraic equations — Smoke layers*

B.2 Symbols and abbreviated terms used in this annex

In addition to the symbols and abbreviated terms used in Annex A, the following terms are used in this annex.

abs(x)	absolute value of x
A_{ij}	area of vent connecting enclosures i and j (m^2)
B_{ij}	width of vent between enclosures i and j (m)
c_p	specific heat of air and smoke (kJ kg^{-1}K^{-1})
h	height above datum (m)
h_m	height of middle segment base above datum in case of two-layers environment (m)
h_n	height of neutral plane above datum (m)
h_t	height of top segment base above datum in case of two-layers environment (m)
$\dot{H}'_{ij}$	enthalpy flux from enclosure i to enclosure j (kW)
min(x_1, x_2)	minimum of x_1 and x_2
$q'_{m,ij}$	mass flux of chemical species from enclosure i to enclosure j (kg s^{-1})
T_i	temperature of enclosure i (K)

T_j	temperature of enclosure j (K)
$T_{a,i}$	temperature of air layer in enclosure i (K)
$T_{a,j}$	temperature of air layer in enclosure j (K)
$T_{s,i}$	temperature of smoke layer in enclosure i (K)
$T_{s,j}$	temperature of smoke layer in enclosure j (K)
w_i	mass fraction of chemical species in enclosure i (kg kg^{-1})
$\rho_{a,i}$	gas density of air layer in enclosure i (kg m^{-3})
$\rho_{a,j}$	gas density of air layer in enclosure j (kg m^{-3})
$\rho_{s,i}$	gas density of smoke layer in enclosure i (kg m^{-3})
$\rho_{s,j}$	gas density of smoke layer in enclosure j (kg m^{-3})

B.3 Formula-set documentation

B.3.1 Flow through vent connecting two enclosures of uniform, identical temperature

When a pressure difference, Δp_{ij}, is imposed across a vent with a uniform temperature profile as shown in Figure B.1, the mass flow rate is calculated by

$$q_{m,ij} = C_D A_{ij} \sqrt{2\rho \ \Delta p_{ij}} \tag{B.1}$$

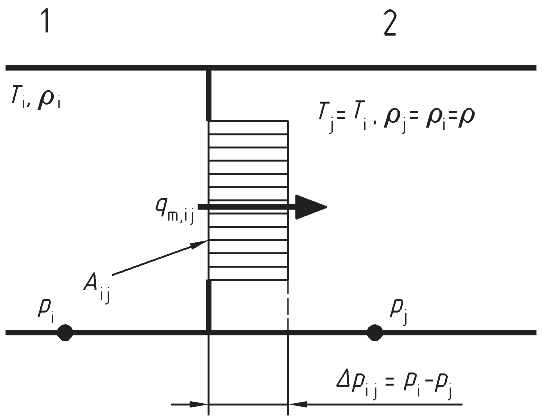
$$\Delta p_{ij} = p_i - p_j \tag{B.2}$$

Enthalpy and chemical species flows are calculated using mass flow rate

$$\dot{H}'_{ij} = c_p (T_i - T_0) q_{m,ij} \tag{B.3}$$

$$q'_{m,ij} = w_i \ q_{m,ij} \tag{B.4}$$

NOTE Formulae for enthalpy and chemical species flows are not repeated in subsequent clauses but Formulae (B.3) and (B.4) are applicable for all cases in this annex.



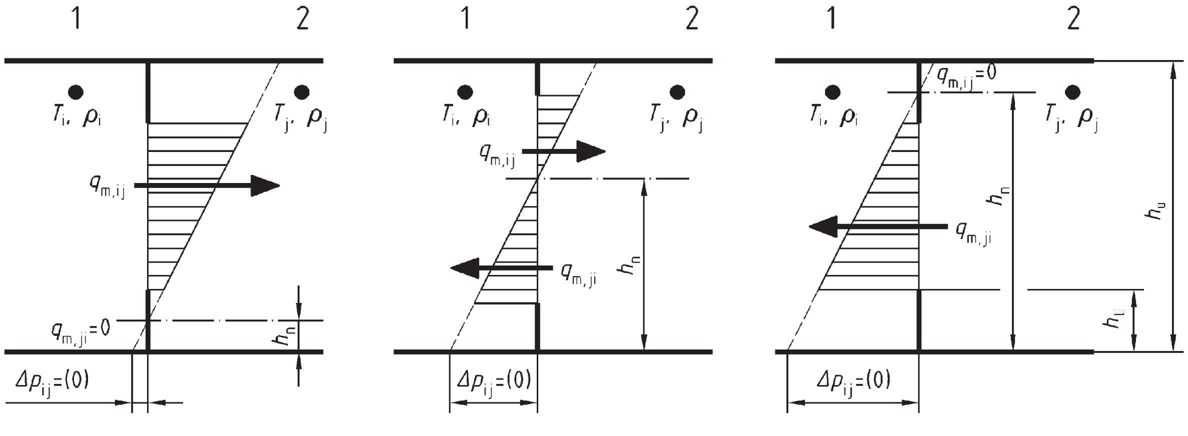
Key

1 enclosure i
2 enclosure j

Figure B.1 — Pressure difference across vertical vent and corresponding flow direction in case of uniform temperature

B.3.2 Flow through single vertical vent connecting two enclosures of uniform but different temperatures — General case

As shown in Figure B.1, flow patterns are classified in accordance with the position of the neutral plane. When the neutral plane exists below the lower edge of the vent, flow is unidirectional from enclosure i to j. When the neutral plane is in the range of opening height, flow is bi-directional. When the neutral plane is above the upper edge of the opening, flow is unidirectional from enclosure j to i [1], [2]. The height of the neutral plane is given by (B.7). Flow rates $q_{m,ij}$, $q_{m,ji}$ are given in Formulae (B.8) to (B.11). Calculation results from this formula set are presented in Figure B.4 in non-dimensional form.



Key

1 enclosure i
2 enclosure j

Figure B.2 — Pressure difference across vertical vent and corresponding flow directions ($\rho_i < \rho_j$)

B.3.2.1 Gas densities of enclosures

$$\rho_{\mathrm{i}} = \frac{353}{T_{\mathrm{i}}} \tag{B.5}$$

$$\rho_{\mathrm{j}} = \frac{353}{T_{\mathrm{j}}} \tag{B.6}$$

B.3.2.2 Height of neutral plane above floor

$$h_{\mathrm{n}} = \frac{\Delta p_{\mathrm{ij}}(0)}{(\rho_{\mathrm{i}} - \rho_{\mathrm{j}})g} \tag{B.7}$$

B.3.2.3 Mass flow rate

In the case of $T_{\mathrm{i}} > T_{\mathrm{j}}$ ($\rho_{\mathrm{i}} < \rho_{\mathrm{j}}$),

$$q_{\mathrm{m,ij}} = \begin{cases} \frac{2}{3} C_{\mathrm{D}} B_{\mathrm{ij}} \sqrt{2\rho_{\mathrm{i}}(\rho_{\mathrm{j}} - \rho_{\mathrm{i}})g}\{(h_{\mathrm{u}} - h_{\mathrm{n}})^{3/2} - (h_{\mathrm{l}} - h_{\mathrm{n}})^{3/2}\} & (h_{\mathrm{n}} < h_{\mathrm{l}}) \\ \frac{2}{3} C_{\mathrm{D}} B_{\mathrm{ij}} \sqrt{2\rho_{\mathrm{i}}(\rho_{\mathrm{j}} - \rho_{\mathrm{i}})g}(h_{\mathrm{u}} - h_{\mathrm{n}})^{3/2} & (h_{\mathrm{l}} \le h_{\mathrm{n}} < h_{\mathrm{u}}) \\ 0 & (h_{\mathrm{u}} \le h_{\mathrm{n}}) \end{cases} \tag{B.8}$$

$$q_{\mathrm{m,ji}} = \begin{cases} 0 & (h_{\mathrm{n}} < h_{\mathrm{l}}) \\ \frac{2}{3} C_{\mathrm{D}} B_{\mathrm{ij}} \sqrt{2\rho_{\mathrm{j}}(\rho_{\mathrm{j}} - \rho_{\mathrm{i}})g}(h_{\mathrm{n}} - h_{\mathrm{l}})^{3/2} & (h_{\mathrm{l}} \le h_{\mathrm{n}} < h_{\mathrm{u}}) \\ \frac{2}{3} C_{\mathrm{D}} B_{\mathrm{ij}} \sqrt{2\rho_{\mathrm{j}}(\rho_{\mathrm{j}} - \rho_{\mathrm{i}})g}\{(h_{\mathrm{n}} - h_{\mathrm{l}})^{3/2} - (h_{\mathrm{n}} - h_{\mathrm{u}})^{3/2}\} & (h_{\mathrm{u}} \le h_{\mathrm{n}}) \end{cases} \tag{B.9}$$

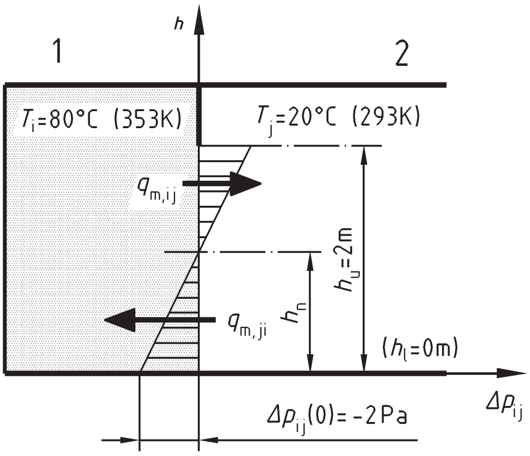
In the case of $T_{\mathrm{i}} < T_{\mathrm{j}}$ ($\rho_{\mathrm{i}} > \rho_{\mathrm{j}}$),

$$q_{\mathrm{m,ij}} = \begin{cases} 0 & (h_{\mathrm{n}} < h_{\mathrm{l}}) \\ \frac{2}{3} C_{\mathrm{D}} B_{\mathrm{ij}} \sqrt{2\rho_{\mathrm{i}}(\rho_{\mathrm{i}} - \rho_{\mathrm{j}})g}\ (h_{\mathrm{n}} - h_{\mathrm{l}})^{3/2} & (h_{\mathrm{l}} \le h_{\mathrm{n}} < h_{\mathrm{u}}) \\ \frac{2}{3} C_{\mathrm{D}} B_{\mathrm{ij}} \sqrt{2\rho_{\mathrm{i}}(\rho_{\mathrm{i}} - \rho_{\mathrm{j}})g}\ \{(h_{\mathrm{n}} - h_{\mathrm{l}})^{3/2} - (h_{\mathrm{n}} - h_{\mathrm{u}})^{3/2}\} & (h_{\mathrm{u}} \le h_{\mathrm{n}}) \end{cases} \tag{B.10}$$

$$q_{\mathrm{m,ji}} = \begin{cases} \frac{2}{3} C_{\mathrm{D}} B_{\mathrm{ij}} \sqrt{2\rho_{\mathrm{j}}(\rho_{\mathrm{i}} - \rho_{\mathrm{j}})g}\ \{(h_{\mathrm{u}} - h_{\mathrm{n}})^{3/2} - (h_{\mathrm{l}} - h_{\mathrm{n}})^{3/2}\} & (h_{\mathrm{n}} < h_{\mathrm{l}}) \\ \frac{2}{3} C_{\mathrm{D}} B_{\mathrm{ij}} \sqrt{2\rho_{\mathrm{j}}(\rho_{\mathrm{i}} - \rho_{\mathrm{j}})g}\ (h_{\mathrm{u}} - h_{\mathrm{n}})^{3/2} & (h_{\mathrm{l}} \le h_{\mathrm{n}} < h_{\mathrm{u}}) \\ 0 & (h_{\mathrm{u}} \le h_{\mathrm{n}}) \end{cases} \tag{B.11}$$

B.3.2.4 Example of calculation

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 [$\Delta p_{\mathrm{ij}}(0) = -2$ Pa] as shown in Figure B.3.



Key

1 enclosure i
2 enclosure j

Figure B.3 — Mass flow rates for T_i = 80 °C (353K), T_j = 20 °C (293K), B_{ij} = 0,9 m, h_u = 2 m, h_l = 0 m, $\Delta p_{ij}(0)$ = –2 Pa

B.3.2.4.1 Gas densities of enclosure

Using Formulae (B.5) and (B.6), the gas densities of smoke in the two enclosures are:

$$\rho_i = \frac{353}{T_i} = \frac{353}{353} = 1{,}000 \qquad \text{(B.12)}$$

$$\rho_j = \frac{353}{T_j} = \frac{353}{293} = 1{,}205 \qquad \text{(B.13)}$$

B.3.2.4.2 Height of neutral plane above floor

Using Formula (B.7), the height of neutral plane is,

$$h_n = \frac{\Delta p_{ij}(0)}{(\rho_i - \rho_j)g} = \frac{-2}{(1{,}0 - 1{,}205)\times 9{,}8} = 0{,}997 \qquad \text{(B.14)}$$

B.3.2.4.3 Mass flow rates

As the height of the neutral plane, h_n, is between h_u and h_l, flow is bi-directional. Using Formulae (B.8) and (B.9), mass flow rates to and from enclosure j are calculated as follows.

$$\begin{aligned} q_{m,ij} &= \frac{2}{3} C_D B_{ij} \sqrt{2\rho_i(\rho_j - \rho_i)g}\,(h_u - h_n)^{3/2} \\ &= \frac{2}{3} \times 0{,}7 \times 0{,}9 \sqrt{2{,}0 \times (1{,}205 - 1{,}0) \times 9{,}8} \times (2{,}0 - 0{,}997)^{3/2} \qquad \text{(B.15)} \\ &= 0{,}846 \end{aligned}$$

$$\begin{aligned} q_{\mathrm{m,ji}} &= \frac{2}{3} C_{\mathrm{D}} B_{\mathrm{ij}} \sqrt{2\rho_{\mathrm{j}}(\rho_{\mathrm{j}}-\rho_{\mathrm{i}})g}\,(h_{\mathrm{n}}-h_{\mathrm{l}})^{3/2} \\ &= \frac{2}{3} \times 0,7 \times 0,9 \sqrt{2 \times 1,205 \times (1,205-1,00) \times 9,8} \times (0,997-0,0)^{3/2} \\ &= 0,919 \end{aligned} \tag{B.16}$$

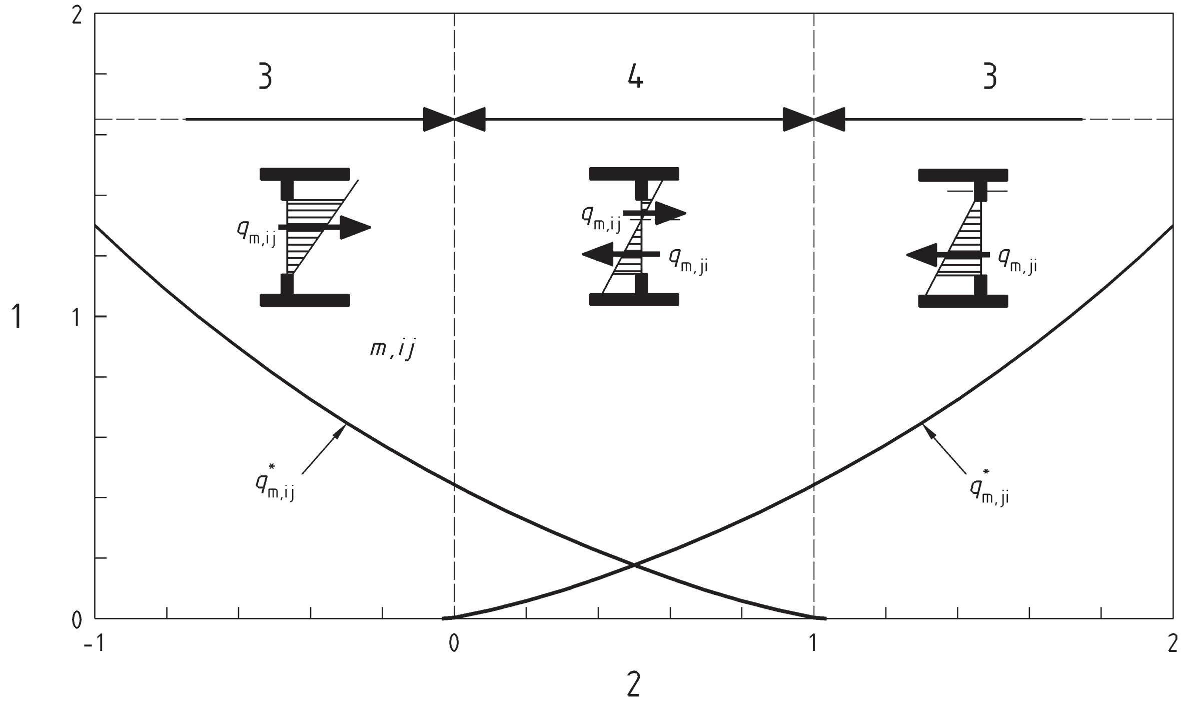
NOTE As for general cases, a non-dimensional diagram is provided in Figure B.4. The non-dimensional mass flow rates,

$$q^{*}_{\mathrm{m,ij}} = \frac{q_{\mathrm{m,ij}}}{\sqrt{2\rho_{\mathrm{i}}(\rho_{\mathrm{j}}-\rho_{\mathrm{i}})}\,B_{\mathrm{ij}}(h_{\mathrm{u}}-h_{\mathrm{l}})^{3/2}} \tag{B.17}$$

$$q^{*}_{\mathrm{m,ji}} = \frac{q_{\mathrm{m,ji}}}{\sqrt{2\rho_{\mathrm{j}}(\rho_{\mathrm{j}}-\rho_{\mathrm{i}})}\,B_{\mathrm{ij}}(h_{\mathrm{u}}-h_{\mathrm{l}})^{3/2}} \tag{B.18}$$

are plotted against non-dimensional neutral plane height

$$h^{*}_{\mathrm{n}} = \frac{h_{\mathrm{n}}-h_{\mathrm{l}}}{h_{\mathrm{u}}-h_{\mathrm{l}}} \tag{B.19}$$



Key

1 non-dimensional mass flow rate, q^*_{m}

2 non-dimensional neutral plane height, h^*_{m}

3 uni-directional flow

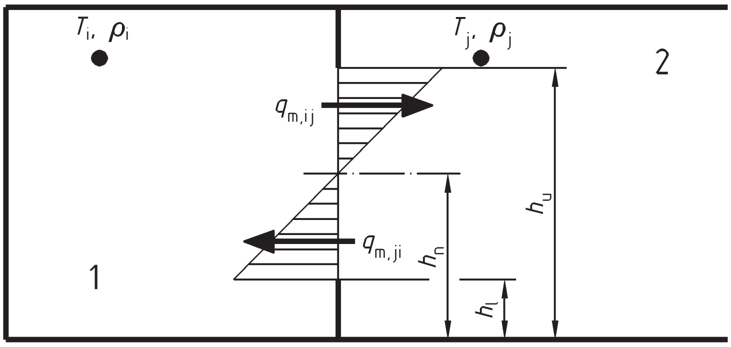
4 bi-directional flow

Figure B.4 — Non-dimensional diagram for mass flow rate through vertical vent in case of $T_{\mathrm{i}} > T_{\mathrm{j}}$

B.3.3 Flow through single vertical vent connecting two enclosures of uniform but different temperatures — Special case of single opening in one enclosure

B.3.3.1 General

If an enclosure has only one opening as shown in Figure B.5, the mass flow rate out of the enclosure, $q_{m,ij}$, is equal to the incoming mass flow rate, $q_{m,ji}$. As a special case of B.3.2, the neutral plane h_n is located so that the mass balance is satisfied in enclosure i.



Key

1 enclosure i
2 enclosure j

Figure B.5 — Pressure difference across single vertical vent and corresponding flow rates in case of $T_i > T_j$ ($\rho_i < \rho_j$)

B.3.3.2 Height of neutral plane above floor

$$h_n = \frac{h_u - h_l}{1+(\rho_j/\rho_i)^{1/3}} + h_l \tag{B.20}$$

B.3.3.3 Mass flow rate

$$q_{m,ij} = \frac{2}{3} C_D \sqrt{2\rho_i(\rho_j - \rho_i)g} \left(\frac{(\rho_j/\rho_i)^{1/3}}{1+(\rho_j/\rho_i)^{1/3}} \right)^{3/2} B_{ij}(h_u - h_l)^{3/2} \tag{B.21}$$

$$q_{m,ji} = \frac{2}{3} C_D \sqrt{2\rho_j(\rho_j - \rho_i)g} \left(\frac{1}{1+(\rho_j/\rho_i)^{1/3}} \right)^{3/2} B_{ij}(h_u - h_l)^{3/2} \tag{B.22}$$

NOTE 1 As the mass flow rates are equal, calculation of either (B.21) or (B.22) is sufficient.

NOTE 2 If the enclosure temperature T_i is greater than 300 °C, the coefficient multiplying $B_{ij}(h_u-h_l)^{3/2}$ is fairly constant, which results in the following useful relationship [3]:

$$q_{m,ij} = q_{m,ij} \approx 0{,}52 B_{ij}(h_u - h_l)^{3/2} \tag{B.23}$$

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

B.3.4 Flow through multiple vertical vents connecting two enclosures of uniform but different temperatures

B.3.4.1 General

In practical situations, an enclosure may have several openings. Mass flow rates of vent flow are calculated in a similar way to B.3.2, but Formulae (B.7) to (B.11) are applied to each vent.

B.3.4.2 Example of calculation

As shown in Figure B.6, two vents connect enclosures i and j. Dimensions of vent 1 are $B_{\mathrm{ij},1}$ = 0,9 m (width), $h_{\mathrm{l},1}$ = 0,7 m (lower height), and $h_{\mathrm{u},1}$ = 1,2 m (upper height). Dimensions of vent 2 are $B_{\mathrm{ij},2}$ = 2,0 m (width), $h_{\mathrm{l},1}$ = 1,8 m (lower height) and $h_{\mathrm{u},2}$ = 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 [$\Delta p_{\mathrm{ij}}(0) = -5$ Pa].

B.3.4.2.1 Gas densities of two enclosures

Using Formulae (B.5) and (B.6), the gas densities of the two enclosures are:

$$\rho_\mathrm{i} = \frac{353}{T_\mathrm{i}} = \frac{353}{353} = 1{,}000 \tag{B.24}$$

$$\rho_\mathrm{j} = \frac{353}{T_\mathrm{j}} = \frac{353}{293} = 1{,}205 \tag{B.25}$$

B.3.4.2.2 Height of neutral plane above floor

Using Formula (B.7), the height of neutral plane is:

$$h_\mathrm{n} = \frac{\Delta p_{\mathrm{ij}}(0)}{(\rho_\mathrm{i} - \rho_\mathrm{j})g} = \frac{-5}{(1{,}000 - 1{,}205)\times 9{,}8} = 2{,}491 \tag{B.26}$$

B.3.4.2.3 Mass flow rates

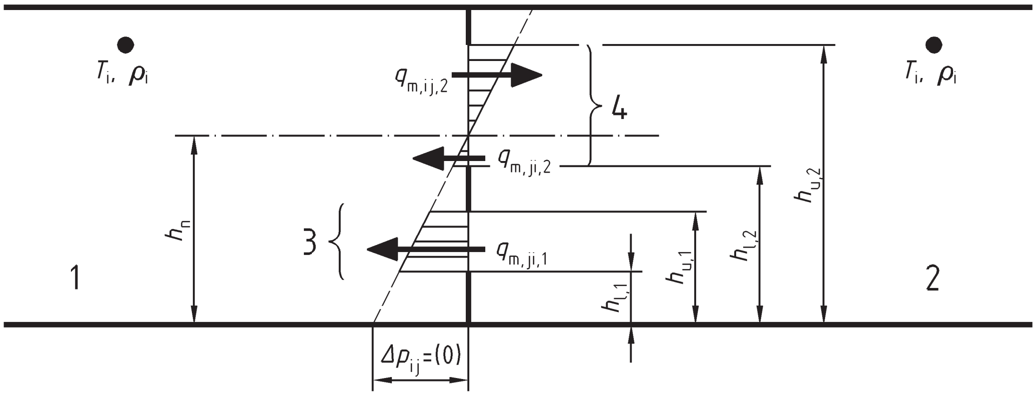
Mass flow rates are calculated for each vent. For vent 1, the neutral plane is higher than the upper height of vent. Thus the flow is uni-directional from enclosure j to enclosure i. By applying the last formula of Formula (B.9), the mass flow rate is calculated as

$$\begin{aligned} q_{\mathrm{m,ji},1} &= \frac{2}{3} C_\mathrm{D} B_{\mathrm{ij},1}\sqrt{2\rho_\mathrm{j}(\rho_\mathrm{j} - \rho_\mathrm{i})g}\{(h_\mathrm{n} - h_{\mathrm{l},1})^{3/2} - (h_\mathrm{n} - h_{\mathrm{u},1})^{3/2}\} \\ &= \frac{2}{3}\times 0{,}7\times 0{,}9\sqrt{2\times 1{,}205\times(1{,}205-1{,}00)\times 9{,}8}\times \\ &\quad \{(2{,}491-0{,}7)^{3/2} - (2{,}491-1{,}2)^{3/2}\} \\ &= 0{,}859 \end{aligned} \tag{B.27}$$

For vent 2, the neutral plane is located within the vent. Thus the flow is bi-directional. Applying the second formula of Formula (B.8), the mass flow rate from enclosure i to j is calculated as

$$\begin{aligned} q_{\mathrm{m,ij},2} &= \frac{2}{3} C_\mathrm{D} B_{\mathrm{ij},2}\sqrt{2\rho_\mathrm{i}(\rho_\mathrm{j} - \rho_\mathrm{i})g}(h_{\mathrm{u},2} - h_\mathrm{n})^{3/2} \\ &= \frac{2}{3}\times 0{,}7\times 2{,}0\sqrt{2\times 1{,}000\times(1{,}205-1{,}000)\times 9{,}8}\times(4{,}0-2{,}491)^{3/2} \\ &= 3{,}46 \end{aligned} \tag{B.28}$$

Applying the second formula of Formula (B.9), the mass flow rate from enclosure j to i is calculated as



$$
\begin{aligned}
q_{\mathrm{m,ji,2}} &= \frac{2}{3} C_{\mathrm{D}} B_{\mathrm{ij,2}} \sqrt{2\rho_{\mathrm{j}}(\rho_{\mathrm{j}}-\rho_{\mathrm{i}})g}\,(h_{\mathrm{n}}-h_{\mathrm{l,2}})^{3/2} \\
&= \frac{2}{3} \times 0{,}7 \times 2{,}0 \sqrt{2 \times 1{,}205 \times (1{,}205-1{,}000) \times 9{,}8} \times (2{,}491-1{,}8)^{3/2} \qquad \text{(B.29)} \\
&= 1{,}18
\end{aligned}
$$

Key

1 enclosure i
2 enclosure j
3 vent 1
4 vent 2

Figure B.6 — Pressure difference across vertical two vents and corresponding flow direction ($\rho_{\mathrm{i}} < \rho_{\mathrm{j}}$)

B.3.5 Flow through multiple vertical vents connecting two enclosures of uniform but different temperatures — Special case of two small vents

B.3.5.1 Scope of calculation formulas

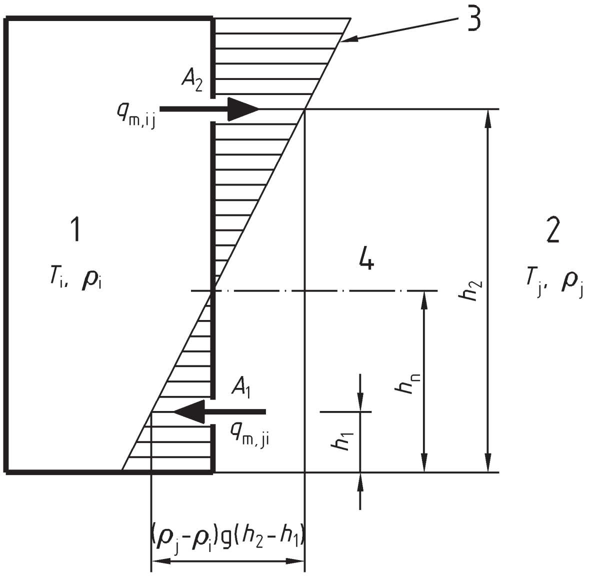
As a special case, a shaft enclosure has two small vents at different heights as shown in Figure B.7. The internal temperature is T_{i}, while the outside temperature is T_{j}. In this case, the pressure difference between the inside and outside space is given by

$$
\Delta p_{\mathrm{ij}}(h) = (\rho_{\mathrm{i}} - \rho_{\mathrm{j}}) g (h_{\mathrm{n}} - h) \qquad \text{(B.30)}
$$

At steady-state, the height of the neutral plane, h_{n}, is located so that incoming and outgoing mass flow rates are balanced.

$$
h_{\mathrm{n}} = \frac{1}{1+\frac{\rho_{\mathrm{j}}}{\rho_{\mathrm{i}}}\left(\frac{A_1}{A_2}\right)^2} (h_2 - h_1) + h_1 \qquad \text{(B.31)}
$$

In this case, the general formulae are simplified using the concept of effective flow area.



Keys

1 shaft (enclosure i)
2 outside (enclosure j)
3 pressure difference $\Delta p_{ij}(h)$
4 neutral plane

Figure B.7 — Pressure difference across shaft enclosure and corresponding flow directions ($\rho_i < \rho_j$)

B.3.5.2 Effective flow area

The effective flow area is calculated to account for total flow resistance of two openings.

$$A_{12} = \frac{1}{\sqrt{(\frac{1}{A_1})^2 + \frac{\rho_j}{\rho_i}(\frac{1}{A_2})^2}} \tag{B.32}$$

B.3.5.3 Mass flow rate

Using the effective flow area, incoming and outgoing mass flow rates are calculated by

$$q_{m,ij} = q_{m,ji} = C_D A_{12} \sqrt{2\rho_j(\rho_j - \rho_i)g(h_2 - h_1)} \tag{B.33}$$

B.3.5.4 Example of calculation

The upper and lower opening areas are A_1 = 1,0 m^2 and A_2 = 2,0 m^2. 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).

Using Formulae (B.5) and (B.6), the gas densities of air (or smoke) in the two enclosures are:

$$\rho_i = \frac{353}{T_i} = \frac{353}{353} = 1{,}000 \tag{B.34}$$

$$\rho_{\mathrm{j}} = \frac{353}{T_{\mathrm{j}}} = \frac{353}{293} = 1{,}205 \qquad \text{(B.35)}$$

The effective flow area is calculated by Formula (B.32) as:

$$A_{12} = \frac{1}{\sqrt{(\frac{1}{A_1})^2 + \frac{\rho_{\mathrm{j}}}{\rho_{\mathrm{i}}}(\frac{1}{A_2})^2}} = \frac{1}{\sqrt{(\frac{1}{1{,}0})^2 + \frac{1{,}205}{1{,}000}(\frac{1}{2{,}0})^2}} = 0{,}877 \qquad \text{(B.36)}$$

The mass flow rate is calculated by Formula (B.33) as

$$q_{\mathrm{m,ij}} = q_{\mathrm{m,ji}} = 0{,}7 \times 0{,}877\sqrt{2 \times 1{,}205 \times (1{,}205 - 1{,}00) \times 9{,}8 \times 20} = 6{,}04 \qquad \text{(B.37)}$$

NOTE For practical calculations, the density fraction, $\rho_{\mathrm{j}}/\rho_{\mathrm{i}}$, in Formula (B.32) can be taken as 1,0. In this example,

$$A_{12} \approx \frac{1}{\sqrt{(\frac{1}{A_1})^2 + (\frac{1}{A_2})^2}} = \frac{1}{\sqrt{(\frac{1}{1{,}00})^2 + (\frac{1}{2{,}00})^2}} = 0{,}894 \qquad \text{(B.38)}$$

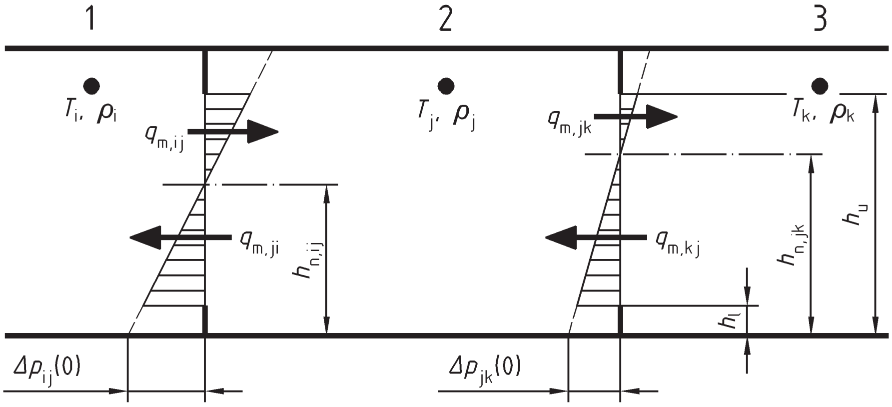
which results in less than 2 % error in comparison with the exact value calculated by Formula (B.36).

B.3.6 Flow through multiple serial vents

B.3.6.1 Scope of calculation formula

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

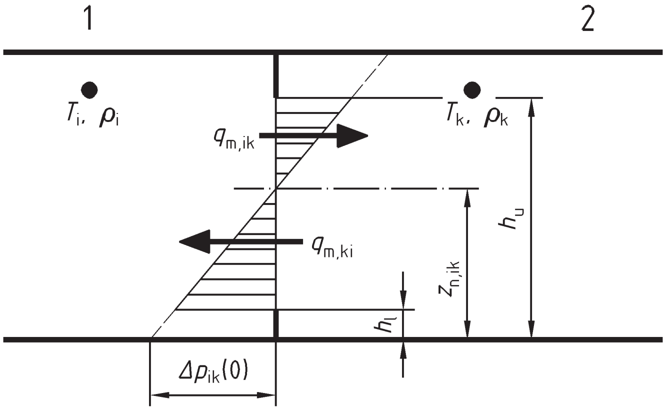
As shown in Figure B.8, three enclosures are connected in series. Given the pressure of enclosures i and k, mass flow rates are calculated. The lower and upper heights of the vents are common to both vents, while the width of vents may differ from each other. Temperatures of enclosures i and k are uniform, but may differ from each other. The temperature in enclosure j is not needed, as it does not influence the final calculation results.



Key

1	enclosure i
2	enclosure j
3	enclosure k

Figure B.8 a — Pressure difference across serial two openings and approximation by single opening (in case of $T_i > T_j > T_k$): Original configuration (lower and upper heights, h_u and h_l, are common to all vents. Vent widths B_{ij} and B_{jk} can be different)



Key

1	enclosure i
2	enclosure k

Figure B.8 b — Pressure difference across serial two openings and approximation by single opening (in case of $T_i > T_j > T_k$): Approximation by single vent by effective flow width

B.3.6.2 Effective vent width

The mass flow rates between enclosures i and k are calculated by basic Formulae (B.7) to (B.11) where the vent width B_{ij} is replaced by the effective width:

$$B_{ik} = \frac{1}{\sqrt{(\frac{1}{B_{ij}})^2 + (\frac{1}{B_{jk}})^2}} \tag{B.39}$$

NOTE To combine more than two vents in series, the formula can be applied recursively:

$$B_{\mathrm{i,j,k\cdots m,n}} = \frac{1}{\sqrt{(\frac{1}{B_{\mathrm{ij}}})^2 + (\frac{1}{B_{\mathrm{jk}}})^2 + \cdots + (\frac{1}{B_{\mathrm{mn}}})^2}} \qquad \text{(B.40)}$$

B.3.6.3 Example of calculation

Enclosures i, j and k are connected by two vents in series. Vent height is $h_\mathrm{u} = 2{,}1$ m, $h_\mathrm{l} = 0$ m. Vent widths are $B_\mathrm{ij} = B_\mathrm{jk} = 1$ m. Temperatures of enclosures are $T_\mathrm{i} = 200$ °C (473 K), $T_\mathrm{k} = 20$ °C (293 K). The pressure difference between enclosures i and k is $\Delta p_\mathrm{ik}(0) = -6$ Pa at the floor level.

Using Formulae (B.5) and (B.6), the gas densities of smoke in the two enclosures are:

$$\rho_\mathrm{i} = \frac{353}{T_\mathrm{i}} = \frac{353}{473} = 0{,}746 \qquad \text{(B.41)}$$

$$\rho_\mathrm{k} = \frac{353}{T_\mathrm{k}} = \frac{353}{293} = 1{,}205 \qquad \text{(B.42)}$$

Using Formula (B.39), the effective vent width is

$$B_\mathrm{ik} = \frac{1}{\sqrt{(\frac{1}{B_\mathrm{ij}})^2 + (\frac{1}{B_\mathrm{jk}})^2}} = \frac{1}{\sqrt{(\frac{1}{1{,}0})^2 + (\frac{1}{1{,}0})^2}} = 0{,}707 \qquad \text{(B.43)}$$

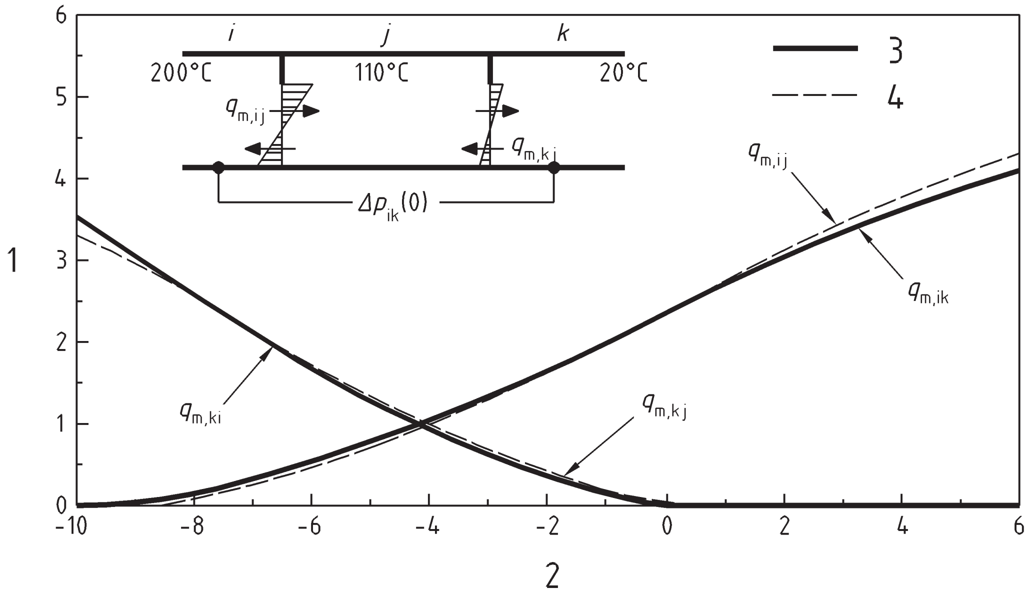
Using Formulae (B.7), (B.8) and (B.9), mass flow rates are calculated as:

$$h_\mathrm{n} = \frac{\Delta p_\mathrm{ik}(0)}{(\rho_\mathrm{i} - \rho_\mathrm{k})g} = \frac{-6}{(0{,}746 - 1{,}205)\times 9{,}8} = 1{,}335 \qquad \text{(B.44)}$$

$$\begin{aligned} q_\mathrm{m,ik} &= \frac{2}{3} C_\mathrm{D} B_\mathrm{ik} \sqrt{2\rho_\mathrm{i}(\rho_\mathrm{k} - \rho_\mathrm{i})g}\ (h_\mathrm{u} - h_\mathrm{n})^{3/2} \\ &= \frac{2}{3} \times 0{,}7 \times 0{,}707 \sqrt{2 \times 0{,}746 \times (1{,}205 - 0{,}746) \times 9{,}8} \times (2{,}1 - 1{,}335)^{3/2} \\ &= 0{,}57 \end{aligned} \qquad \text{(B.45)}$$

$$\begin{aligned} q_\mathrm{m,ki} &= \frac{2}{3} C_\mathrm{D} B_\mathrm{ik} \sqrt{2\rho_\mathrm{k}(\rho_\mathrm{k} - \rho_\mathrm{i})g}\ (h_\mathrm{n} - h_\mathrm{l})^{3/2} \\ &= \frac{2}{3} \times 0{,}7 \times 0{,}707 \sqrt{2 \times 1{,}205 \times (1{,}205 - 0{,}746) \times 9{,}8} \times (1{,}335 - 0)^{3/2} \\ &= 1{,}68 \end{aligned} \qquad \text{(B.46)}$$

NOTE The exact solution considering two separate vents is: $q_\mathrm{m,ij} = 0{,}44$, $q_\mathrm{m,ji} = 1{,}24$, $q_\mathrm{m,jk} = 0{,}76$ and $q_\mathrm{m,kj} = 1{,}56$. For general cases, mass flow rates calculated by exact calculation and by effective width are compared in Figure B.9 for the same temperature profile ($T_\mathrm{i} = 200$ °C, $T_\mathrm{j} = 110$ °C and $T_\mathrm{k} = 20$ °C). The pressure difference between enclosures at floor level varies in the range of –12 to 4 Pa. The flow rates $q_\mathrm{m,jk}$ and $q_\mathrm{m,ji}$ are calculated by using the effective vent width, while the flow rates $q_\mathrm{m,ij}$, $q_\mathrm{m,ji}$, $q_\mathrm{m,jk}$ and $q_\mathrm{m,kj}$ are calculated for two independent vents coupled with mass balance of enclosure j. The error is sufficiently small enough to be acceptable for most engineering calculations.



Key

1	mass flow rate [kg/s]
2	pressure difference at floor level, $\Delta p_{ik}(0)[\mathrm{Pa}]$
3	approximation by effective width
4	exact calculation

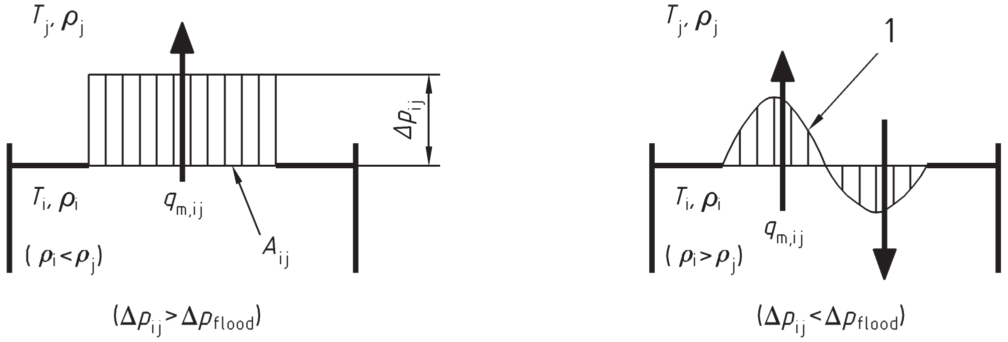
Figure B.9 — Comparison of calculated results with exact solutions (in the case of T_i = 473 K, T_j = 383 K, T_k = 293 K for various pressure differences between enclosures i and k)

B.3.7 Flow through horizontal vent connecting two enclosures of uniform but different temperatures

Flow through a horizontal vent can be calculated in a manner similar to the case of flow through a vertical vent connecting two uniform temperature enclosures.

$$q_{m,ij} = C_D A_{ij}\sqrt{2\rho_i \Delta p_{ij}}\ , (\text{if } \Delta p_{ij} > \Delta p_{\text{flood}}) \tag{B.47}$$

However, caution should be used, since there is a minimum pressure difference for flooding. If the pressure difference is too small, bi-directional flow may arise as shown in Figure B.10. The critical condition Δp_{flood} for the onset of bi-directional flow is still under investigation. Examples of formulae are those developed by Yamada et al. [4] and Cooper [5]. An explicit formula for flow rate under the bi-directional flow situation is not well established at present.



Key

1 velocity profile

Figure B.10 — Pressure difference across vertical vent and corresponding flow direction ($\rho_i < \rho_j$)

B.3.8 Two-layer environment — Flow through single vertical vent connecting two enclosures

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

Mass flow rates are calculated by applying the basic Formulae (B.7) to (B.11) to each segment independently. The heights of middle and top segment bases are determined by

$$h_m = \min(h_i, h_j) \tag{B.48}$$

$$h_t = \max(h_i, h_j) \tag{B.49}$$

to be used as datums in calculation formulae.

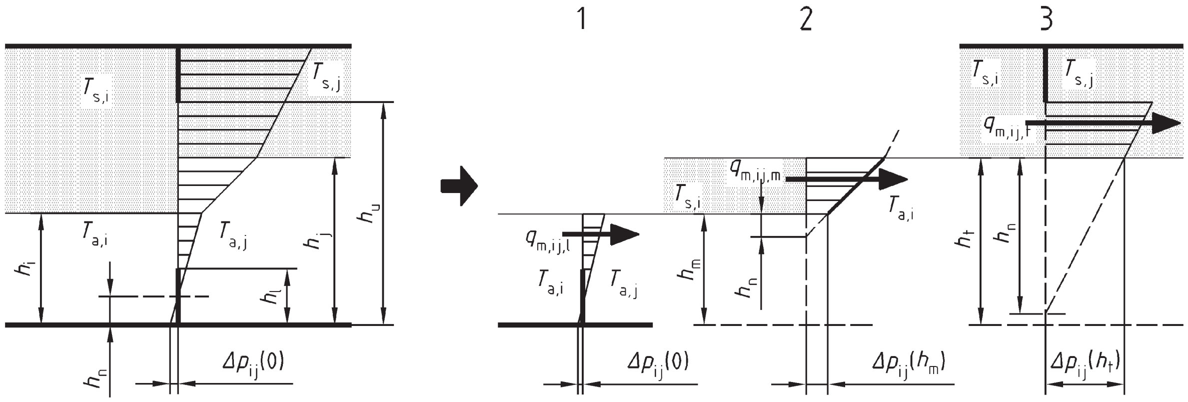
The height of the neutral plane shall be calculated for each segment. Using the pressure difference between enclosures i and j at the segment base, the heights of the neutral plane relative to the segment base are calculated by

$$h_n = \frac{\Delta p_{ij}(h_m)}{(\rho_i - \rho_j)g} \tag{B.50}$$

for the middle segment, and

$$h_n = \frac{\Delta p_{ij}(h_t)}{(\rho_i - \rho_j)g} \tag{B.51}$$

for the top segment.



Key

1 bottom segment
2 middle segment
3 top segment

Figure B.11 — Pressure difference and mass flow profile in two-layer environment

B.3.8.1 Mass flow rates in bottom segment

Mass flow rates in the bottom segment ($h < h_m$) are calculated by the formulae in B.3.2 for a vertical vent connecting two enclosures of uniform but different temperatures. The following replacements are necessary to apply Formulae (B.7) to (B.11)

$$T_i \rightarrow T_{a,i} \tag{B.52}$$

$$T_j \rightarrow T_{a,j} \tag{B.53}$$

$$h_u \rightarrow \min(h_u, h_m) \tag{B.54}$$

B.3.8.2 Mass flow rates in middle segment

Mass flow rates in the middle segment ($h_m < h < h_u$) can be calculated by Formulae (B.7) to (B.11) after the following replacements:

$$T_i \rightarrow \begin{cases} T_{s,i} & (h_i \le h_j) \\ T_{a,i} & (h_i > h_j) \end{cases} \tag{B.55}$$

$$T_j \rightarrow \begin{cases} T_{a,j} & (h_i \le h_j) \\ T_{s,j} & (h_i > h_j) \end{cases} \tag{B.56}$$

$$h_l \rightarrow \max(h_l - h_m, 0) \tag{B.57}$$

$$h_u \rightarrow \min(h_t - h_m, h_u - h_m) \tag{B.58}$$

The height of the neutral plane above the segment base is calculated by

$$h_n = \begin{cases} \dfrac{\Delta p_{ij}(h_m)}{(\rho_{s,i} - \rho_{a,j})g} & (h_i \le h_j) \\ \dfrac{\Delta p_{ij}(h_m)}{(\rho_{a,i} - \rho_{s,j})g} & (h_i > h_j) \end{cases} \tag{B.59}$$

using the pressure difference at the segment base

$$\Delta p_{ij}(h_m) = \Delta p_{ij}(0) - (\rho_{a,i} - \rho_{a,j})gh_m \tag{B.60}$$

B.3.8.3 Mass flow rates in top segment

Similar to the previous two segments, flow in the top segment ($h_t < h$) can be calculated by Formulae (B.7) to (B.11) after the following replacements:

$$T_i \rightarrow T_{s,i} \tag{B.61}$$

$$T_j \rightarrow T_{s,j} \tag{B.62}$$

$$h_l \rightarrow \max(h_l - h_t, 0) \tag{B.63}$$

$$h_u \rightarrow h_u - h_t \tag{B.64}$$

Similar to the middle segment, the height of the neutral plane is calculated relative to the segment base as

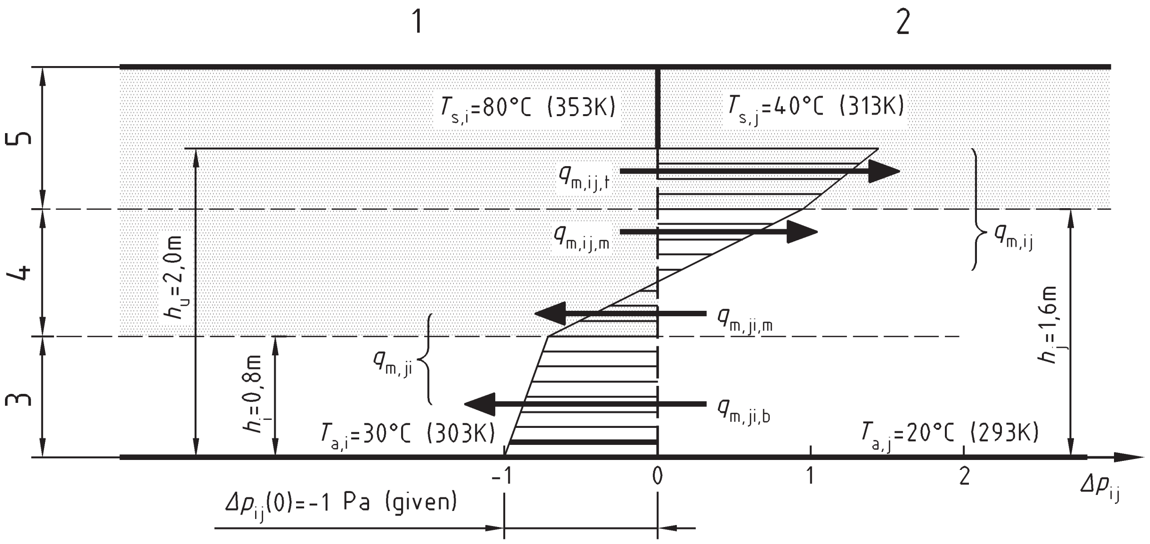
$$h_n = \frac{\Delta p_{ij}(h_t)}{(\rho_{s,i} - \rho_{s,j})g} \tag{B.65}$$

using the pressure difference at the base of the top segment,

$$\Delta p_{ij}(h_t) = \Delta p_{ij}(h_m) - \begin{cases} (\rho_{s,i} - \rho_{a,j})g(h_t - h_m), & (h_i < h_j) \\ (\rho_{a,i} - \rho_{s,j})g(h_t - h_m), & (h_i \ge h_j) \end{cases} \tag{B.66}$$

B.3.8.4 Example of calculation

As shown in Figure B.12, smoke layers are formed in the upper parts of two enclosures. The interface 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 (313K). Lower layer temperatures are 30 °C (303 K) and 20 °C (293 K). It is given that the pressure in enclosure j is higher than that in enclosure i by 1 Pa [Δp_{ij} (0) = –1 Pa]. The vent width is 0,9 m and the vent height is 2,0 m (h_l = 0,0 m, h_u = 2,0 m). Calculations of mass flow rate are carried out for each segment.



Key

1 enclosure i
2 enclosure j
3 bottom segment $h < h_\mathrm{m}$
4 middle segment $h_\mathrm{m} < h < h_\mathrm{t}$
5 top segment $h_\mathrm{u} < h$

Figure B.12 — Example of calculation of mass flow rates in two-layer environment

B.3.8.4.1 Mass flow rate in the bottom segment

The height of the bottom segment is $0 < h < h_\mathrm{m}$ (= 0,8 m) for this case. Using Formulae (B.5) and (B.6)

$$\rho_\mathrm{a,i} = \frac{353}{T_\mathrm{i}} = \frac{353}{303} = 1{,}165 \tag{B.67}$$

$$\rho_\mathrm{a,j} = \frac{353}{T_\mathrm{j}} = \frac{353}{293} = 1{,}205 \tag{B.68}$$

The height of the neutral plane is calculated by Formula (B.7) as

$$h_\mathrm{n} = \frac{\Delta p_\mathrm{ij}(0)}{(\rho_\mathrm{a,i} - \rho_\mathrm{a,j})g} = \frac{-1}{(1{,}165 - 1{,}205)\times 9{,}8} = 2{,}566 \tag{B.69}$$

which is larger than segment height h_m. Thus the flow is unidirectional from enclosure j to i. Using the last formula of Formula (B.9), we get

$$\begin{aligned} q_\mathrm{m,ji,b} &= \frac{2}{3} C_\mathrm{D} B_\mathrm{vent} \sqrt{2\rho_\mathrm{a,j}(\rho_\mathrm{a,j} - \rho_\mathrm{a,i})g}\,\{h_\mathrm{n}^{3/2} - (h_\mathrm{n} - h_\mathrm{m})^{3/2}\} \\ &= \frac{2}{3} \times 0{,}7 \times 0{,}9 \sqrt{2 \times 1{,}205 \times (1{,}205 - 1{,}165) \times 9{,}8}\,\{2{,}566^{3/2} - (2{,}566 - 0{,}8)^{3/2}\} \\ &= 0{,}718 \end{aligned} \tag{B.70}$$

B.3.8.4.2 Mass flow rates in the middle segment

The height of the middle segment is h_m (= 0,8 m) < h < h_t (= 1,6 m) for this case. The pressure difference at the base of the middle segment is calculated by Formula (B.60).

$$\begin{aligned} \Delta p_{ij}(h_m) &= \Delta p_{ij}(0) - (\rho_{a,i} - \rho_{a,j})\, g\, h_m \\ &= -1 - (1{,}165 - 1{,}205) \times 9{,}8 \times 0{,}8 \\ &= -0{,}689 \end{aligned} \tag{B.71}$$

Using Formulae (B.6) and (B.59), the height of the neutral plane for this segment is located at:

$$\rho_{s,i} = \frac{353}{T_i} = \frac{353}{353} = 1{,}000 \tag{B.72}$$

$$h_n = \frac{\Delta p_{ij}(h_m)}{(\rho_{s,i} - \rho_{a,j})g} = \frac{-0{,}686}{(1{,}000 - 1{,}205) \times 9{,}8} = 0{,}343 \tag{B.73}$$

above the base of the middle segment. As 0 < h_n < h_u - h_m, flow is bi-directional. Using the second formula in Formula (B.8) and second formula in Formula (B.9), the mass flow rates are

$$\begin{aligned} q_{m,ij,m} &= \frac{2}{3} C_D\, B_{vent} \sqrt{2\rho_{s,i}(\rho_{a,j} - \rho_{s,i})\, g}\, \{(h_j - h_i) - h_n\}^{3/2} \\ &= \frac{2}{3} \times 0{,}7 \times 0{,}9 \times \sqrt{2 \times 1{,}0 \times (1{,}205 - 1{,}000) \times 9{,}8} \times \{(1{,}6 - 0{,}8) - 0{,}343\}^{3/2} \\ &= 0{,}260 \end{aligned} \tag{B.74}$$

$$\begin{aligned} q_{m,ji,m} &= \frac{2}{3} C_D B_{vent} \sqrt{2\rho_{a,j}(\rho_{a,j} - \rho_{s,i})g}\, h_n^{3/2} \\ &= \frac{2}{3} \times 0{,}7 \times 0{,}9 \times \sqrt{2 \times 1{,}205 \times (1{,}205 - 1{,}000) \times 9{,}8} \times 0{,}343^{3/2} \\ &= 0{,}186 \end{aligned} \tag{B.75}$$

B.3.8.4.3 Mass flow rate in the top segment

The height of the top segment is h_t (= 1,6 m) < h for this case. The pressure difference at the base of the top segment is calculated by Formula (B.66) as

$$\begin{aligned} \Delta p_{ij}(h_t) &= \Delta p_{ij}(h_m) - (\rho_{s,i} - \rho_{a,j})\, g (h_t - h_m) \\ &= -0{,}689 - (1{,}000 - 1{,}205) \times 9{,}8 \times 0{,}8 \\ &= 0{,}917 \end{aligned} \tag{B.76}$$

Using Formulae (B.6) and (B.65), the height of neutral plane above the base of top segment is

$$\rho_{s,j} = \frac{353}{T_j} = \frac{353}{313} = 1{,}128 \tag{B.77}$$

$$h_{\mathrm{n}} = \frac{\Delta p_{\mathrm{ij}}(h_{\mathrm{j}})}{(\rho_{\mathrm{s,i}} - \rho_{\mathrm{s,j}})\,g} = \frac{0{,}917}{(1{,}000 - 1{,}128) \times 9{,}8} = -0{,}731\ . \tag{B.78}$$

The negative sign indicates that the neutral plane is 0,731m below the segment base. As $h_{\mathrm{n}} < 0$, flow is uni-directional. Using the first formula in Formula (B.8), the result is:

$$\begin{aligned} q_{\mathrm{m,ij,t}} &= \frac{2}{3} C_{\mathrm{D}}\, B_{\mathrm{ij}} \sqrt{2\rho_{\mathrm{s,i}}(\rho_{\mathrm{s,j}} - \rho_{\mathrm{s,i}})\,g}\left(\{(h_{\mathrm{u}} - h_{\mathrm{j}}) - h_{\mathrm{n}}\}^{3/2} - (-h_{\mathrm{n}})^{3/2}\right) \\ &= \frac{2}{3} \times 0{,}7 \times 0{,}9 \times \\ &\sqrt{2 \times 1{,}0 \times (1{,}128 - 1{,}0) \times 9{,}8}\left(\{(2{,}0 - 1{,}6) - (-0{,}731)\}^{3/2} - \{-(-0{,}731)\}^{3/2}\right) \\ &= 0{,}384 \end{aligned} \tag{B.79}$$

B.3.8.4.4 Total mass flow rates between enclosures

Total mass flow rate through vents is given by the sum of the flow rates in the three segments.

$$q_{\mathrm{m,ij}} = q_{\mathrm{m,ij,m}} + q_{\mathrm{m,ij,t}} = 0{,}261 + 0{,}384 = 0{,}644 \tag{B.80}$$

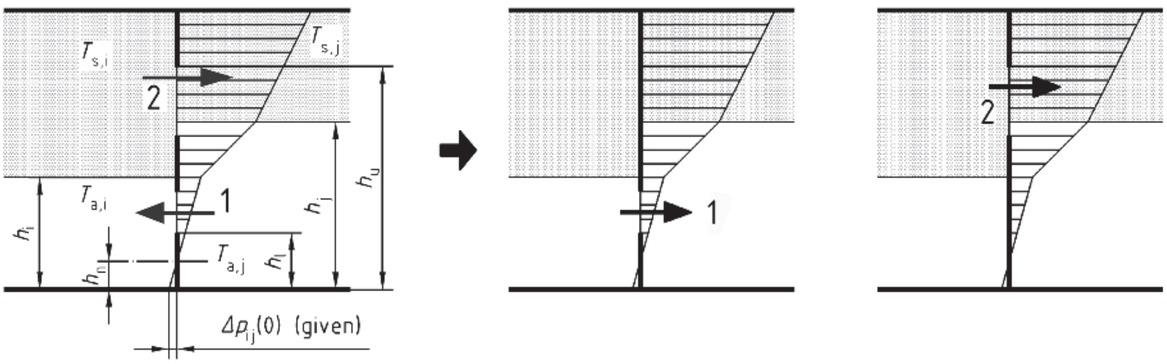
$$q_{\mathrm{m,ji}} = q_{\mathrm{m,ji,b}} + q_{\mathrm{m,ji,m}} = 0{,}720 + 0{,}185 = 0{,}903 \tag{B.81}$$

NOTE If mixing at the air-smoke interface is neglected, mass flow in the middle segment $q_{\mathrm{m,ij}}$ is identical to the flow rate coming into the smoke layer in enclosure j. Similarly, $q_{\mathrm{m,ji}}$ is identical to the air flow rate coming into the lower layer in enclosure i.

B.3.9 Two-layer environment — Flow through multiple vertical vents connecting two enclosures

B.3.9.1 General

In the case of multiple vents in a two-layer environment, as shown in Figure B.13, the same procedure as given in B.3.8 is applied to each vent independently.



Key

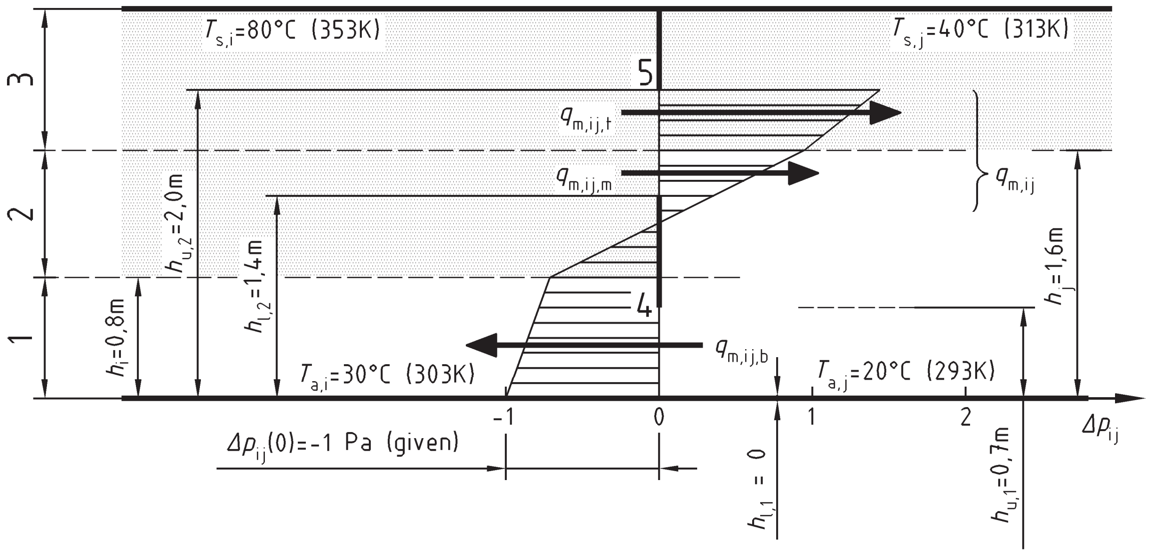
1 vent 1

2 vent 2

Figure B.13 — Calculation in case of multiple vents in two-layer environment

B.3.9.2 Example of calculation

As shown in Figure B.14, smoke layers are formed in the upper parts of two enclosures. The smoke layer heights and layer temperatures are the same as for the example in B.3.8.4. There are two vents between enclosures. The range of height of vent 1 is $h_{l,1} = 0$ m to $h_{u,1} = 0{,}7$ m. The range of height of vent 2 is $h_{l,2} = 1{,}4$ m to $h_{u,2} = 2{,}0$ m. The widths of the two vents are $B_{ij,1} = B_{ij,2} = 0{,}9$ m. Calculations of mass flow rate are carried out for each vent.



Key

1 bottom segment $h < h_m$
2 middle segment $h_m < h < h_t$
3 top segment $h_t < h$
4 vent 1
5 vent 2

Figure B.14 — Example of calculation of mass flow rates in a two-layer environment with multiple vents

B.3.9.2.1 Mass flow rate in vent 1

As the mass flow rates in the middle and top segments are zero, the calculation is carried out only for the bottom segment. The neutral plane height for the bottom segment is 2,566 m as calculated by Formula (B.69). The flow rate is calculated in the same way as Formula (B.70), but differing by the interval of height.

$$\begin{aligned} q_{\text{m,ji,l}} &= \frac{2}{3} C_{\text{D}}\, B_{\text{ij,1}} \sqrt{2\rho_{\text{a,j}}(\rho_{\text{a,j}} - \rho_{\text{a,i}})g}\,\{(h_{\text{n}} - h_{\text{l,1}})^{3/2} - (h_{\text{n}} - h_{\text{u,1}})^{3/2}\} \\ &= \frac{2}{3} \times 0{,}7 \times 0{,}9 \sqrt{2 \times 1{,}205 \times (1{,}205 - 1{,}165) \times 9{,}8}\,\{(2{,}566 - 0)^{3/2} - (2{,}566 - 0{,}7)^{3/2}\} \qquad \text{(B.82)} \\ &= 0{,}635 \end{aligned}$$

B.3.9.2.2 Mass flow rate in vent 2

Mass flow rates in the middle and top segments are to be calculated. The neutral plane height for the middle segment is 0,343 m above the segment base as calculated by Formula (B.73). The flow rate is calculated in the same way as Formula (B.74), but differing by the interval of height.

$$\begin{aligned} q_{\mathrm{m,ij,m}} &= \frac{2}{3} C_{\mathrm{D}} B_{\mathrm{ij,2}} \sqrt{2\rho_{\mathrm{s,i}}(\rho_{\mathrm{a,j}} - \rho_{\mathrm{s,i}})\, g} \left(\{(h_{\mathrm{j}} - (h_{\mathrm{m}} + h_{\mathrm{n}})\}^{3/2} - \{(h_{\mathrm{l,2}} - (h_{\mathrm{m}} + h_{\mathrm{n}})\}^{3/2} \right) \\ &= \frac{2}{3} \times 0{,}7 \times 0{,}9 \times \sqrt{2 \times 1{,}0 \times (1{,}205 - 1{,}000) \times 9{,}8} \times \\ &\quad \left(\{(1{,}6 - (0{,}8 + 0{,}343)\}^{3/2} - \{(1{,}4 - (0{,}8 + 0{,}343)\}^{3/2} \right) \\ &= 0{,}150 \end{aligned} \tag{B.83}$$

The mass flow rate in the top segment is identical to that presented for the example in B.3.4.7 as calculated by Formula (B.79).

$$q_{\mathrm{m,ij,t}} = 0{,}384 \tag{B.84}$$

B.4 Scientific basis for the formula set

Vent flow has been analysed in relation to quantitative prediction of enclosure fires. Early studies include prediction of fully-developed fire temperatures by Kawagoe [4] based on the suggestions of Sekine. Extensions were made to a two-layer environment by Prahl et al. [7] and Rockett [8]. For these early studies, flow equations were derived by fundamental flow theory. Direct full scale measurements were carried out in the 1980s by Steckler et al. [9], [10], [11] and Nakaya et al. [12]. 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 [13].

B.5 Formula-set limitations

The formula set cannot be applied in the following situations:

B.5.1 Uniformity of smoke layer

The formula set assumes uniform or a two-layer profile of enclosure temperature adjacent to the vent. When this assumption is not valid, use of the general flow formula in Annex A is recommended.

B.5.2 Dynamic pressure

The effect of dynamic pressure caused by external wind or mechanical fans is not taken into account. In such cases, there shall be careful consideration of the dynamic pressure distribution.

B.6 Output parameters

The formula set outputs mass flow rate through the vent in kg/s. When bi-directional flow exists, the position of the neutral plane is also calculated.

B.7 Formula-set input parameters

B.7.1 Pressure difference across vents

The parameter, Δp_{ij}, is defined as the pressure difference at the datum, which is normally taken as the lowest boundary elevation.

B.7.2 Enclosure temperature profile adjacent to vent

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

B.8 Domain of applicability of the formula set

The domain of applicability of the formula set can be determined from the studies by Steckler et al. [9] and Nakaya et al. [12] and by other authors. Steckler's experiments were carried out in a room of 2,8 m by 2,8 m wide and 2,13 m high. Doorway opening width was 0,74 m, while the doorway height varied in the range of 0,46 m to 1,38 m. The heat release rate of the fire was in the range of 31,6 kW to 158 kW. The enclosure temperature was 250 °C at maximum. Nakaya's experiments correspond to a somewhat larger room of 3,45 m by 3,55 m wide, 2,12 m high. The opening height was 1,6 m or 1,7 m. The opening width varied in the range of 0,29 m to 0,89 m. Enclosure temperatures were in the range of 50 °C in the two-layer case to 1 000 °C in the well-mixed case at maximum.

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