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Fire safety engineering — Requirements governing algebraic equations — Vent flows

Ingénierie de la sécurité incendie — Exigences régissant les équations algébriques — Écoulements au travers d'une ouverture

Reference number
ISO 16737:2006(E)

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Foreword

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

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

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

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

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

Introduction

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

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

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

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

INTERNATIONAL STANDARD ISO 16737:2006(E)

Fire safety engineering — Requirements governing algebraic equations — Vent flows

1 Scope

1.1 The requirements in this International Standard govern the application of algebraic equation sets to the calculation of specific characteristics of vent flows.

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

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

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

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

c) limitations of the calculation method;

d) input parameters for the calculation method;

e) domain of applicability of the calculation method.

1.4 Examples of sets of algebraic equations meeting all the requirements of this International Standard are provided in separate annexes to this International Standard for each different type of vent-flow scenario. Currently, there is one informative annex containing general information and conservation relationships for vent flows and a second informative annex with specific algebraic equations for calculation of vent-flow characteristics.

2 Normative references

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

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

ISO 13943, *Fire safety — Vocabulary*

3 Terms and definitions

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

NOTE 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 enclosed space having one or more openings is a complex thermo-physical phenomenon that can be highly transient or nearly steady-state. Vent flows can 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 Scenarios elements (e.g. a two-layer environment, uniform mixture, etc.) to which specific equations apply shall be clearly identified.

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

5 Requirements governing documentation

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

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

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

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

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

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

6 Requirements governing limitations

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

6.2 Cautions on the use of the algebraic equation set within a more general calculation method shall be provided, which shall include checks of consistency with the other relations used in the calculation method and the numerical procedures employed. For example, the use of a given equation set for vent flows in a zone model can yield results inconsistent with those from another equation set for smoke layers in the zone model, where the vent flow is caused by a smoke layer, leading to errors.

7 Requirements governing input parameters

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

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

7.3 The valid ranges for input parameters shall be listed as specified in ISO/TR 13387-3.

8 Requirements governing domain of applicability

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

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

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

Annex A
(informative)

General aspects of vent flows

A.1 Terms and definitions used in Annex A

The terms and definitions given in ISO 13943 and the following should 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 elevation

A.1.6
interface position
smoke layer height
elevation of the smoke layer interface relative to a reference elevation, 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 of relatively smoke-free air

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 Symbols and abbreviated terms used in Annex A

A_{vent}	area of vent (m^2)
B_{vent}	width of vent (m)
C_{D}	flow coefficient (–)
g	gravity acceleration ($\text{m}\cdot\text{s}^{-2}$)
H_{l}	height of lower edge of vent above reference elevation (m)
H_{u}	height of upper edge of vent above reference elevation (m)
$\max(x_1,x_2)$	maximum of x_1 and x_2
$\dot{m}_{\text{ij}}$	mass flow rate of smoke or air flowing from enclosure i to adjacent space j ($\text{kg}\cdot\text{s}^{-1}$)
$\dot{m}_{\text{ji}}$	mass flow rate of smoke or air flowing from adjacent space j to enclosure i ($\text{kg}\cdot\text{s}^{-1}$)
$p_{\text{i}}(z)$	pressure in enclosure i at height z above reference elevation (Pa)
$p_{\text{j}}(z)$	pressure in enclosure j at height z above reference elevation (Pa)
v	flow velocity ($\text{m}\cdot\text{s}^{-1}$)
ρ_{i}	density of smoke (or air) in enclosure i ($\text{kg}\cdot\text{m}^{-3}$)
ρ_{j}	density of smoke (or air) in enclosure j ($\text{kg}\cdot\text{m}^{-3}$)
$\Delta p_{\text{ij}}(z)$	pressure difference between enclosure i and j at height z; that is, $p_{\text{i}}(z)$-$p_{\text{j}}(z)$, (Pa)
z	height above reference elevation (m)

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

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

A.3.1 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 can 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 enclosure and the adjacent spaces that the vent connects, mass flow rate is calculated by using an orifice flow theory.

The properties of an enclosure, such as smoke layer interface height, temperature and other properties, are calculated from the principle of heat and mass conservation for the smoke layer. The vent flow is then calculated by use of the conservation of heat and mass for flow rates through boundaries. The description of smoke layer properties is given in ISO 16735.

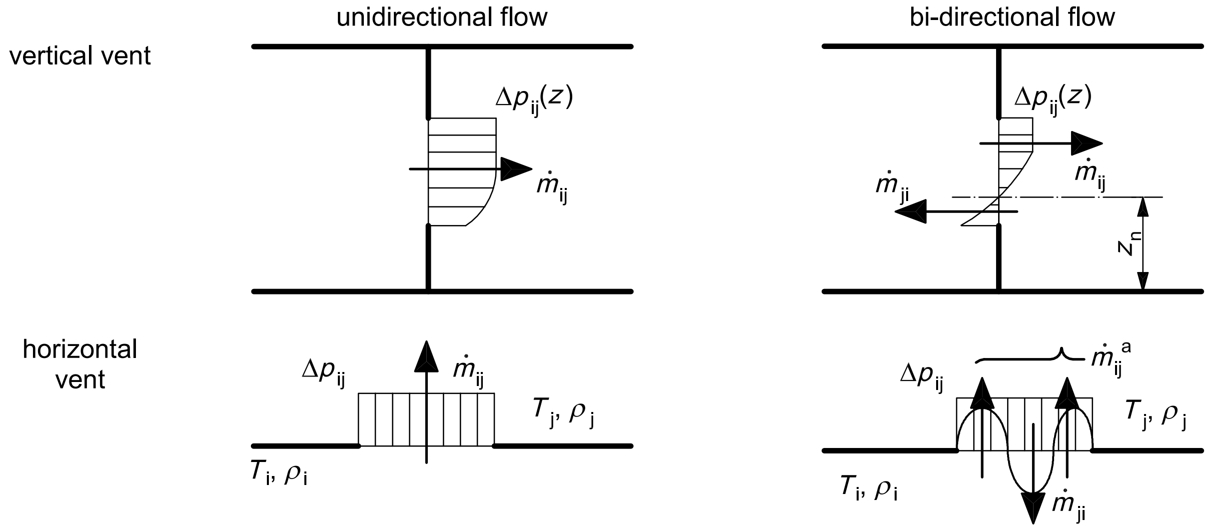
A.3.2 Vent-flow characteristics to be calculated

Equations provide the rate of mass, enthalpy and chemical species flow.

A.4 Equation set documentation

A.4.1 Equation sets

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



a Flow is unstable. No explicit equation is available at present.

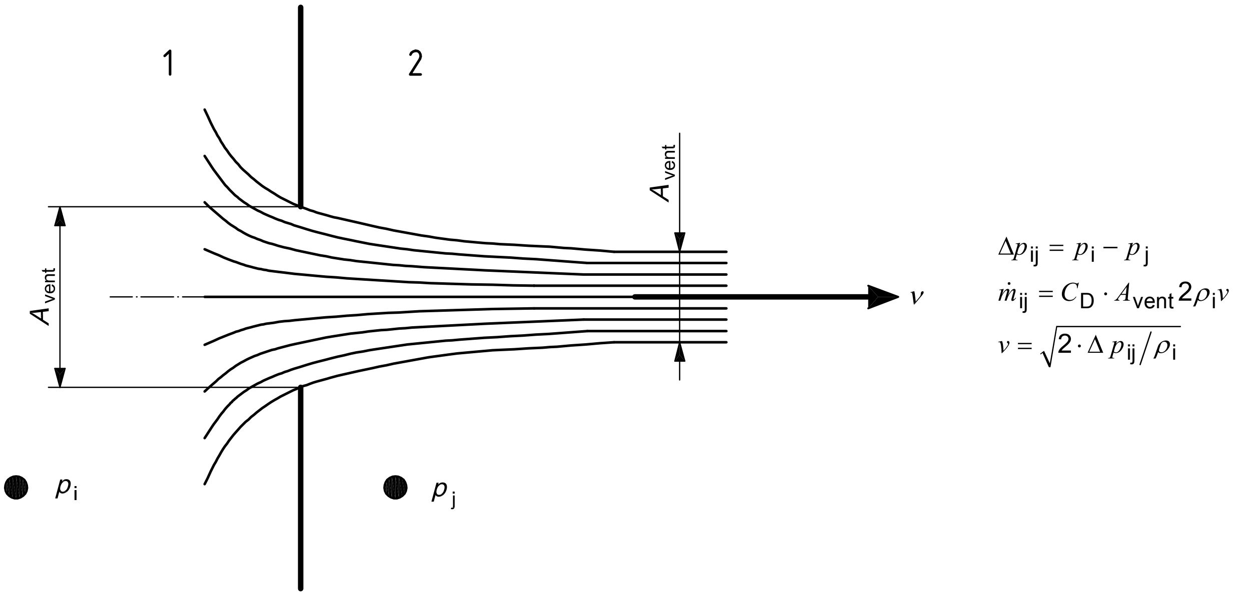
Figure A.1 — Conditions of vent-flow calculation

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

When the pressure difference is created by actions such as external wind or mechanical fans, the flow, $\dot{m}_{\mathrm{ij}}$, expressed in kilograms per second, through the vent is given by Equation (A.1):

$$\dot{m}_{\mathrm{ij}} = C_{\mathrm{D}} \cdot A_{\mathrm{vent}} \sqrt{2\rho_{\mathrm{i}} \Delta p_{\mathrm{ij}}} \qquad \text{(A.1)}$$

where $\Delta p_{\mathrm{ij}} = p_{\mathrm{i}} - p_{\mathrm{j}}$ and the assumption is made that the pressure difference across the vent is uniform over the entire vent area, as shown in Figure A.2:



Key

1 enclosure i

2 enclosure j

Figure A.2 — Streamlines and flow coefficient for isothermal orifice flow

A.4.3 Hydrostatic pressure difference

When a vertical temperature profile, $T_{\mathrm{i}}(z)$, exists in enclosure i, as shown in Figure A.3, the density ρ_{i}, expressed in kilograms per cubic metre, at height z above the lowest enclosure boundary is calculated by Equation (A.2):

$$\rho_{\mathrm{i}}(z) = \frac{\rho_0 T_0}{T_{\mathrm{i}}(z)} \approx \frac{353}{T_{\mathrm{i}}(z)} \qquad \text{(A.2)}$$

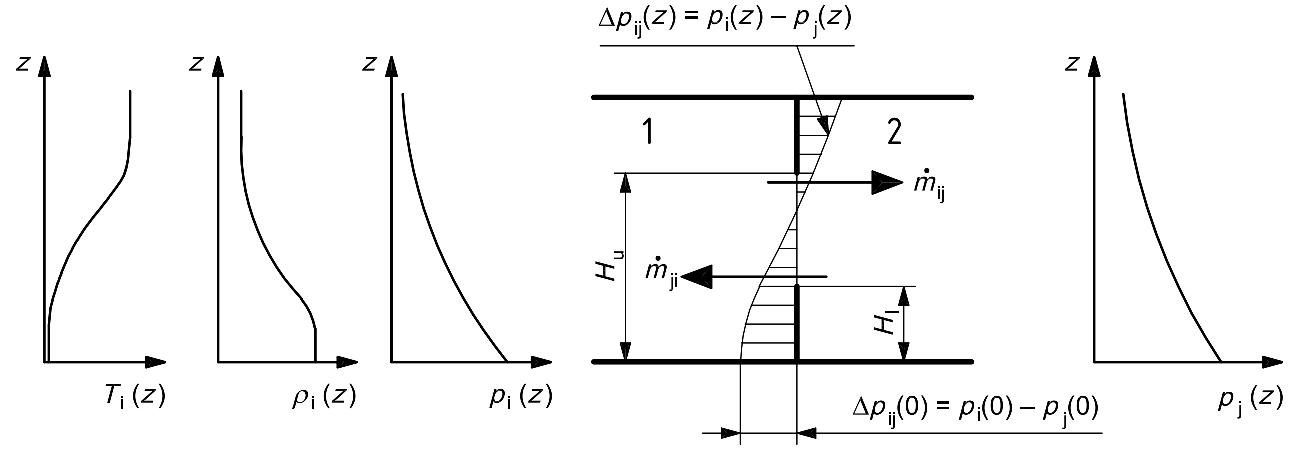
NOTE To derive Equation (A.2), smoke is approximated by an ideal gas whose properties are identical with those of air. In addition, for most of the applications, the absolute value of pressure remains close to the normal atmospheric value.

The hydrostatic pressure, $p_{\mathrm{i}}(z)$, expressed in pascals, in enclosure i is calculated by integrating the density over height as given in Equation (A.3):

$$p_\mathrm{i}(z) = p_\mathrm{i}(0) - \int_0^z \rho_\mathrm{i}(\zeta) g \mathrm{d}\zeta \tag{A.3}$$

Hydrostatic pressure difference, $\Delta p_\mathrm{ij}(z)$, expressed in pascals, between enclosures i and j is as given in Equation (A.4):

$$\Delta p_\mathrm{ij}(z) = p_\mathrm{i}(z) - p_\mathrm{j}(z) = \left[p_\mathrm{i}(0) - p_\mathrm{j}(0)\right] - \int_0^z \left[\rho_\mathrm{i}(\zeta) - \rho_\mathrm{j}(\zeta)\right] g\, \mathrm{d}\zeta \tag{A.4}$$



Key

1 enclosure i

2 enclosure j

Figure A.3 — Hydrostatic pressure difference between two adjacent enclosures

A.4.4 General flow equation — Flow through 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.3. Given the hydrostatic pressure difference from Equation (A.4), mass flow rates between enclosures are calculated by Equations (A.5) and (A.6):

$$\dot{m}_\mathrm{ij} = C_\mathrm{D} \cdot B_\mathrm{vent} \int_{H_\mathrm{l}}^{H_\mathrm{u}} \sqrt{2\rho_\mathrm{i}(z) \cdot \max\left[\Delta p_\mathrm{ij}(z), 0\right]}\ \mathrm{d}z \tag{A.5}$$

$$\dot{m}_\mathrm{ji} = C_\mathrm{D} \cdot B_\mathrm{vent} \int_{H_\mathrm{l}}^{H_\mathrm{u}} \sqrt{2\rho_\mathrm{j}(z) \cdot \max\left[-\Delta p_\mathrm{ij}(z), 0\right]}\ \mathrm{d}z \tag{A.6}$$

Annex B
(informative)

Specific equations for vent flows meeting the requirements of Annex A

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

B.1.1 General

These calculation methods 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 equation set is applicable

The set of equations 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 temperature profiles: one is a uniform temperature profile while the other is a two-layered profile.

B.1.3 Vent-flow characteristics to be calculated

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

B.1.4 Vent-flow conditions to which equations apply

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

B.1.5 Self-consistency of the equation set

The equation sets are developed in a self-consistent manner.

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

None specified.

B.2 Symbols and abbreviated terms used in Annex B

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

abs(x)	absolute value of x
H_{vent}	height of upper edge of vent above reference elevation (m), which is the same definition as for H_{u}, but distinguished from H_{u} during the calculation procedure
min(x_1,x_2)	minimum of x_1 and x_2
T_{i}	temperature of enclosure i (K)
T_{j}	temperature of enclosure j (K)
$T_{\text{a,i}}$	temperature of lower layer in enclosure i (K)

$T_{\mathrm{a,j}}$	temperature of lower layer in enclosure j (K)
$T_{\mathrm{s,i}}$	temperature of smoke layer in enclosure i (K)
$T_{\mathrm{s,j}}$	temperature of smoke layer in enclosure j (K)
z_{n}	height of neutral plane (m)
$\rho_{\mathrm{a,i}}$	density of lower layer in enclosure i (kg m^{-3})
$\rho_{\mathrm{a,j}}$	density of lower layer in enclosure j (kg m^{-3})
$\rho_{\mathrm{s,i}}$	density of smoke layer in enclosure i (kg m^{-3})
$\rho_{\mathrm{s,j}}$	density of smoke layer in enclosure j (kg m^{-3})

B.3 Equation-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 by a fire-induced phenomenon, as shown in Figure B.1, the flow rate is calculated by Equations (B.1) and (B.2):

$$\dot{m}_{\mathrm{ij}} = C_{\mathrm{D}} \cdot A_{\mathrm{vent}} \sqrt{2\rho\Delta p_{\mathrm{ij}}} \tag{B.1}$$

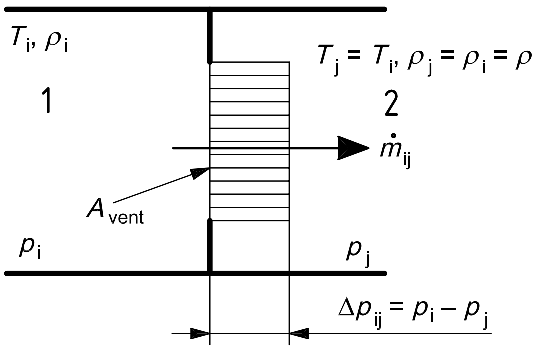
$$\Delta p_{\mathrm{ij}} = p_{\mathrm{i}} - p_{\mathrm{j}} \tag{B.2}$$

Enthalpy and chemical species flows are calculated using the mass flow rate given by Equations (B.3) and (B.4):

$$\dot{E}_{\mathrm{ij}} = c_{\mathrm{p}}\left(T_{\mathrm{i}} - T_{0}\right)\dot{m}_{\mathrm{ij}} \tag{B.3}$$

$$\dot{C}_{\mathrm{ij}} = Y_{\mathrm{i}}\dot{m}_{\mathrm{ij}} \tag{B.4}$$

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



Key

1 enclosure i

2 enclosure j

Figure B.1 — Pressure difference across vertical vent and corresponding flow direction ($\rho = \rho_{\mathrm{i}} = \rho_{\mathrm{j}}$)

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

B.3.2.1 General

As shown in Figure B.2, flow patterns are classified in accordance with the position of the neutral plane. When a 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 (see References [1] and [2]). Height of the neutral plane, z_n, is given by Equation (B.5). The equations for the flow rates, $\dot{m}_{ij}$ and $\dot{m}_{ji}$, expressed in kilograms per second, are given in Equations (B.8) and (B.9). The calculation result from this equation set is presented in Figure B.4 in non-dimensional form.

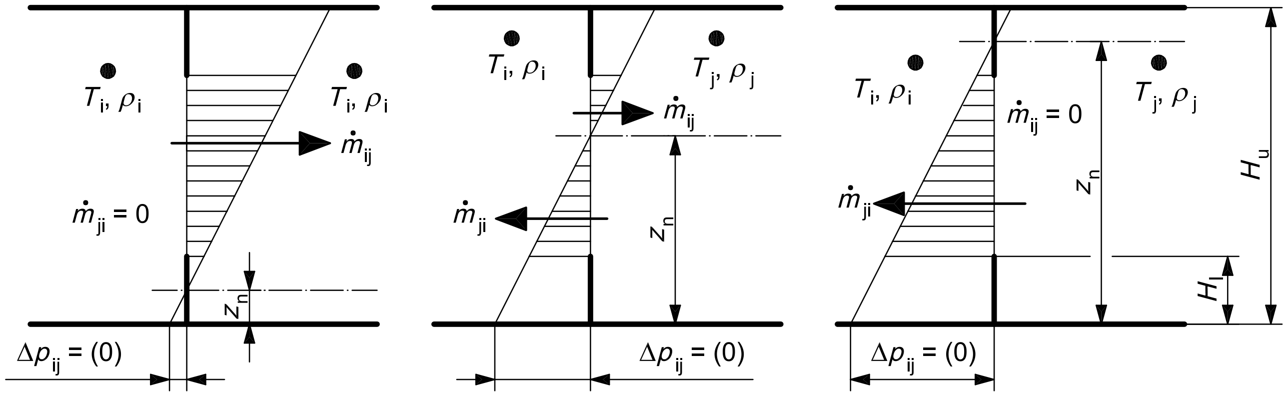


Figure B.2 — Pressure difference across vertical vent and corresponding flow direction ($\rho_i < \rho_j$)

B.3.2.2 Position of neutral plane

The position of the neutral plane, z_n, expressed in metres is given by Equation (B.5):

$$z_n = \frac{\Delta p_{ij}(0)}{(\rho_i - \rho_j)g} \tag{B.5}$$

where

$$\rho_i = \frac{353}{T_i} \tag{B.6}$$

$$\rho_j = \frac{353}{T_j} \tag{B.7}$$

B.3.2.3 Mass flow rate

Equations (B.8) and (B.9) apply when $T_i > T_j$ ($\rho_i < \rho_j$):

$$\dot{m}_{ij} = \begin{cases} \frac{2}{3} C_D \cdot B_{vent} \sqrt{2\rho_i(\rho_j - \rho_i)g} \cdot \left[(H_u - z_n)^{3/2} - (H_l - z_n)^{3/2} \right] & (z_n < H_l) \\ \frac{2}{3} C_D \cdot B_{vent} \sqrt{2\rho_i(\rho_j - \rho_i)g} \cdot (H_u - z_n)^{3/2} & (H_l \leqslant z_n < H_u) \\ 0 & (H_u \leqslant z_n) \end{cases}$$

$$\dot{m}_{\mathrm{ji}} = \begin{cases} 0 & (z_{\mathrm{n}} < H_{\mathrm{l}}) \\ \dfrac{2}{3} C_{\mathrm{D}} \cdot B_{\mathrm{vent}} \sqrt{2\rho_{\mathrm{j}}(\rho_{\mathrm{j}} - \rho_{\mathrm{i}})g} \cdot (z_{\mathrm{n}} - H_{\mathrm{l}})^{3/2} & (H_{\mathrm{l}} \leqslant z_{\mathrm{n}} < H_{\mathrm{u}}) \\ \dfrac{2}{3} C_{\mathrm{D}} \cdot B_{\mathrm{vent}} \sqrt{2\rho_{\mathrm{j}}(\rho_{\mathrm{j}} - \rho_{\mathrm{i}})g} \cdot \left[(z_{\mathrm{n}} - H_{\mathrm{l}})^{3/2} - (z_{\mathrm{n}} - H_{\mathrm{u}})^{3/2}\right] & (H_{\mathrm{u}} \leqslant z_{\mathrm{n}}) \end{cases} \qquad \text{(B.9)}$$

Equations (B.10) and (B.11) apply when $T_{\mathrm{i}} < T_{\mathrm{j}}$ ($\rho_{\mathrm{i}} > \rho_{\mathrm{j}}$):

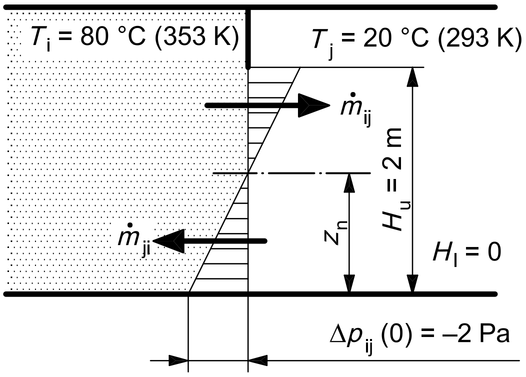
$$\dot{m}_{\mathrm{ij}} = \begin{cases} 0 & (z_{\mathrm{n}} < H_{\mathrm{l}}) \\ \dfrac{2}{3} C_{\mathrm{D}} \cdot B_{\mathrm{vent}} \sqrt{2\rho_{\mathrm{i}}(\rho_{\mathrm{i}} - \rho_{\mathrm{j}})g} \cdot (z_{\mathrm{n}} - H_{\mathrm{l}})^{3/2} & (H_{\mathrm{l}} \leqslant z_{\mathrm{n}} < H_{\mathrm{u}}) \\ \dfrac{2}{3} C_{\mathrm{D}} \cdot B_{\mathrm{vent}} \sqrt{2\rho_{\mathrm{i}}(\rho_{\mathrm{i}} - \rho_{\mathrm{j}})g} \cdot \left[(z_{\mathrm{n}} - H_{\mathrm{l}})^{3/2} - (z_{\mathrm{n}} - H_{\mathrm{u}})^{3/2}\right] & (H_{\mathrm{u}} \leqslant z_{\mathrm{n}}) \end{cases} \qquad \text{(B.10)}$$

$$\dot{m}_{\mathrm{ji}} = \begin{cases} \dfrac{2}{3} C_{\mathrm{D}} \cdot B_{\mathrm{vent}} \sqrt{2\rho_{\mathrm{j}}(\rho_{\mathrm{i}} - \rho_{\mathrm{j}})g} \cdot \left[(H_{\mathrm{u}} - z_{\mathrm{n}})^{3/2} - (H_{\mathrm{l}} - z_{\mathrm{n}})^{3/2}\right] & (z_{\mathrm{n}} < H_{\mathrm{l}}) \\ \dfrac{2}{3} C_{\mathrm{D}} B_{\mathrm{vent}} \sqrt{2\rho_{\mathrm{j}}(\rho_{\mathrm{i}} - \rho_{\mathrm{j}})g} \cdot (H_{\mathrm{u}} - z_{\mathrm{n}})^{3/2} & (H_{\mathrm{l}} \leqslant z_{\mathrm{n}} < H_{\mathrm{u}}) \\ 0 & (H_{\mathrm{u}} \leqslant z_{\mathrm{n}}) \end{cases} \qquad \text{(B.11)}$$

B.3.2.4 Calculation example

B.3.2.4.1 Calculation condition

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



Conditions: $T_{\mathrm{i}} = 80$ °C (353 K); $T_{\mathrm{j}} = 20$ °C (293 K); $B_{\mathrm{vent}} = 0{,}9$ m; $H_{\mathrm{u}} = 2{,}0$ m; $H_{\mathrm{l}} = 0{,}0$ m; $\Delta p_{\mathrm{ij}}(0) = -2{,}0$ Pa.

Figure B.3 — Mass flow rates for given conditions

B.3.2.4.2 Smoke densities of two enclosures

Using Equations (B.6) and (B.7), the density of smoke in the two enclosures is given by Equations (B.12) and (B.13):

$$\rho_{\mathrm{i}} = \frac{353}{T_{\mathrm{i}}} = \frac{353}{353} = 1{,}0 \tag{B.12}$$

$$\rho_{\mathrm{j}} = \frac{353}{T_{\mathrm{j}}} = \frac{353}{293} = 1{,}205 \tag{B.13}$$

B.3.2.4.3 Neutral plane height

Using Equation (B.5), the height of neutral plane, z_{n}, expressed in metres, is given by Equation (B.14):

$$z_{\mathrm{n}} = \frac{\Delta p_{\mathrm{ij}}(0)}{(\rho_{\mathrm{i}} - \rho_{\mathrm{j}})g} = \frac{-2}{(1{,}0 - 1{,}205) \times 9{,}8} = 1{,}00 \tag{B.14}$$

B.3.2.4.4 Mass flow rates

As the neutral plane height, z_{n}, is lower than the doorway height, H_{u}, flow is bi-directional. Using Equations (B.8) and (B.9), the mass flow rates, in kilograms per second, to and from enclosure j are given by Equations (B.15) and (B.16):

$$\dot{m}_{\mathrm{ij}} = \frac{2}{3} C_{\mathrm{D}} \cdot B_{\mathrm{vent}} \sqrt{2\rho_{\mathrm{i}}(\rho_{\mathrm{j}} - \rho_{\mathrm{i}})} \cdot (H_{\mathrm{u}} - z_{\mathrm{n}})^{3/2}$$

$$= \frac{2}{3} \times 0{,}7 \times 0{,}9 \sqrt{2 \times 1{,}0 \times (1{,}205 - 1{,}0) \times 9{,}8} \times (2{,}0 - 1{,}00)^{3/2} \tag{B.15}$$

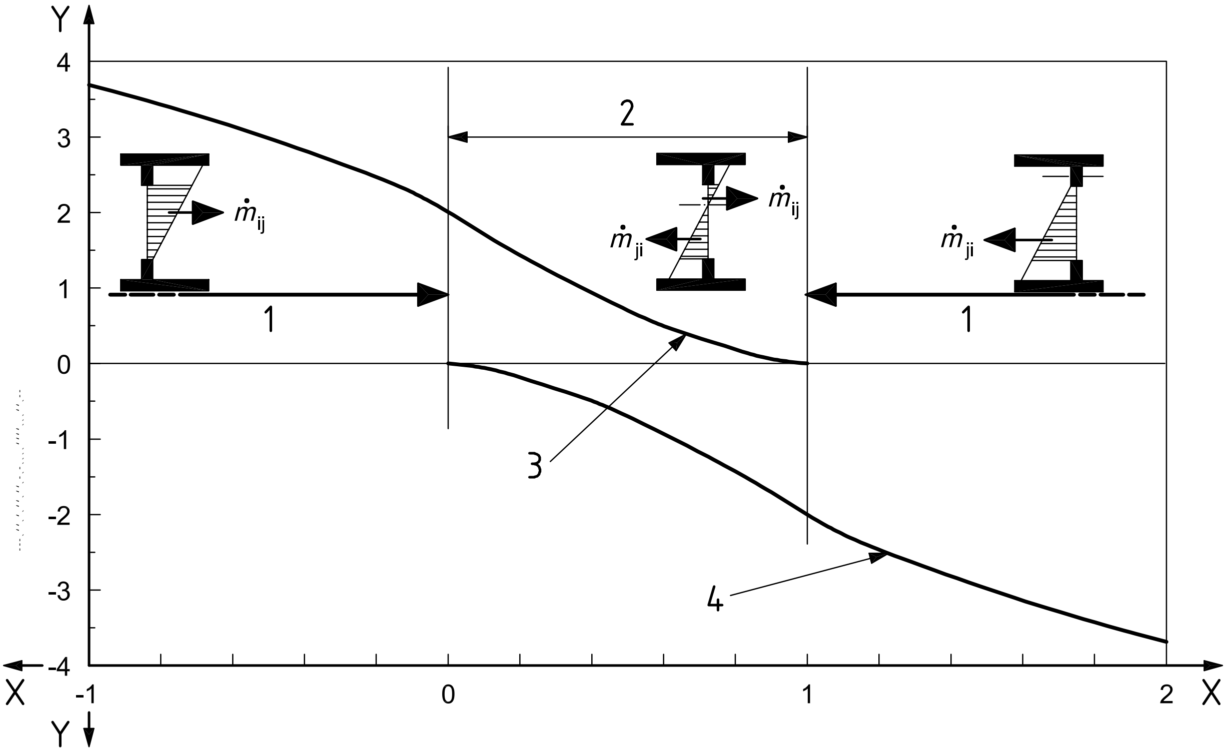
$$= 0{,}841$$

$$\dot{m}_{\mathrm{ji}} = \frac{2}{3} C_{\mathrm{D}} \cdot B_{\mathrm{vent}} \sqrt{2\rho_{\mathrm{j}}(\rho_{\mathrm{j}} - \rho_{\mathrm{i}})g} \cdot (z_{\mathrm{n}} - H_{\mathrm{l}})^{3/2}$$

$$= \frac{2}{3} \times 0{,}7 \times 0{,}9 \sqrt{2 \times 1{,}205 \times (1{,}205 - 1{,}00) \times 9{,}8} \times (1{,}00 - 0{,}0)^{3/2} \tag{B.16}$$

$$= 0{,}924$$

As for general cases, a diagram is provided in Figure B.4.



Key

X non-dimensional neutral plane height $(z_n - H_l)/(H_u - H_l)$

Y non-dimensional mass flow rate $\dot{m}\Big/\left[\rho\left(\rho_j-\rho_i\right)\right]^{1/2}\cdot B_{vent}\cdot\left(H_u-H_l\right)^{3/2}$

1 unidirectional flow

2 bi-directional flow

3 $\dot{m}_{ij}\Big/\left[\rho_i\left(\rho_j-\rho_i\right)\right]^{1/2}\cdot B_{vent}\cdot\left(H_u-H_l\right)^{3/2}$

4 $-\dot{m}_{ji}\Big/\left[\rho_j\left(\rho_j-\rho_i\right)\right]^{1/2}\cdot B_{vent}\cdot\left(H_u-H_l\right)^{3/2}$

NOTE 1 Negative value corresponds to flow from enclosure j to i.

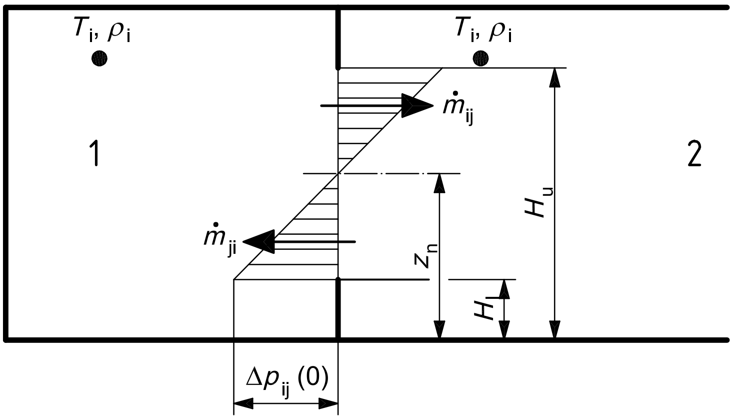
NOTE 2 The symbol ρ without subscript denotes density of upstream enclosure (ρ_i or ρ_j).

Figure B.4 — Diagram for mass flow rate through vertical vent in case of $T_i > T_j$

B.3.3 Flow through 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, mass flow rate out of the enclosure, $\dot{m}_{\mathrm{ij}}$, equals the incoming mass flow rate, $\dot{m}_{\mathrm{ji}}$. As a special case of B.3.2, the neutral plane, z_{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 for the case $T_{\mathrm{i}} > T_{\mathrm{j}}$ ($\rho_{\mathrm{i}} < \rho_{\mathrm{j}}$)

B.3.3.2 Position of neutral plane

The position of the neutral plane is given by Equation (B.17):

$$z_{\mathrm{n}} = \frac{H_{\mathrm{u}} - H_{\mathrm{l}}}{1 + (\frac{\rho_{\mathrm{j}}}{\rho_{\mathrm{i}}})^{1/3}} + H_{\mathrm{l}} \tag{B.17}$$

B.3.3.3 Mass flow rate

The mass flow rates are given by Equations (B.18) and (B.19):

$$\dot{m}_{\mathrm{ij}} = \frac{2}{3} C_{\mathrm{D}} \sqrt{2\rho_{\mathrm{i}}(\rho_{\mathrm{j}} - \rho_{\mathrm{i}})g} \cdot \left(\frac{(\rho_{\mathrm{j}} / \rho_{\mathrm{i}})^{1/3}}{1 + (\rho_{\mathrm{j}} / \rho_{\mathrm{i}})^{1/3}} \right)^{3/2} \cdot B_{\mathrm{vent}} (H_{\mathrm{u}} - H_{\mathrm{l}})^{3/2} \tag{B.18}$$

$$\dot{m}_{\mathrm{ji}} = \frac{2}{3} C_{\mathrm{D}} \sqrt{2\rho_{\mathrm{j}}(\rho_{\mathrm{j}} - \rho_{\mathrm{i}})g} \cdot \left(\frac{1}{1 + (\rho_{\mathrm{j}} / \rho_{\mathrm{i}})^{1/3}} \right)^{3/2} \cdot B_{\mathrm{vent}} (H_{\mathrm{u}} - H_{\mathrm{l}})^{3/2} \tag{B.19}$$

NOTE 1 Because the flow rates are identical, calculation of either Equation (B.18) or (B.19) is sufficient.

NOTE 2 If enclosure temperature, T_{i}, is greater than 300 °C, the coefficient is fairly constant, which results in Equation (B.20), a useful relationship from Reference [3]:

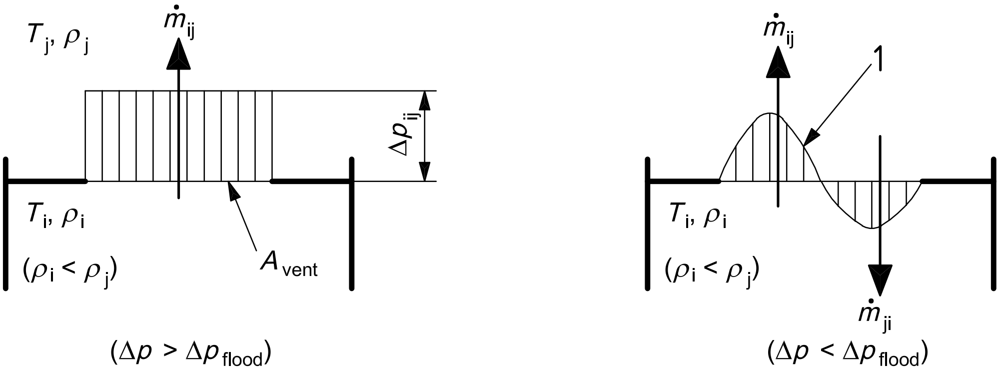
$$\dot{m}_{\mathrm{ij}} = \dot{m}_{\mathrm{ji}} \approx 0{,}52 B_{\mathrm{vent}} (H_{\mathrm{u}} - H_{\mathrm{l}})^{3/2} \tag{B.20}$$

B.3.4 Flow through horizontal vent connecting two enclosures of uniform but different temperatures — Special case of single opening in one enclosure

Flow, $\dot{m}_{ij}$, expressed in kilograms per second, through a horizontal vent can be calculated in a manner similar to the case of flow through a vertical vent connecting uniform temperature enclosures as given in Equation (B.21):

$$\dot{m}_{ij} = C_D \cdot A_{vent} \sqrt{2\rho_i \Delta p_{ij}} \qquad (\text{if } \Delta p_{ij} \geqslant \Delta p_{flood}) \tag{B.21}$$

However, caution should be used, since there is a minimum pressure difference for flooding. If the pressure difference is too small, a bi-directional flow can arise. The critical condition, Δp_{flood}, for the onset of bi-directional flow is still under investigation. Examples of equations are those developed by Yamada[4] and Cooper[5]. An explicit equation for flow rate under the bi-directional flow situation is not established at present.



Key

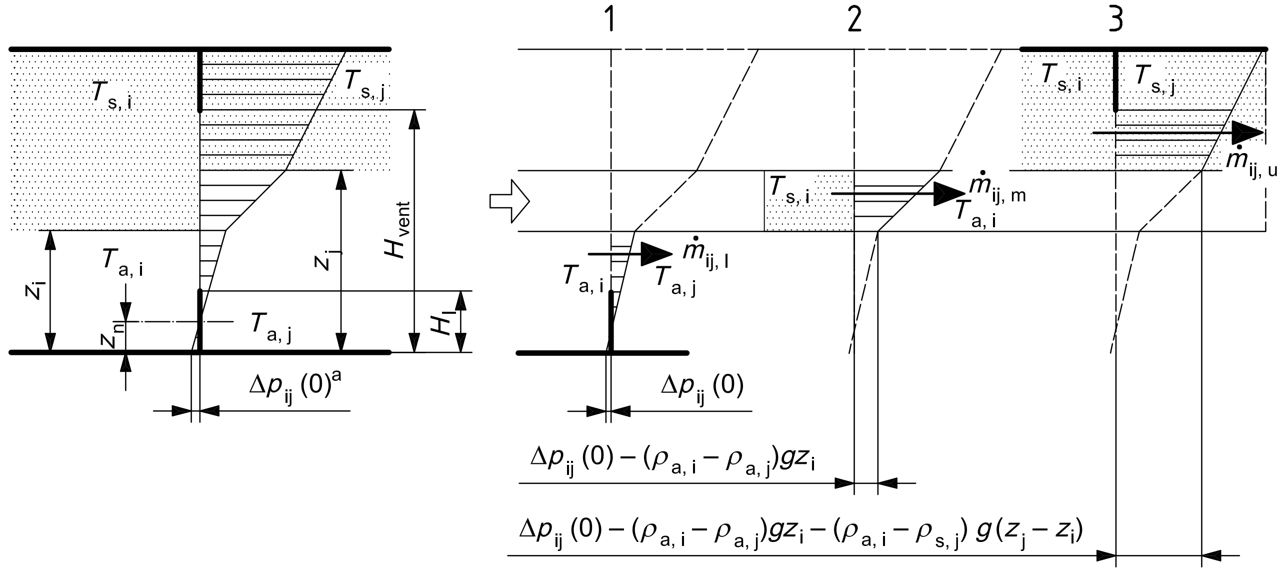
1 velocity profile

Figure B.6 — Pressure difference across vertical vent and corresponding flow direction ($\rho_i < \rho_j$)

B.3.5 Two-layer environment — Flow through vertical vent connecting two enclosures

B.3.5.1 General

In a two-layer environment, the flow through a vent is rather complicated. As shown in Figure B.7, flow through a vent is calculated in three segments. The bottom segment is in contact with the lower layer on both sides. The middle segment is in contact with smoke and lower layer on either side. The upper segment is in contact with smoke on both sides. Mass flow rates are calculated by applying the concepts of B.3.1 and B.3.2 to each segment.



Key

1 lower segment
2 middle segment
3 upper segment

[a] Given.

Figure B.7 — Pressure difference and mass flow profile in two-layer environment

B.3.5.2 Mass flow rates in lower segment

Referring to Figure B.7, flow in the lower segment [$0 < z < \min(z_i, z_j)$] is calculated by the equations in B.3.2 for a vertical vent connecting two enclosures of uniform but different temperatures. The following substitutions are necessary to apply Equation (B.5) to Equation (B.11):

$$T_i = T_{a,i} \tag{B.22}$$

$$T_j = T_{a,j} \tag{B.23}$$

$$H_u = \min(z_i, z_j) \tag{B.24}$$

B.3.5.3 Mass flow rates in middle segment

Similar to the lower segment, flow in the middle segment can be calculated from Equations (B.5) to (B.11) after the following substitutions:

$$T_\mathrm{i} = \begin{cases} T_\mathrm{s,i} \ (z_\mathrm{i} < z_\mathrm{j}) \\ T_\mathrm{a,i} \ (z_\mathrm{i} \geqslant z_\mathrm{j}) \end{cases} \tag{B.25}$$

$$T_\mathrm{j} = \begin{cases} T_\mathrm{a,j} \ (z_\mathrm{i} < z_\mathrm{j}) \\ T_\mathrm{s,j} \ (z_\mathrm{i} \geqslant z_\mathrm{j}) \end{cases} \tag{B.26}$$

$$H_\mathrm{u} = \mathrm{abs}(z_\mathrm{i} - z_\mathrm{j}) \tag{B.27}$$

$$H_\mathrm{l} = 0 \tag{B.28}$$

Use the formula in Equation (B.29) in place of $\Delta p_\mathrm{ij}(0)$:

$$\Delta p_\mathrm{ij}(0) - \left(\frac{353}{T_\mathrm{a,i}} - \frac{353}{T_\mathrm{a,j}} \right) \times g \times \min(z_\mathrm{i}, z_\mathrm{j}) \tag{B.29}$$

B.3.5.4 Mass flow rates in upper segment

Similar to the previous two segments, flow in the upper segment can be calculated from the Equations (B.5) to (B.11) after the following substitutions:

$$T_\mathrm{i} = T_\mathrm{s,i} \tag{B.30}$$

$$T_\mathrm{j} = T_\mathrm{s,j} \tag{B.31}$$

Use the formula in Equation (B.32) in place of H_u:

$$H_\mathrm{vent} - \max(z_\mathrm{i}, z_\mathrm{j}) \tag{B.32}$$

$$H_\mathrm{l} = 0 \tag{B.33}$$

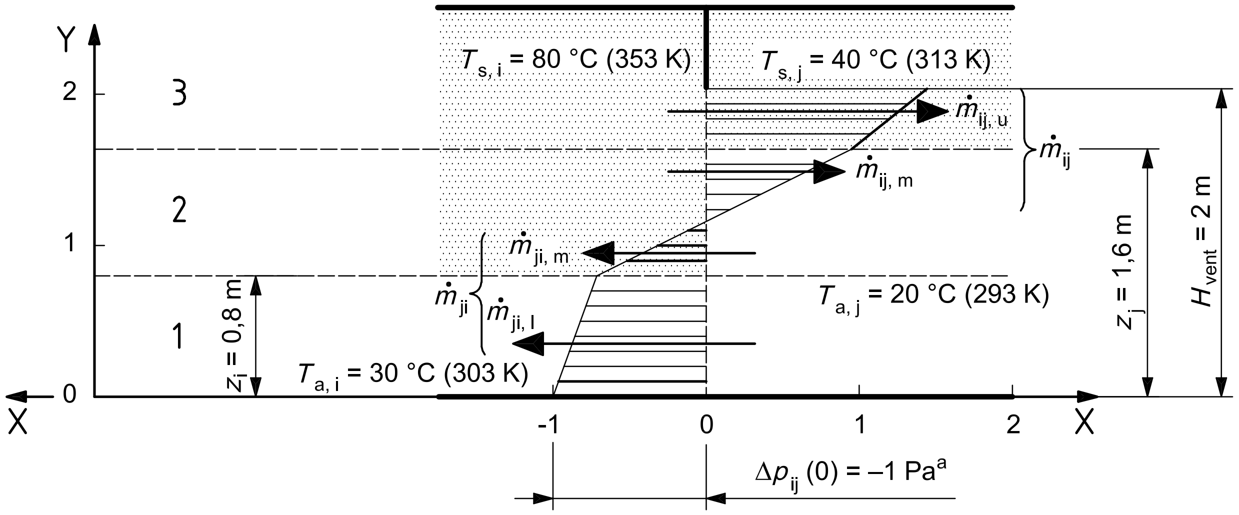
Use the formulas in Equation (B.34) in place of $\Delta p_\mathrm{ij}(0)$:

$$\Delta p_\mathrm{ij}(0) - \left(\frac{353}{T_\mathrm{a,i}} - \frac{353}{T_\mathrm{a,j}} \right) \times g \times \min(z_\mathrm{i}, z_\mathrm{j}) - \begin{cases} \left(\frac{353}{T_\mathrm{s,i}} - \frac{353}{T_\mathrm{a,j}} \right) \times g \times \mathrm{abs}(z_\mathrm{i} - z_\mathrm{j}), & (z_\mathrm{i} < z_\mathrm{j}) \\ \left(\frac{353}{T_\mathrm{a,i}} - \frac{353}{T_\mathrm{s,j}} \right) \times g \times \mathrm{abs}(z_\mathrm{i} - z_\mathrm{j}), & (z_\mathrm{i} \geqslant z_\mathrm{j}) \end{cases} \tag{B.34}$$

B.3.5.5 Calculation example

B.3.5.5.1 Calculation condition

As shown in Figure B.8, 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 (313 K). Temperatures in the lower layer are 30 °C (303 K) and 20 °C (293K). It is given that the pressure in enclosure j is higher than that in enclosure i by 1 Pa ($\Delta p_\mathrm{ij} = -1$ Pa). Calculations of mass flow rates are carried out for each segment.



Key

X Δp_{ij}, expressed in pascals

Y height above floor, expressed in metres

1 lower segment

2 middle segment

3 upper segment

[a] Given.

Figure B.8 — Calculation example of mass flow rates in two-layer environment

B.3.5.5.2 Mass flow rate in lower segment

The extent of the lower segment is $0 < z < z_i$, where $z_i = 0{,}8$ m, for this case. Using Equation (B.5), the neutral plane height, z_n, expressed in metres, for this segment is given by Equation (B.35):

$$z_n = \frac{\Delta p_{ij}(0)}{(\rho_i - \rho_j)g} = \frac{-1}{(1{,}165 - 1{,}205) \times 9{,}8} = 2{,}57 \tag{B.35}$$

In this case, the neutral plane height, z_n, is larger than segment height, z_i. Thus, the flow is unidirectional from enclosure j to i. The versions of Equation (B.36) for $m_{ji,l}$, expressed in kilograms per second, are derived using the last version of Equation (B.9):

$$\begin{aligned} \dot{m}_{ij} &= \frac{2}{3} C_D \times B_{vent} \sqrt{2\rho_j(\rho_j - \rho_i)g} \times \left[(z_n - H_u)^{3/2} - (z_n - H_l)^{3/2} \right] \\ &= \frac{2}{3} \times 0{,}7 \times 0{,}9 \sqrt{2 \times 1{,}205 \times (1{,}205 - 1{,}165) \times 9{,}8} \times \left[(2{,}57 - 0)^{3/2} - (2{,}57 - 0{,}8)^{3/2} \right] \\ &= 0{,}720 \end{aligned} \tag{B.36}$$

B.3.5.5.3 Mass flow rates in middle segment

The extent of the middle segment is $z_i < z < z_j$, where z_i and z_j equal 0,8 m and 1,6 m, respectively, for this case. Following Equations (B.27) and (B.28), the reference height, H_u, expressed in metres above bottom of segment, is moved to the bottom of the segment as given in Equations (B.37) and (B.38):

$$H_u = \text{abs}(z_i - z_j) = \text{abs}\ (0{,}8 - 1{,}6) = 0{,}8 \tag{B.37}$$

$$H_l = 0. \tag{B.38}$$

The pressure difference, $\Delta p_{\text{ij(bottom of segment)}}$, expressed in pascals, at the bottom of middle segment is calculated from Equation (B.29) as given in Equation (B.39):

$$\begin{aligned}\Delta p_{\text{ij(bottom of segment)}} &= \Delta p_{ij}(0) - \left(\frac{353}{T_{a,i}} - \frac{353}{T_{a,j}}\right) \times g \times \min(z_i, z_j)\\ &= -1 - (1{,}165 - 1{,}205) \times 9{,}8 \times 0{,}8\\ &= -0{,}686\end{aligned} \tag{B.39}$$

Using Equation (B.5), neutral plane height, z_n, expressed in metres, above bottom of middle segment is given by Equation (B.40):

$$z_n = \frac{\Delta p_{ij}}{(\rho_i - \rho_j)g} = \frac{-0{,}686}{(1{,}00 - 1{,}205) \times 9{,}8} = 0{,}342 \tag{B.40}$$

As $0 < z_n < \text{abs}(z_i - z_j)$, flow is bi-directional. Using the second versions of Equations (B.8) and (B.9), the result for the flows, $\dot{m}_{\text{ij,m}}$ and $\dot{m}_{\text{ji,m}}$, expressed in kilograms per second, is given in Equations (B.41) and B.42):

$$\begin{aligned}\dot{m}_{\text{ij,m}} &= \frac{2}{3} C_D \times B_{\text{vent}} \sqrt{2\rho_i(\rho_j - \rho_i) \times g} \times (H_u - z_n)^{3/2}\\ &= \frac{2}{3} \times 0{,}7 \times 0{,}9 \times \sqrt{2 \times 1{,}0 \times (1{,}205 - 1{,}0) \times 9{,}8} \times (0{,}8 - 0{,}342)^{3/2}\\ &= 0{,}261\end{aligned} \tag{B.41}$$

$$\begin{aligned}\dot{m}_{\text{ji,m}} &= \frac{2}{3} C_D \times B_{\text{vent}} \sqrt{2\rho_j(\rho_j - \rho_i)g} \times (z_n - H_l)^{3/2}\\ &= \frac{2}{3} \times 0{,}7 \times 0{,}9 \times \sqrt{2 \times 1{,}205 \times (1{,}205 - 1{,}0) \times 9{,}8} \times (0{,}342 - 0)^{3/2}\\ &= 0{,}185\end{aligned} \tag{B.42}$$

B.3.5.5.4 Mass flow rates in upper segment

The extent of the upper segment is $z_j < z < H_{\text{vent}}$, where z_i and H_{vent} equal 1,6 m and 2,0 m, respectively, for this case. Following Equations (B.32) and (B.33), reference height, H_u, expressed in metres, is moved to the bottom of the segment as given in Equations (B.43) and (B.44):

$$H_u = H_{\text{vent}} - \max(z_i, z_j) = 2{,}0 - 1{,}6 = 0{,}4 \tag{B.43}$$

$$H_l = 0 \tag{B.44}$$

The pressure difference, $\Delta p_{\mathrm{ij(bottom\ of\ segment)}}$, expressed in pascals, at the bottom of upper segment is calculated from Equation (B.34) as given in Equation (B.45):

$$\begin{aligned}\Delta p_{\mathrm{ij(bottom\ of\ segment)}} &= \Delta p_{\mathrm{ij}}(0) - \left(\frac{353}{T_{\mathrm{a,i}}} - \frac{353}{T_{\mathrm{a,j}}}\right) \times g \times \min(z_{\mathrm{i}}, z_{\mathrm{j}}) - \left(\frac{353}{T_{\mathrm{s,i}}} - \frac{353}{T_{\mathrm{a,j}}}\right) \times g \times \mathrm{abs}(z_{\mathrm{i}} - z_{\mathrm{j}}) \\ &= -0{,}686 - \left(\frac{353}{353} - \frac{353}{293}\right) \times 9{,}8 \times 0{,}8 \\ &= 0{,}919\end{aligned} \tag{B.45}$$

NOTE The first two terms in the first version of Equation (B.45) have already been calculated from Equation (B.39).

Using Equation (B.5), the neutral plane height, z_{n}, expressed in metres, above the bottom of the upper segment is given in Equation (B.46):

$$z_{\mathrm{n}} = \frac{\Delta p_{\mathrm{ij}}}{(\rho_{\mathrm{i}} - \rho_{\mathrm{j}}) \times g} = \frac{0{,}919}{(1{,}00 - 1{,}128) \times 9{,}8} = -0{,}731 \tag{B.46}$$

As $z_{\mathrm{n}} < 0$, flow is unidirectional. Using the first version of Equation (B.8), the result for the flow, $\dot{m}_{\mathrm{ij,u}}$, expressed in kilograms per second, is given in Equation (B.47):

$$\begin{aligned}\dot{m}_{\mathrm{ij,u}} &= \frac{2}{3} C_{\mathrm{D}} \times B_{\mathrm{vent}} \sqrt{2\rho_{\mathrm{i}}(\rho_{\mathrm{j}} - \rho_{\mathrm{i}}) \times g} \times \left[(H_{\mathrm{u}} - z_{\mathrm{n}})^{3/2} - (H_{\mathrm{l}} - z_{\mathrm{n}})^{3/2}\right] \\ &= \frac{2}{3} \times 0{,}7 \times 0{,}9 \times \sqrt{2 \times 1{,}0 \times (1{,}128 - 1{,}0) \times 9{,}8} \times \left\{\left[0{,}4 - (-0{,}731)\right]^{3/2} - \left[0 - (-0{,}731)\right]^{3/2}\right\} \\ &= 0{,}384\end{aligned} \tag{B.47}$$

B.3.5.5.5 Total mass flow rates between enclosures

Total mass flow rates, $\dot{m}_{\mathrm{ij}}$ and $\dot{m}_{\mathrm{ji}}$, expressed in kilograms per second, through vents are the sum of the flow rates in the three segments as given in Equations (B.48) and (B.49):

$$\dot{m}_{\mathrm{ij}} = \dot{m}_{\mathrm{ij,m}} + \dot{m}_{\mathrm{ij,u}} = 0{,}261 + 0{,}384 = 0{,}645 \tag{B.48}$$

$$\dot{m}_{\mathrm{ji}} = \dot{m}_{\mathrm{ji,l}} + \dot{m}_{\mathrm{ji,m}} = 0{,}720 + 0{,}185 = 0{,}909 \tag{B.49}$$

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

B.4 Scientific basis for the equation-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[3] based on the suggestions of Sekine. Extensions were made to a two-layer environment by Prahl and Emmons[6] and Rockett[7]. 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.*[8], [9], Quintiere *et al.*[10] and Nakaya *et al.*[11]. These measurements determined that the flow coefficient is in the range of 0,68 to 0,73, typically 0,7. Further historical aspects are reviewed by Belyer[12].

B.5 Equation-set limitations

B.5.1 Uniformity of smoke layer

The equation 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 equation 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 should be careful consideration of the dynamic pressure distribution.

B.6 Output parameters

The equation set outputs mass flow rate through the vent, expressed in kilograms per second. When bi-directional flow exists, the position of the neutral plane is also obtained.

B.7 Equation-set input parameters

B.7.1 Pressure difference across vents

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

B.7.2 Enclosure temperature profile adjacent to vent

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

B.8 Domain of applicability of the equation set

The domain of applicability of the equation set can be determined from the studies by Steckler *et al.*[8] and Nakaya *et al.*[11] and by other authors. Steckler's experiments were carried out in a room of 2,8 m by 2,8 m and 2,13 m high. Doorway opening width was 0,74 m, while the doorway height was varied in the range of 0,46 m to 1,38 m. Heat release rate of fire was in the range of 31,6 kW to 158 kW. Enclosure temperature was 250 °C at maximum. Nakaya's experiments correspond to a somewhat larger room of 3,45 m by 3,55 m and 2,12 m high. Opening height was 1,6 m or 1,7 m. Opening width was 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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[13] ISO 5725 (all parts), *Accuracy (trueness and precision) of measurement methods and results*

[14] ISO 16735, *Calculation methods for smoke layers*

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