Fire Safety in Buildings – Smoke Management Guidelines

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Foreword

REHVA, now 55 years old, is the European Federation of HVAC Association representing more than 100,000 experts from 27 European countries. REHVA’s mission is to promote energy efficient and healthy technologies for mechanical services of buildings, and to disseminate knowledge among professionals and practitioners in Europe and beyond. REHVA Guidebooks are the most important tools to diffuse knowledge on latest developments, and advanced technologies providing practical guidance to practitioners. REHVA has published 23 guidebooks to date, this guide on Fire safe in buildings is the 24th in the REHVA Guidebook series.

– Anita Derjanecz, REHVA Managing Director

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1 Introduction to smoke control systems

1.1 Starting point

Fire events in buildings cause substantial material damage and loss of life all over the world each year. Construction and building laws contain various provisions for preventing the risk of fire and on how the use of appropriate building materials, a construction style involving smaller compartments and suitable partitions can prevent the spread of fire and smoke in the event of a fire. The objective is to detect a fire as early as possible, so that people can be taken to safety, automatic fire-extinguishing systems can be activated, and the fire brigade’s intervention time can be shortened. But fire protection often fails to meet the requirements posed by modern-day buildings with respect to their architecture, dimensions, number of people and technical sensitivity.

Figure 1 shows the number of fire-related deaths by country in relation to population and number of fires for a select group of countries. These statistics generally only account for victims who were recovered dead at the scene. Persons who died from fire-related injuries after removal from the scene are generally not included in these figures. Estimates indicate that more than 90% of fire-related deaths are not caused by fire, but rather by inhalation of toxic fire gases (smoke).

1.2 Objectives of smoke management systems

At a minimum, smoke control can aid the fire-extinguishing and rescue efforts of the fire brigade. The creation of low-smoke layers enables identification of the source of the fire and, thus, effective fire-extinguishing measures. At the same time, it helps to find and rescue people in distress. Extraction of hot fire gases and the supply of fresh air ventilate the fire compartment and ensure continuous combustion processes. This way, a flashover can be delayed, and feared rollover and backdraft effects can be prevented.
In addition to its toxic effects, smoke can also greatly hinder visibility, thus causing people trying to escape the fire to panic.

Smoke control also serves to enhance people’s ability to save themselves, particularly in buildings with large crowds of people, where escape routes for full evacuation must be kept low-smoke for as long as possible. Evacuation scenarios are used to determine the time during which low-smoke escape routes are required. Smoke and heat control systems in this context also often serve to compensate for deviations from building-regulatory requirements.

1.3 Fire stages

The first stage of a fire is the smouldering, or incipient stage, where a fire may develop over a longer period of time without any noticeable rise in temperature and eventually transitions into the growth stage, where it is an open burning fire with visible flames. Smoke detectors are capable of detecting fires at a very early stage \( t_1 \). Early warning is important for a fire brigade to arrive on time \( t_3 \). It typically takes ten minutes for the fire brigade to respond after detection.

Combustible material in the same room as the fire suddenly aids incineration once it has built up sufficient thermal layering. The fire moves into the fully developed stage when the growth stage has reached its maximum temperature. Thermal trigger devices (fire dampers or fire extinguisher systems, for example) are triggered when the fire transitions from the growth to the fully developed stage \( t_2 \).

This stage eventually progresses to the decay stage (in chart, red curve), depending on the availability of combustible material, smoke/heat extraction and/or effectiveness of fire extinguishing measures. The development of smoke does not directly correspond to the development of temperature. For example, there can be sizeable quantities of smoke developing in the incipient stage already that represent a risk to people and assets (grey curve).

Figure 3 shows the stages through which a fire typically passes as well as the effectiveness of the corresponding measures for smoke control systems and firefighting operations. The individual stages are described in more detail in the following:

**Protection objective:**

**Rescue of people and animals**

Whether or not people can reliably save themselves or others depends greatly on whether the fire is detected as early as possible and an alarm is sounded.

**Partition measures**

Partition measures are taken in an effort to prevent the spread of fire and smoke for as long as possible.

Ventilation systems rely on fire dampers for partitioning. If they only have a thermal activation unit, they are only able to prevent the spread of smoke at a very late point in time. For this reason, they should be equipped with smoke-based activation.

**Smoke control systems**

Ventilation systems are not suitable for ensuring a constant level of smoke removal. However, they can help in measures for smoke extraction, for example, as fresh air supply for mechanical smoke extraction.

Mechanical smoke extraction systems ensure a continuous smoke extraction volume flow once they are activated. On the other hand, natural smoke extraction systems require high temperatures in the smoke gas layer to ‘drive’ the smoke removal.
1. Introduction to smoke control systems

**Figure 3. Fire phases and corresponding measures.**
For this reason, they play only a subordinate role in effective life-saving measures.

Pressure differential systems (PDS) are activated at an early point in time and prevent the penetration of smoke into emergency (escape, rescue) routes.

Mobile smoke control fans used by the fire brigade primarily help with fire-fighting efforts.

**Fire extinguishing measures**

The different measures for extinguishing fires also have a different impact depending on the fire stage in which they were activated.

Small fires can be extinguished with handheld fire extinguishers in the incipient stage.

Gas extinguishing systems are usually activated at a very early point in time via smoke-based activation devices and can help save lives.

Thermally activated extinguishing systems, such as sprinkler systems, are also suitable for preventing the fire from spreading; however, they only play an indirect role in protection of personnel because they are activated at a much later point in time.

Often the fire brigade can only begin to extinguish the fire in the fully developed stage and prevent the fire from spreading to adjacent fire compartments. And generally, it is then only possible to save people from these adjacent fire compartments.

### 1.4 How to use this guidebook

This guidebook describes the different principles of smoke prevention and their practical implementation by way of natural and mechanical smoke extraction systems, smoke control by pressurization systems and appropriate partition measures. In the event of fire, smoke can spread through ventilation systems, but these systems can play an active support role in smoke prevention.

Real-fire and model experiments, as well as consistently improved-upon simulation methods, allow for robust conclusions to be drawn regarding the effectiveness of smoke extraction measures, even at the planning stage. This smoke management Guidebook provides the reader with suitable tools, also through references to standards and regulations, for evaluating, selecting and implementing a smoke control concept that is commensurate with the protection objective.
# Terms and Abbreviations

## 2.1 Terms and definitions

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backdraft</td>
<td>Smoke explosion through addition of oxygen</td>
</tr>
<tr>
<td>Flashover</td>
<td>Fire flash; abrupt ignition of pyrolysis gases at approx. 500°C; transition to full fire</td>
</tr>
<tr>
<td>Cold smoke</td>
<td>Smoke whose temperature is not very different from that of the ambient air and below the activation temperature of thermal trigger devices (cold smoke extraction = discharge of cold smoke)</td>
</tr>
<tr>
<td>Plug holing</td>
<td>Funnel-shaped, point-by-point suction through the smoke layer from the low-smoke layer. The condition where air from below the smoke layer is pulled through the smoke layer into the smoke exhaust due to a high exhaust rate.</td>
</tr>
<tr>
<td>Plume</td>
<td>Thermal upward column</td>
</tr>
<tr>
<td>Rollover</td>
<td>Sudden smoke ignition if there is sufficient oxygen</td>
</tr>
<tr>
<td>Escape stairwell</td>
<td>Stairwell whose structural or technical measures help to prevent fire and/or smoke penetration in the event of fire.</td>
</tr>
</tbody>
</table>

## 2.2 Abbreviations

<table>
<thead>
<tr>
<th>Deutsch / German</th>
<th>Englisch / English</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brandraum</td>
<td>Fire compartment</td>
</tr>
<tr>
<td>BFSM</td>
<td>Brandfallsteuermatrix</td>
</tr>
<tr>
<td>—</td>
<td>Safety matrix</td>
</tr>
<tr>
<td>BL</td>
<td>Brandlüfter der Feuerwehr</td>
</tr>
<tr>
<td>—</td>
<td>Fan</td>
</tr>
<tr>
<td>ETK</td>
<td>Einheits-Temperatur-/ Zeitkurve</td>
</tr>
<tr>
<td>—</td>
<td>Standard Time / Temperature curve</td>
</tr>
<tr>
<td>AA</td>
<td>Automatische Auslösung</td>
</tr>
<tr>
<td>—</td>
<td>Automatic activation</td>
</tr>
<tr>
<td>Lüftung</td>
<td>AC</td>
</tr>
<tr>
<td>—</td>
<td>Air conditioning</td>
</tr>
<tr>
<td>Bewertung und Überprüfung der Leistungsbeständigkeit</td>
<td>AVCP</td>
</tr>
<tr>
<td>—</td>
<td>Assessment and verification of constancy of performance</td>
</tr>
<tr>
<td>GA</td>
<td>Gebäudeautomatation</td>
</tr>
<tr>
<td>—</td>
<td>Building management system</td>
</tr>
<tr>
<td>CE</td>
<td>Communautés Européennes oder Conformité Européenne</td>
</tr>
<tr>
<td>—</td>
<td>Communautés Européennes or Conformité Européenne</td>
</tr>
<tr>
<td>CFD</td>
<td>Numerische Strömungsmechanik</td>
</tr>
<tr>
<td>—</td>
<td>Computational fluid dynamics</td>
</tr>
<tr>
<td>BPR</td>
<td>Bauprodukte Richtlinie</td>
</tr>
<tr>
<td>—</td>
<td>Construction product regulation</td>
</tr>
<tr>
<td>EXAP</td>
<td>Erweiterter Anwendungsbereich</td>
</tr>
<tr>
<td>—</td>
<td>Extended field of application</td>
</tr>
<tr>
<td>BMZ</td>
<td>Brandmeldezentrale</td>
</tr>
<tr>
<td>—</td>
<td>Fire alarm control panel</td>
</tr>
<tr>
<td>BSK</td>
<td>Brandschutzklappe</td>
</tr>
<tr>
<td>—</td>
<td>Fire Damper</td>
</tr>
<tr>
<td>BMA</td>
<td>Brandmeldeanlage</td>
</tr>
<tr>
<td>—</td>
<td>Fire detection system?</td>
</tr>
<tr>
<td>WPK</td>
<td>Werkseigene Produktionskontrolle</td>
</tr>
<tr>
<td>—</td>
<td>Factory production control</td>
</tr>
<tr>
<td>HOT</td>
<td>Betrieb unter erhöhten Temperaturen</td>
</tr>
<tr>
<td>—</td>
<td>High operating temperature</td>
</tr>
<tr>
<td>ITT</td>
<td>Erprüfung</td>
</tr>
<tr>
<td>—</td>
<td>Initial type testing</td>
</tr>
<tr>
<td>MA</td>
<td>Manuelle Auslösung</td>
</tr>
<tr>
<td>—</td>
<td>Manual activation</td>
</tr>
<tr>
<td>NRA</td>
<td>Natürliche Rauchabzugsanlage</td>
</tr>
<tr>
<td>—</td>
<td>Natural smoke and heat exhaust ventilation</td>
</tr>
<tr>
<td>RDA</td>
<td>Rauchschutz Druckanlage</td>
</tr>
<tr>
<td>—</td>
<td>Pressure differential system</td>
</tr>
<tr>
<td>EK</td>
<td>Entrauchungsklappe</td>
</tr>
<tr>
<td>—</td>
<td>Smoke Control Damper</td>
</tr>
<tr>
<td>NRWG</td>
<td>Naturliches Rauch- und Abzugsgerät</td>
</tr>
<tr>
<td>—</td>
<td>Smoke and heat exhaust ventilation</td>
</tr>
<tr>
<td>RWA</td>
<td>Rauch- und Wärmeabzugsanlage</td>
</tr>
<tr>
<td>—</td>
<td>Smoke and heat exhaust ventilation system</td>
</tr>
<tr>
<td>MRA</td>
<td>Maschinelle Rauchabzugsanlage</td>
</tr>
<tr>
<td>—</td>
<td>Smoke and heat exhaust ventilation system</td>
</tr>
<tr>
<td>SIL</td>
<td>Sicherheits-Integritätslevel</td>
</tr>
<tr>
<td>—</td>
<td>Safety integrity level</td>
</tr>
</tbody>
</table>
3 Smoke management principles

Different methods are used for different protection objectives to control smoke and heat and/or to keep areas low-smoke or entirely smoke-free.

3.1 Dilution

As concerns the room conditions, smoke control is characterised by dilution due to largely homogeneous areas of concentration of temperature (and smoke). This air flow condition of the room is mainly shaped by the room’s air intake, which is influenced substantially by the size and position of the air supply surfaces. Particularly small air supply surfaces, located in the upper area of the room, create supply air streams with relatively high flow speeds. The induction effect of the supply air streams creates a flow that fills the room, causing smoke to be distributed virtually evenly throughout the entire room volume in the event of a fire.

Figure 4 shows dilution of fire gases (for example, through operating ventilation system or unregulated supply of fresh air by air inlets).

The special advantage of dilution is the cooling of the smoke gases and preventing unburnt components from self-igniting (backdraft and rollover are prevented, reducing temperature for people and building components). The smoke temperature is directly dependent on the amount of heat released by the fire and the incoming amount of fresh air, which is heated by the fire. Figure 5 shows the fresh air volume flow relative to the fire’s heat release for different allowable smoke temperatures. The smoke volume flow to be extracted corresponds almost entirely to the fresh air volume flow and depends on the size of the fire compartment.

The required dilution ratios \((v = \text{ratio of volume or volume flow and fresh air supplied for dilution purposes, relative to the volume or volume flow of the smoke created by combustion})\) may differ greatly due to the complex factors described above, depending on whether they are intended to reach a specific lower temperature level, minimum visibility or allowable pollutant concentrations.

Figure 4. Dilution of fire gases (smoke).
While the required dilution for limiting the temperature only depends on the heat release and specification of the temperature limit, the specifications for necessary dilution ratios to create visibility and allowable gas concentrations are much more complex due to the toxic effects. For example, combustion of dry wood requires a minimum dilution ratio of $v_{min} = 18$, and combustion of heating fuel $v_{min} = 1400$, to create a visibility of 25 m from a luminescent escape route sign with an illuminance of 80 lux in the escape route$^{1,2}$.

A minimum dilution ratio of $v_{min} = 160$ to 200 must be achieved$^{3,4}$ in order to stay below harmful concentrations, for example, of carbon monoxide (CO) as an essential combustion component with known risk values, to allow people to remain in the area for around 30 minutes without suffering adverse health effects. If the composition of the fire load suggests that there may be relevant concentrations of further pollutants besides carbon monoxide, the required minimum dilution ratio will have to be checked in view of the circumstances. Since the effects of compositions of different toxins in varying concentrations on the human body have not yet been studied fully, with the composition depending on the fire event, no blanket statements can be made about generally required overall dilution factors.

If one assumes the amount of smoke generated in$^5$ an average, ventilated fire, the dilution volume flows shown in Figure 6 will be necessary in order to remain below the limits of allowable carbon monoxide concentrations in connection with the combustion of mixed fire loads of 25% plastic and 75% wood as defined by John and Purser$^6$.

Using the studies of John, a particle and aerosol concentration of 40 mg/m³, for a visibility of 10 m with reflecting escape route signs, should generally not be exceeded with respect to visibility. According to John and Hosser, a very substantial fresh air volume flow will be necessary to maintain visibility criteria relative to the heat release, the burning material, the combustion conditions, the contrast of escape route signs and the intensity of ambient lighting.

![Figure 5. Required volume flow to limit smoke temperatures.](image-url)
A mixed fire load of 25% plastic and 75% wood produces a smoke temperature of 48°C with a visibility of 10 m and a smoke temperature of only 28°C with a visibility of 35 m. The required supply air volume flows to produce minimum visibility, which generally also correspond to the smoke volume flows to be extracted, are represented relative to the heat release of the fire in Figure 7.

Fresh air volume flows, as are necessary to create reasonable pollutant concentrations or required visibility, cannot be achieved through natural or mechanical smoke extraction systems or mobile smoke fans (aerators) used by the fire brigade in regular fire compartments in the case of a fire that has been developing for several minutes. When it comes to dilution, therefore, the focus can merely be on limiting the smoke temperatures that must be below flashover conditions.

---

**Figure 6.** Required volume flow to limit smoke temperatures.

**Figure 7.** Required dilution volume flow rate to produce visibility range.
3. Smoke management principles

3.2 Layering

An essential element of smoke extraction through layering is a low-impulse air supply in the lower section of the room. In this case, the supply air speeds are so small (typical values ≤ 1 m/s) that the supply air does not trigger a room-filling flow. The air flow is then primarily defined by the plume forming above the source of the fire. This plume transports the combustion products created by the fire and the heat flow convectively released to the upper section of the room. They will be extracted and discharged from the room naturally – ideally, through vents in the ceiling – or mechanically by means of fans. Two gas layers on top of each other form in the room under such conditions.

The mass flow transported via the plume increases continuously along the plume path due to the induction of ambient air. At the height of the layer boundary, therefore, the mass flow flows into the upper smoke layer. By raising the mass flow, the low-smoke layer becomes thicker – the layer boundary shifts towards the ceiling. A reduction causes the thickness of this layer to decrease. The height of the assumed low-smoke layer is crucial to the dimensioning of smoke extraction systems since the increase in volume is disproportionate to the path of the thermal plume. The layer boundary is the result of a room height where the smoke volume flow extracted is equivalent to the volume flow transported to the smoke layer.

Disruptions in the smoke layer, such as supply air vents of ventilation systems in the ceiling, must be switched off immediately upon detection of a fire, preferably automatically, and fresh air supply flows should be created automatically through activation of the smoke extraction. To achieve this, supply air vents must be arranged in the low-smoke area and should generate low-impulse supply flows towards the floor or horizontal source air. Where there is natural additional flow into the fire compartment, the wind factor, too, must be taken into account.

Figure 8. Layering of smoke gases (for example, in case of a mechanical smoke extraction system).
3.3 **Pressure differential systems (PDS)**

Ideally, escape routes are kept free of smoke for a sufficient amount of time in the event of a fire. Smoke control by pressurization systems have proved to be a qualified method of displacement. This involves a fan that creates excess pressure for the escape route, thus preventing smoke penetration. The approach is based on vent surfaces in the area affected by the fire and/or in upstream airlocks. Through special air discharge vents, the pressure differential is controlled in such a manner that doors to the escape route can still be opened. Small amounts of smoke that might have spread into the escape route can be discharged. In addition, the temperature in the escape route is also decreased by blowing in fresh air. In the event of fire, users will be alerted quickly and can escape, or be rescued, without any risk. This facilitates the fire-brigade’s fire-extinguishing access.

3.4 **Creation of smoke compartments by isolation or displacement**

In many cases, it is useful to divide fire compartments into smoke compartments. Smoke compartments prevent or contain the spread of smoke in the building. In ideal circumstances, it allows for smoke to be extracted at the source, thus keeping escape routes usable for a sufficient amount of time. Smoke compartments can be created through structural (e.g., smoke curtains) or equipment-specific measures.

A special type of creating a smoke compartment is vortex smoke extraction. This method uses special extraction elements (vortex hoods). They allow for a constant, linear capture of the smoke across the width of the smoke compartment. In addition, they create a high negative pressure near the extraction point.

---

**Figure 9. Displacement of smoke gases (for example, through pressure differential systems).**

**Figure 10. Principle of vortex smoke extraction.**

**Figure 11. An example of ventilation-based isolation of smoke gases (e.g., through vortex hoods).**
Jet fans are often used in underground parking and tunnels that move the smoke in a specific direction depending on the situation. As a rule, additional supply air and mechanical smoke control fans for the extraction are necessary. Jet fans destroy the smoke layering in the direction of the extraction. This is why jet fans should be activated only once the self-rescue of people in the affected area has been completed.

Mobile smoke control fans used by the fire brigade help with fire-fighting efforts by displacing the smoke. But they are only of limited use when it comes to creating smoke compartments. What is more, the formation of low-smoke layers is prevented by the high pulse load of the fans.
4 Smoke control systems

4.1 Natural smoke and heat exhaust ventilation (NSHEV)

![Figure 15. Principle of natural smoke extraction.](image)

The differences in function of natural smoke and heat exhaust ventilation (NSHEV) and smoke and heat exhaust ventilation systems (SHEVS) have already been pointed out. As concerns the flow-mechanical processes, the main components of NSHEV are the natural smoke and heat exhaust ventilation equipment (NSHEV or smoke vents) in the roof or upper wall area of the room – or, ideally, supply air surfaces near the floor. The smoke extraction and/or flow of the room is based on the pressure differentials resulting from varying temperatures between the room and the environment. Dimensioning such systems essentially involves the task of determining the size of the NSHEV and supply air surfaces.

4.2 Smoke and heat exhaust ventilation system (SHEVS)

![Figure 16. Examples of mechanical smoke extraction.](image)

In the case of smoke and heat exhaust ventilation systems, smoke is extracted by means of smoke control fans installed in the room’s ceiling. There may be additionally mounted smoke control ducts between a fan and individual extraction points in the room and motor-driven smoke control dampers for targeted guidance and efficient control of the fire gases. The designing of smoke and heat exhaust ventilation systems is primarily about determining the fan data with respect to the conveyed volume flow, the necessary increase in pressure as well as the temperature class of the smoke control fan and the size of the required supply air surface.
4.3 Pressure differential systems (PDS)

Pressure differential systems (PDS) are installed to prevent the inflow of smoke in safety staircases, their lobbies as well as in fire-brigade lift shafts and their lobby areas.

The typical spread of smoke across lobby doors, which connect the corridor of a floor of origin to a stairwell, is shown in Figure 18. In the upper door area, smoke flows from the corridor into the stairwell, while air from the stairwell is conveyed to the corridor at floor level. This is caused by the temperature difference between the two room areas. The intensity of such exchange flow increases as the temperature differential rises.

**Figure 17.** Principle shows smoke control by pressure differential systems.

**Figure 18.** Spreading of smoke from a floor into the stairwell with open lobby doors, without PDS (schematic outline). ① Stairwell; ② Lobby (airlock); ③ Corridor (Accommodation).
5 Dimensioning methods and how these are applied to systems

5.1 Dimensioning methods

5.1.1 General

The dimensioning of systems for smoke control is generally based on the protection objective to maintain a low-smoke layer, the height of which is relative to the height of the building and/or utilisation. Essentially, three methods are used for dimensioning in this context:
- Zone models,
- CFD models (field models),
- Model experiments.

Especially the first two methods are available to users today as computer programs. Thanks to modern graphical user interfaces, they are easy to use. But this ease of handling comes at the risk that application conditions may be ignored and/or application limits exceeded.

The engineering methods for dimensioning smoke control systems are all derived from the flow-mechanical conservation equations for mass:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_x)}{\partial x} + \frac{\partial (\rho u_y)}{\partial y} + \frac{\partial (\rho u_z)}{\partial z} = 0,
\]

(1)

pulse (only the $x$ component is stated here; the equations for the $y$ and $z$ components are obtained through simple index permutation)

\[
\frac{\partial (\rho u_x)}{\partial t} + \frac{\partial (\rho u_x^2)}{\partial x} + \frac{\partial (\rho u_x u_y)}{\partial y} + \frac{\partial (\rho u_x u_z)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + g_x \rho
\]

(2)

and (thermal) energy

\[
\frac{\partial (\rho c_p T)}{\partial t} + \frac{\partial (\rho c_p T u_x)}{\partial x} + \frac{\partial (\rho c_p T u_y)}{\partial y} + \frac{\partial (\rho c_p T u_z)}{\partial z} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + q_i,
\]

(3)
that are noted here in Cartesian coordinates \((x, y, z)\). Where

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho)</td>
<td>is density in (\text{kg/m}^3)</td>
</tr>
<tr>
<td>(u_x, u_y, u_z)</td>
<td>are the speed components of the flow speed in (\text{m/s})</td>
</tr>
<tr>
<td>(p)</td>
<td>is the pressure in (\text{Pa})</td>
</tr>
</tbody>
</table>
| \(\tau_{xx}, \tau_{yx}, \tau_{zx}\) | is the shear stress on the surfaces of the volume element in \(\text{N/m}^3\) considered in the derivation; according to Newton’s shear stress hypothesis (by way of example):
\[
\tau_{yx} = \eta \left( \frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y} \right)
\]
with dynamic viscosity \(\eta\) in \(\text{Pa} \cdot \text{s}\) |
| \(g_x\) | is the \(x\) component (of the vector) of gravitational acceleration in \(\text{m/s}^2\) |
| \(c_p\) | is thermal capacity in \(\text{J/(kg} \cdot \text{K)}\) |
| \(T\) | is the temperature in \(\text{K}\) |
| \(\lambda\) | is thermal conductivity in \(\text{W/(m} \cdot \text{K)}\) |
| \(\dot{q}_i\) | is the source term to account for an internal heat source and/or sink in \(\text{W/m}^3\) |
| \(t, x, y, z\) | are time and location coordinates. |

The conservation equations are obtained formally by preparing balance summaries on an infinitesimal volume element. To describe an interesting flow, they must be integrated on the basis of the room volume observed. Such integration yields the flow speed \(u\) with the components \(u_x, u_y\) and \(u_z\), as well as the temperature \(T\) and pressure \(p\) at any points in the room at any given time.

The objective pursued by applying the individual methods is to solve the set of equations described, taking into account certain boundary conditions. The choice of such boundary conditions is subject to method-specific limits; compliance with which is crucial to the usefulness of the results obtained by means of the models.

### 5.1.2 Zone models

The integration of the conservation Equations (1), (2) and (3) for designing a smoke control system is highly complex. What is more, having a detailed picture of the flow condition in the room is often of lesser importance. Instead, parameters of a global nature are considered more interesting, such as the mean temperature in the upper (smoke) layer, the height of the layer boundary or the smoke extraction volume flow to be discharged.

![Figure 19. Concept model of the flow conditions during a fire that underlies the application of a zone model.](image)
The zone model represents a method for determining such global parameters. The model of this method is based on the assumption that the air flow in the room during a fire can be described by way of two gas layers that lie on top of each other. Homogeneous temperature conditions are assumed for each of the two layers. One other requirement is that the layers are stationary. The flow-mechanical coupling between the two layers is realized by the plume that forms above the source of the fire. This plume is produced by the (convective) heat release $\dot{Q}_K$ of the fire, with heated air and oxidation products created in the combustion being sent upwards. The plume mass flow $\dot{m}_{AS}$ increases continuously as the plume’s throw length $z$ increases as a result of the induction processes at the plume edge.

As for determining the mass flow $\dot{m}_{AB}$ to be discharged from the smoke layer, the assumption that the two gas layers in the room are stationary considerably facilitates solving the conservation equations. It follows from it that there is no direct exchange of mass between the layers via the separating plane located at height $h_{ER}$. A mass balance for the upper layer, thus, yields, under stationary conditions, the simple relation

$$\dot{m}_{AB} = \dot{m}_{AS}(z = h_{ER}),$$  \hspace{1cm} (4)

i.e., the mass flow to be discharged corresponds to the mass flow conveyed by the plume to the upper layer if the height of the layer boundary is to remain at a constant level. Accordingly, the determination of $\dot{m}_{AB}$ requires a model equation to describe the plume mass flow relative to the plume throw length.

Plumes can be divided into two categories in flow-mechanical terms (Figure 20).

![Figure 20. (Round) turbulent plume.](image)

The plume forms in direct proximity to a heat source. This area is characterised by an unstable flow with locally immense turbulence. The height of the plume-forming area can be estimated as $1,5 \, d_B \ldots 2 \, d_B$ for plumes with a circular cross-section if $d_B$ refers to the diameter of the heat source. There are only empirical calculation equations for the mass flow conveyed by the plume in the plume-forming area.

A customary relation for this is

$$\dot{m}_{AS} = 0,19 \, \pi \, d_B \, z^{3/2}. \hspace{1cm} (5)$$

The similarity area that follows the plume formation is characterised by affine (self-similar) speed and temperature profiles. The geometry of a round plume in this area looks like a cone standing on its tip. The tip, the ‘virtual origin’, is at a vertical distance $z_0$ from the plane of heat release.
For the similarity area of a round (turbulent) plume, one can derive from the conservation equations and a simple turbulence model for the throw length-dependent mass flow the correlation

\[ \dot{m}_{AS} = 0.071 \dot{Q}_K^{1/3} (z - z_0)^{5/3} \]  \hspace{1cm} (6)

where

- \( \dot{m}_{\text{Waste code (AS number)}} \) is the mass flow conveyed in the plume in kg/s
- \( \dot{Q}_K \) is the heat flow convectively conveyed in the plume in kW
- \( z \) is the vertical coordinate in m according to Figure 20
- \( z_0 \) is the distance between the heat release plane and the ‘virtual origin’ in m

The parameter \( \dot{Q}_K \) in Equation (6) considers only the convective heat flow of the heat source that, together with the heat release, forms the total heat release of a fire through pluming. The ratio of pluming and convection depends on the fuels involved in the combustion.

\textbf{Table 1} yields several numerical values for this. For dimensioning calculations, it is customary to estimate the convection heat flow with

\[ \dot{Q}_K = (0.7 \ldots 0.8) \dot{Q}, \]  \hspace{1cm} (7)

where

- \( \dot{Q} \) is the total heat release in kW

The parameter \( z_0 \) necessary to evaluate Equation (6) is essentially dependent on the heat flow released by the fire and on its geometry. At this point, there are no general correlations regarding the relationship of these parameters to each other; Heskestad\(^8\) has done experiments with pool fires and produced the following empirical equation.

\[ z_0 = 0.083 \dot{Q}^{2/5} - 1.02 d_B \]  \hspace{1cm} (8)

where

- \( \dot{Q} \) is the total heat release of the fire in kW
- \( d_B \) is the diameter of the burn area in m

\textbf{Table 1. Distribution of total heat release \( \dot{Q}=1 \) kW in a convective and pluming section.}

<table>
<thead>
<tr>
<th>Fuel</th>
<th>( \dot{Q}_K ) (kW)</th>
<th>( \dot{Q}_S ) (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>0.859</td>
<td>0.141</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.746</td>
<td>0.254</td>
</tr>
<tr>
<td>Propane</td>
<td>0.714</td>
<td>0.286</td>
</tr>
<tr>
<td>Butane</td>
<td>0.695</td>
<td>0.305</td>
</tr>
<tr>
<td>Ethylene</td>
<td>0.658</td>
<td>0.342</td>
</tr>
<tr>
<td>Propylene</td>
<td>0.632</td>
<td>0.368</td>
</tr>
<tr>
<td>1,3 butadiene</td>
<td>0.458</td>
<td>0.542</td>
</tr>
<tr>
<td>Wood</td>
<td>0.629</td>
<td>0.371</td>
</tr>
<tr>
<td>Plexiglas</td>
<td>0.686</td>
<td>0.314</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.407</td>
<td>0.593</td>
</tr>
</tbody>
</table>

It is possible to evaluate the mass flow conveyed by a plume at the height of the intended layer boundary if the vertical coordinate is set to \( z = h_{ER} \) using Equations (5) and (6). Due to Equation (4), this results directly in the mass flow \( \dot{m}_{AB} \) to be discharged from the room.

The volume flow \( \dot{V}_{AB} \) that is generally sought to be discharged when dimensioning SHEV systems then results from

\[ \dot{V}_{AB} = \frac{\dot{m}_{AB}}{\rho_{AB}}, \]  \hspace{1cm} (9)

where

- \( \rho_{AB} \) is the density of the smoke gas discharged from the room.
By using the General Gas Equation under isobaric conditions, the density can be expressed as a function of the temperature $T_{AB}$ of the smoke gas:

$$\rho_{AB} = \frac{\rho_{ref} T_{ref}}{T_{AB}} = \frac{353.18 \, K \, kg/m^3}{T_{AB}}. \quad (10)$$

$T_{AB}$ is also the temperature $T_O$ of the (upper) smoke layer since the model of a zone model is based on the assumption of homogeneous layer temperatures. This temperature can be derived from a heat balance of the smoke layer.

The heat balance contains three essential terms (Figure 21),

• the heat flow $\dot{Q}_K$ conveyed to the smoke layer by the plume,

• the (convective) heat flow $\dot{Q}_{AB}$ discharged from the smoke layer with the mass flow $\dot{m}_{AB}$, as well as

• the heat loss flow $\dot{Q}_V$ that is created by the convective and radiative heat release to components (walls, ceilings, floors, etc.).

With these parameters, the balance equation is as follows:

$$\dot{Q}_{AB} = \dot{Q}_K - \dot{Q}_V. \quad (11)$$

The heat loss flow $\dot{Q}_V$, in particular, is relatively difficult to determine. On the one hand, given the heat storage and conductivity properties of the components, it is highly non-stationary. On the other hand, it also substantially shaped by the predominant radiation conditions in the room observed, which are defined by a large number of factors. These include geometric properties of component surfaces subject to radiation exchange, their degrees of emission and reflection, the degree of transmission of the gas in the smoke layer, which depends on the gas composition and predominant soot concentration, as well as component and gas temperature. An equation system resulting from this is relatively complex and can be solved only through computational methods.

On the basis of manual calculations, the heat loss flow is generally estimated by way of

$$\dot{Q}_V \approx (0.2 \ldots 0.3) \dot{Q}_K \quad (12)$$

Thus Equation (11) yields

$$\dot{Q}_{AB} \approx (0.7 \ldots 0.8) \dot{Q}_K. \quad (13)$$

Figure 21. Regarding the heat balance of the smoke layer.
In addition, the following applies to the heat flow discharged convectively:

\[ \dot{Q}_{AB} = \dot{m}_{AB} c_p (T_{AB} - T_{ZU}), \]  
\( \text{(14)} \)

and the combination of Equations (13) and (14) yields

\[ T_{AB} \approx \frac{(0.7 \ldots 0.8) \dot{Q}_K}{\dot{m}_{AB} c_p} + T_{ZU} \]  
\( \text{(15)} \)

for use in Equation (10).

When using a zone model, one must ensure that the requirements underlying the model are taken into account. Generally, therefore, the following application limits and/or conditions exist:

- The plume must be able to spread freely, i.e., deflection of the plume, such as by false ceilings, must be ruled out,
- The plume must be able to spread in a stationary environment; there must not be any overlaid air flows in the room, such as due to room ventilation systems that work according to the air-mixing principle (pulsed air supply) or high flow speeds in the reflow surfaces (→ switching off supply air systems, low-pulse air supply via reflow surfaces),
- Reflow surfaces must be close to the floor, in the area of the low-smoke (bottom) layer,
- The footprint of the smoke section 1,600 m² to be observed should not be exceeded,
- The aspect ratio of the smoke section to be observed should not exceed 1.5.

### 5.1.3 CFD models

Using CFD codes (field models), it is possible to determine comprehensively complex, three-dimensional flow conditions within the flow area (room) to be observed. They are generally based on the previously mentioned conservation equations for mass, pulse and energy, extended to include models to describe physical effects, such as radiation, turbulence or combustion.

The existing differential equations are transformed to algebraic equations for the purpose of the computational treatment of the set of equations. As part of such discretisation, the balance and/or flow area observed is divided into a finite number of small volume elements, for each of which a set of conservation equations is formulated. (Locally) constant values for all flow-mechanically relevant parameters are assumed, i.e., each cell has a temperature, a flow speed in the \( x \), \( y \) and \( z \) direction as well as pressure, within the individual volume elements and/or cells.

Therefore, these field parameters, which exist continuously in reality, are approximated by way of discrete values within the locations defined by the cell position in the course of computational evaluation. The number of cells used in the computation thus influences the quality of the calculation result – the greater the number of volume elements, the higher the degree of precision. But this also increases the calculation effort.
**Figure 22** shows the calculation result for the distribution of the uplift speed above a small heat source, with the calculation being based on a relatively fine grid. Under identical boundary conditions, the calculation yields the result represented in **Figure 23**, when based on a very rough grid. The discretisation for this calculation is deliberately kept very broad in order to illustrate the effect of the grid size on its result.

Generally, when applying a CFD code, one expects to strike a compromise between computational accuracy and calculation effort. Modern software packages allow for discretisation of the calculation area on unstructured grids.

The elements of such grids typically consist of tetrahedrons and thus allow for local refinement of the structure. An example of such a grid is shown in **Figure 24**.

Grid refinement is necessary in areas where the flow field has large gradients of flow-mechanical parameters, that is, in areas where, for example, the temperature or flow speed is subject to considerable changes. This requires a certain measure of experience with respect to the flow conditions to be expected.

For a CFD simulation, special attention must not only be paid to the design of the computational grid, but also to the choice of models used to describe physical effects. Particularly the modelling of a turbulent manifestation of a flow bears mentioning in this context. A ‘turbulent flow’ is generally a type of flow where the basic movement of the fluid (air, smoke, etc.) is overlaid with lateral components that fluctuate irregularly in terms of time and location.
Figure 25 shows an example of this behaviour regarding flow speed $u$ (dashed line) that could result, for example, from continuous measurements at a fixed location in a genuine flow field.

Figure 25. Chronological sequence of flow speed at a fixed location within a (stationary) flow area.

In this case, the mean speed $\bar{u}$ is overlaid with irregular fluctuation components $u'$ that stem from the turbulent nature of the flow. A detailed resolution (in terms of time and location) of this momentary speed $u$ in the context of a CFD calculation requires an extremely fine grid, which cannot be realised efficiently with today’s computing power. Since primarily the mean parameters in the flow field, such as the mean speed $\bar{u}$, in Figure 25 are of great interest at the same time, the conservation equations are subjected to a method for determining average values. One should note in this context the suggestion made by O. Reynolds to average the conservation equations over time. Such an approach would yield one set of conservation equations, the structure of which resembles very much the Equations (1), (2) and (3). But there would be additional terms in the momentum equations and in the (thermal) energy equation. Thus, the time-averaged $x$ momentum equation would be, for example as presented in Equation (16).

The terms added to Equation (2) in the bracketed expression on the right-hand side of this equation are called correlations. In a turbulent flow, the fluctuation speeds $u'_x$, $u'_y$ and $u'_z$ trigger a momentum exchange that is transverse to the main flow. As such, they appear to increase the friction within the flow, which is why the correlations may also be interpreted as turbulent friction stress.

The averaged form of the conservation equations allows for fluctuation movements to be considered in the calculation of turbulent flows, without having to resolve them in detail in terms of time and location. But there is an added difficulty: new unknowns are added to the original five unknown variables in the flow field ($u_x$, $u_y$, $u_z$, $p$, $T$) contrasted with five equations (equation for mass conservation, momentum conservation equations for the $x$-, $y$- and $z$-components, energy conservation equation). Turbulence models that establish a semi-empirical relation between the fluctuation parameters and mean parameters ($\bar{u}_x$, $\bar{u}_y$, $\bar{u}_z$, $\bar{p}$, $\bar{T}$) in the flow field are employed to determine the unknown correlations.

\[
\frac{\partial (\rho \bar{u}_x)}{\partial t} + \frac{\partial (\rho \bar{u}_x^2)}{\partial x} + \frac{\partial (\rho \bar{u}_x \bar{u}_y)}{\partial y} + \frac{\partial (\rho \bar{u}_x \bar{u}_z)}{\partial z} = \\
- \frac{\partial \bar{p}}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + g_x \rho - \left( \frac{\partial (\rho u'_x^2)}{\partial x} + \frac{\partial (\rho u'_x u'_y)}{\partial y} + \frac{\partial (\rho u'_x u'_z)}{\partial z} \right). \tag{16}
\]
Most of the turbulence models are based on the Boussinesq assumption since the fluctuation movement seems to increase the friction within the flow field. Boussinesq proposed that the turbulent friction stress can be described in the same manner as viscous friction in the movement equations, i.e., adapted from the shear stress ($\tau_{xx}$, $\tau_{yx}$, $\tau_{zx}$, etc.; cf. Equation (2)). Based on this proposal, one obtains Equation (17) from Equation (16), where $\eta_t$ represents turbulent viscosity, which must be described as part of the turbulence modelling.

There are generally several turbulence models to choose from in today’s CFD codes. For the most part, there are models with a single or two equations and large eddy simulations (LES). The first two models use one or two differential equations to determine turbulent viscosity $\eta_t$ in Equation (17). In large eddy simulations, the turbulence structure, which may be interpreted as a spectrum of turbulence of varying size, is divided into two parts using a filter function. The filter width in this case is frequently a generalised mesh size of the calculation grid. Any turbulence that exceeds the mesh width is resolved directly within the calculation grid and does not require a turbulence model. Any turbulence smaller than the mesh width is modelled using a ‘fine structure approach’. A commonly used fine structure approach is the Smagorinsky model, which represents a relatively simple description of the influence of small-scale turbulence on the flow field. Large eddy simulations, therefore, yield realistic results only if a sufficient portion of the turbulence spectrum is reflected directly in the calculation. In contrast to turbulence modelling on the basis of one or two equations, this requires relatively fine grids and thus computing times that are ten to a hundred times higher.

The conditions described make it clear that a high-quality grid is key in applying CFD codes when dimensioning smoke extraction systems. This also requires, in particular, that areas where higher gradients of the flow parameters are to be expected must be resolved adequately, apart from the fact that the room or building in question must be recreated precisely. Furthermore, the grid also depends on the model used to describe the turbulence in the flow field. A two-equation model represents a minimum requirement in this context.

\[
\frac{\partial (\rho \bar{u}_x)}{\partial t} + \frac{\partial (\rho \bar{u}_x^2)}{\partial x} + \frac{\partial (\rho \bar{u}_x \bar{u}_y)}{\partial y} + \frac{\partial (\rho \bar{u}_x \bar{u}_z)}{\partial z} =
\]

\[
- \frac{\partial \bar{p}}{\partial x} + \frac{\partial \bar{\tau}_{xx}}{\partial x} + \frac{\partial \bar{\tau}_{yx}}{\partial y} + \frac{\partial \bar{\tau}_{zx}}{\partial z} + g_x \rho + \frac{\partial}{\partial x} \left( \eta_t \left( \frac{\partial \bar{u}_x}{\partial x} + \frac{\partial \bar{u}_x}{\partial z} \right) \right) \]

\[
+ \frac{\partial}{\partial y} \left( \eta_t \left( \frac{\partial \bar{u}_y}{\partial x} + \frac{\partial \bar{u}_y}{\partial y} \right) \right) + \frac{\partial}{\partial z} \left( \eta_t \left( \frac{\partial \bar{u}_z}{\partial x} + \frac{\partial \bar{u}_z}{\partial z} \right) \right). \tag{17}
\]
5. Dimensioning methods and how these are applied to systems

5.1.4 Model experiments

Model experiments to determine indoor air flows have been used in ventilation technology since the 1970s. The conservation equations for mass, momentum and energy are solved ‘experimentally’. For this purpose, the flow conditions in a (mostly) miniaturised model of a room or building are recreated. An example of an experimental model is shown in Figure 26.

![Figure 26. Experimental model (1:10 scale) for dimensioning a smoke extraction system.](image)

The nondimensionalised form of the time-averaged conservation equations forms the basis for identifying the conditions necessary to transfer the results obtained from the model experiments to the corresponding original structures. In the process, all physical parameters in the equations are standardised by means of reference parameters, such as

\[
x^* = \frac{x}{L_B}, \quad y^* = \frac{y}{L_B}, \quad z^* = \frac{z}{L_B},
\]

\[
\bar{u}_x^* = \frac{\bar{u}_x}{U_B}, \quad \bar{u}_y^* = \frac{\bar{u}_y}{U_B}, \quad \bar{u}_z^* = \frac{\bar{u}_z}{U_B},
\]

\[
\bar{T}^* = \frac{\bar{T}}{T_B}, \quad g^* = \frac{g}{g_B}, \quad \cdots
\]

The individual reference parameters are labelled here with the index \(B\) (\(L_B\): reference length, \(U_B\): reference speed, etc.). Initially, they can be chosen freely. For example, the height of the room can be used for the reference length. In this case, the dimensionless coordinate \(x^*\) would specify any dimensioned coordinate \(x\) as a multiple of the room height. Conversely, the dimensionless coordinate and the (known) reference length can be used in combination with \(x = x^* \cdot L_B\) to calculate the dimensioned coordinate.

By way of example (Equation (19)), the introduction of the non-dimensionalised parameters yields for the \(x\) momentum Equation (17).

\[
\frac{L_B}{U_B t_B} \frac{\partial \bar{u}_x^*}{\partial t^*} + \frac{\partial \bar{u}_x^*}{\partial x^*} + \frac{\partial (\bar{u}_x^* \bar{u}_y^*)}{\partial y^*} + \frac{\partial (\bar{u}_x^* \bar{u}_z^*)}{\partial z^*} = - \frac{\Delta p^*}{U_B^2 \rho^*} \frac{\partial \bar{p}^*}{\partial x^*} + \frac{g_B L_B \Delta T_B}{T_B U_B^2} \frac{\partial \bar{T}^*}{T_\infty} + \frac{\partial}{\partial x^*} \left( \frac{\nu_B}{U_B L_B} \nu^* + \nu_t^* \right) \left( \frac{\partial \bar{u}_x^*}{\partial x^*} + \frac{\partial \bar{u}_y^*}{\partial y^*} \right) + \frac{\partial}{\partial y^*} \left( \frac{\nu_B}{U_B L_B} \nu^* + \nu_t^* \right) \left( \frac{\partial \bar{u}_y^*}{\partial x^*} + \frac{\partial \bar{u}_z^*}{\partial z^*} \right) + \frac{\partial}{\partial z^*} \left( \frac{\nu_B}{U_B L_B} \nu^* + \nu_t^* \right) \left( \frac{\partial \bar{u}_z^*}{\partial x^*} + \frac{\partial \bar{u}_x^*}{\partial z^*} \right).
\]
In the derivation of this equation, the so-called Boussinesq approximation is used, which postulates that material properties \((\rho, c_p, \lambda, \eta)\) are constant in the flow field. The temperature dependence of density is accounted for only in the uplift term (second term on the right-hand side of Equation (19)).

Without going into further details on the derivation of Equation (19), one observes that it is identical to Equation (17) in mathematical terms. This also means that solving either equation will produce an identical result. Such an identical solution in two geometrically similar flow areas (original and model) is also given when the reference parameters used in the non-dimensionalisation of the momentum equation differ, provided that the factors derived from them before the individual terms of this equation have the same values for both flow areas. These factors may be identified as dimensionless quantities (20, 21, 22 and 23).

Indoor air flows and particularly the flow conditions in the event of a fire are highly turbulent flows, i.e., very high Re numbers are involved. From this it follows that the influence of the term in Equation (24) that contains such quantity can be ignored for its solution, because \(\frac{1}{Re} \nu^* \to 0\) follows directly for \(Re \to \infty\). Thus, the Re number is of subordinate importance where experimental analyses of indoor air flows are concerned. Crucially important to the study of how smoke spreads, however, is the Ar number that describes the influence of uplift in a flow.

\[
\begin{align*}
\text{Strouhal number: } & \quad Sr = \frac{L_B}{U_B t_B} 
\text{(20)} \\
\text{Euler number: } & \quad Eu = \frac{\Delta p_B}{U_B^2 \rho_B} 
\text{(21)} \\
\text{Archimedes number: } & \quad Ar = \frac{g_B L_B \Delta T_B}{T_B U_B^2} 
\text{(22)} \\
\text{Reynolds number: } & \quad Re = \frac{U_B L_B}{\nu_B} 
\text{(23)}
\end{align*}
\]

With expressions (20, 21, 22 and 23), Equation (19) becomes Equation (24):

\[
Sr \frac{\partial \bar{u}_x^*}{\partial t^*} + \frac{\partial \bar{u}_x^2}{\partial x^*} + \frac{\partial \left( \bar{u}_x^* \bar{u}_y^* \right)}{\partial y^*} + \frac{\partial \left( \bar{u}_x^* \bar{u}_z^* \right)}{\partial z^*} =
- Eu \frac{1}{\rho^*} \frac{\partial \Delta \bar{p}^*}{\partial x^*} + Ar \frac{\Delta \bar{T}^*}{T_{\infty}} \\
+ \frac{\partial}{\partial x^*} \left( \left( \frac{1}{Re} \nu^* + \nu_t^* \right) \left( \frac{\partial \bar{u}_x^*}{\partial x^*} + \frac{\partial \bar{u}_x^*}{\partial y^*} \right) \right) \\
+ \frac{\partial}{\partial y^*} \left( \left( \frac{1}{Re} \nu^* + \nu_t^* \right) \left( \frac{\partial \bar{u}_y^*}{\partial x^*} + \frac{\partial \bar{u}_x^*}{\partial y^*} \right) \right) \\
+ \frac{\partial}{\partial z^*} \left( \left( \frac{1}{Re} \nu^* + \nu_t^* \right) \left( \frac{\partial \bar{u}_z^*}{\partial x^*} + \frac{\partial \bar{u}_x^*}{\partial z^*} \right) \right). \tag{24}
\]
What follows, therefore, from the aforementioned requirement that the factors and/or dimensionless quantities before the individual terms of the momentum equation must be identical for two geometrically similar flow areas, so that the solutions of the equation are identical for the original and the model, is:

\[ Ar_O = Ar_C \] (25)

Here, the ‘O’ index refers to the original, and the ‘C’ index to the model. Initially, the introduction of the expression (22) into this relation produces

\[ \frac{g_{B,O} L_{B,O} \Delta T_{B,O}}{T_{B,O} U_{B,O}^2} = \frac{g_{B,M} L_{B,M} \Delta T_{B,M}}{T_{B,M} U_{B,M}^2} \] (26)

and, when slightly transformed,

\[ \frac{g_{B,M} L_{B,M} \Delta T_{B,M}}{g_{B,O} L_{B,O} \Delta T_{B,O}} \left( \frac{T_{B,M} U_{B,M}^2}{T_{B,O} U_{B,O}^2} \right) = 1. \] (27)

The quotients on the left-hand side of the equation represent scale factors of the individual physical parameters, that is

- **Gravitational acceleration scale:**
  \[ f_g = \frac{g_{B,M}}{g_{B,O}} \] (28)

- **Longitudinal scale:**
  \[ f_l = \frac{L_{B,M}}{L_{B,O}} \] (29)

- **Temperature differential scale:**
  \[ f_{\Delta T} = \frac{\Delta T_{B,M}}{\Delta T_{B,O}} \] (30)

- **Reference temperature scale:**
  \[ f_T = \frac{T_{B,M}}{T_{B,O}} \] (31)

- **Velocity scale:**
  \[ f_u = \frac{U_{B,M}}{U_{B,O}} \] (32)

Equation (27) can be described as a pure relation of scales:

\[ \frac{f_g f_l f_{\Delta T}}{f_T f_u^2} = 1. \] (33)

For the scale factor of gravitational acceleration, \( f_g = 1 \) applies initially for natural reasons, because gravitational acceleration has the same value in the original and in the model. Generally, \( f_T = 1 \) also applies if, for example, the supply air temperature is used as a reference temperature for the original and the model, and if this temperature is the same in both instances. With such values, Equation (33) can be simplified to

\[ \frac{f_l f_{\Delta T}}{f_u^2} = 1, \] (34)

or

\[ f_u = \sqrt{f_l f_{\Delta T}} \] (35)

The longitudinal scale \( f_l \) is derived from the space conditions of the available experimental field and the associated, necessary miniaturisation of the original. As experience has shown, the value should not be substantially less than 1:20.

The remaining temperature differential scale is not subject to any further requirement, which means that it can generally be chosen freely. Usually the selection is such that there are no temperatures in the experimental model that would lead to the destruction of the model. This scale is ALSO often derived from the heat flow scale \( f_\dot{Q} = \dot{Q}_C/\dot{Q}_O \), because there is usually a boundary condition for the heat release of the source of a fire where dimensioning tasks for smoke extraction systems are concerned.
On principle, the following context applies to the (convective) heat flow

$$\dot{Q}_K = \dot{m} \ c_p \ \Delta T = \rho \ u \ A \ c_p \ \Delta T$$  \hspace{1cm} (36)$$

and thus, to the heat flow scale

$$f_\dot{Q}^C = \frac{\dot{Q}_{K,C}}{\dot{Q}_{K,O}} = \frac{\rho_C u_C A_C c_{p,C} \Delta T_C}{\rho_O u_O A_O c_{p,O} \Delta T_O} = f_u f_l^2 f_{\Delta T}.$$  \hspace{1cm} (37)$$

The material values, density $\rho$ and thermal capacity $c_p$, are each obtained from the reference temperature $T_B$, so that $f_T = 1$ applies, as do $f_\rho = 1$ and $f_{cp} = 1$. As for the surface area scale, $f_A = A_C/A_O = f_l^2$ applies because a surface is formed by the product of two lengths.

From Equation (37) follows

$$f_{\Delta T} = \frac{f_\dot{Q}}{f_u f_l^2}$$  \hspace{1cm} (38)$$

and when placed in Equation (35), following a slight transformation,

$$f_u = \left( \frac{f_\dot{Q}}{f_l} \right)^{1/3}.$$  \hspace{1cm} (39)$$

If one knows the longitudinal and heat flow scales, one can determine the velocity scale. The origin of the longitudinal scale has already been discussed previously. Regarding the heat flow scale, the heat release of the (original) fire is generally specified as a boundary condition for the dimensioning of smoke extraction systems. The maximum, technically feasible heat release in the model is limited by the heat source used in the model and is therefore known.

First, the values of the original are transferred to the model by means of the individual physical scales serving as a boundary condition as part of the model experiments. Once the experiments have resulted in a solution concept that meets the protection requirements for smoke extraction, the data thus obtained, such as required smoke extraction volume flow, will be transferred to the original, again using the corresponding scales.
In summary, the following applies to the conditions that are relevant to the execution of model experiments to determine the spread of smoke in the event of a fire:

- Maintenance of geometric similarity in all details concerning the flow,
- Model scales $\geq 1:20$, up to $1:30$ in exceptional circumstances,
- Maintenance of the $Ar$ criterion.

5.2 Dimensioning of systems

5.2.1 Dimensioning of natural smoke ventilation systems

The dimensioning of natural smoke ventilation systems can be implemented by way of a simplified zone model without the need for complex computational methods. Models are created in the manner depicted in Figure 28. The quantities sought are the discharge surface $A_{AB}$ and the reflow surface $AZU$.

For reasons of continuity, the following applies to the mass flow of the balance area ‘room’:

$$\dot{m}_{ZU} = \dot{m}_{AS}(h_{ER}) = \dot{m}_{AB}. \quad (43)$$

where

- $\dot{m}_{ZU}$ is the mass flow in kg/s that enters the room via the reflow surface
- $\dot{m}_{AS}(h_{ER})$ is the mass flow in kg/s conveyed by the plume at the height $h_{ER}$ of the (intended) boundary layer
- $\dot{m}_{AB}$ is the mass flow in kg/s discharged from the room.

From the momentum balance for the room, neglecting any wind-induced flow, follows:

$$\Delta p_A = \Delta p_{ZU} + \Delta p_{Room} + \Delta p_{AB}. \quad (44)$$

where

- $\Delta p_A$ is the pressure increase in Pa as a result of the thermal uplift of the smoke layer
- $\Delta p_{ZU}$ is the pressure loss in Pa caused by the flow passing through the reflow surface
- $\Delta p_{Room}$ is the pressure loss in Pa caused by the flow passing through the room
- $\Delta p_{AB}$ is the pressure loss in Pa caused by the flow passing through the smoke vent.

Figure 28. Regarding the creation of models in the dimensioning of natural smoke ventilation systems.
To simplify the dimensioning, homogeneous temperatures are assumed for the bottom and upper layers. It is further assumed that the temperature of the low-smoke layer corresponds to the ambient temperature. One can then write for the uplift pressure:

\[ \Delta p_A = (\rho_{ZU} - \rho_{AB}) g h_{RS} \]  

(45)

where

- \( \rho_{ZU} \) is the density of the reflow air and/or air in the low-smoke layer in kg/m\(^3\)
- \( \rho_{AB} \) is the density of the smoke gas in kg/m\(^3\) that is discharged via the room’s ceiling
- \( g \) is the gravitational acceleration in m/s\(^2\)
- \( h_{RS} \) is the thickness of the upper layer in m.

The pressure losses created during the air flow passing through the supply and discharge surfaces are subject to

\[ \Delta p_{ZU} = \frac{1}{c_{v,ZU}^2} \frac{\rho_{ZU}}{2} u_{ZU}^2 \]  

(46)

or

\[ \Delta p_{AB} = \frac{1}{c_{v,AB}^2} \frac{\rho_{AB}}{2} u_{AB}^2 \]  

(47)

where

- \( c_{v,ZU} \) is the flow rate coefficient of the reflow surface
- \( c_{v,AB} \) is the flow rate coefficient of the discharge surface
- \( u_{ZU} \) is the speed at which air flow passes through the reflow surface, in m/s
- \( u_{AB} \) is the speed at which the air flow passes through the discharge surface, in m/s.

\[ \Delta p_{Room} \approx 0 \] also applies to the pressure loss created when the air flow passes through the room as a result of the assumption that the two gas layers in the room are stationary (cf. Section 5.1.2).

Inserting Equations (45), (46) and (47) in the pressure balance (44) yields

\[ (\rho_{ZU} - \rho_{AB}) g h_{RS} = \frac{1}{c_{v,ZU}^2} \frac{\rho_{ZU}}{2} u_{ZU}^2 + \frac{1}{c_{v,AB}^2} \frac{\rho_{AB}}{2} u_{AB}^2. \]  

(48)

In analogy to Equation (10), using the General Gas Equation, one can also write for the density \( \rho_{AB} \) of the discharging smoke gas

\[ \rho_{AB} = \frac{\rho_{ZU} T_{ZU}}{T_{AB}} \]  

(49)

The insertion of this expression in the pressure balance (44) yields the following, after a brief calculation,

\[ 2 \Delta T g h_{RS} = \frac{1}{c_{v,ZU}^2} u_{ZU}^2 T_{AB} + \frac{1}{c_{v,AB}^2} u_{AB}^2 T_{ZU}, \]  

(50)

with the abbreviation \( \Delta T = T_{AB} - T_{ZU} \) having been used. If the continuity equation is now used to substitute the speed in the discharge surface,

\[ u_{AB} = \frac{\dot{V}_{AB}}{A_{AB}}, \]  

(51)

Equation (50) yields

\[ 2 \Delta T g h_{RS} = \frac{1}{c_{v,ZU}^2} u_{ZU}^2 T_{AB} + \frac{\dot{V}_{AB}^2}{c_{v,AB}^2 A_{AB}^2} T_{ZU}. \]  

(52)
5. Dimensioning methods and how these are applied to systems

Solving this equation for $A_{AB}$ and/or the aerodynamically effective surface $A_{AB,ae} = A_{AB} c_v,AB$ finally yields

$$A_{AB,ae} = \frac{T_{ZU}}{\sqrt{2 \Delta T g h_{RS} - \frac{1}{c_v, ZU^2} u_{ZU}^2 T_{AB}}}$$  \quad (53)

Equation (53) is a conditional equation for the required surface $A_{AB,ae}$ of the natural smoke and heat ventilation equipment. For its evaluation, in general, the (smoke) volume flow $\dot{V}_{AB}$ and its temperature $T_{AB}$ must be determined. Known parameters, or parameters to be specified, however, are the temperature $T_{ZU}$ of the reflow air, the thickness $h_{RS}$ of the smoke layer, the flow rate coefficient $c_v, ZU$ of the reflow vent and the (allowable) flow speed $u_{ZU}$ of this vent. As a rule, a value of $T_{ZU} = 293$ K is assumed for the supply air temperature. The thickness of the smoke layer is derived from the difference between the room height and the thickness of the low-smoke layer,

$$h_{RS} = H - h_{ER}.$$  \quad (54)

The flow rate coefficient depends on the geometry of the reflow vent. Reference values for this parameter can be found in Table 2.

The flow speed $u_{ZU}$ must be limited to values that do not produce a room-filling flow. Particularly the plume above the source of the fire must not be impaired permanently by the incoming supply air. As experience has shown, a value of $u_{ZU} = 1$ m/s² should not be exceeded.

**Flow rate coefficients of various components**

**Table 2. Flow rate coefficients of various components.**

<table>
<thead>
<tr>
<th>Designation</th>
<th>Outline</th>
<th>Opening angle $\alpha$ in degrees</th>
<th>$\frac{h}{l} = 1:1$</th>
<th>$\frac{h}{l} = 1:2$</th>
<th>$\frac{h}{l} = 1:3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top hung window</td>
<td></td>
<td>15</td>
<td>0.25</td>
<td>0.22</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>0.42</td>
<td>0.38</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td>0.52</td>
<td>0.50</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.57</td>
<td>0.56</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
<td>0.62</td>
<td>0.62</td>
<td>0.62</td>
</tr>
<tr>
<td>Top hung window</td>
<td></td>
<td>15</td>
<td>0.30</td>
<td>0.24</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>0.45</td>
<td>0.38</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td>0.56</td>
<td>0.50</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.63</td>
<td>0.57</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
<td>0.67</td>
<td>0.63</td>
<td>0.63</td>
</tr>
<tr>
<td>Casement window</td>
<td></td>
<td>15</td>
<td>0.15</td>
<td>–</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>0.30</td>
<td>–</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td>0.44</td>
<td>–</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.56</td>
<td>–</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
<td>0.64</td>
<td>–</td>
<td>0.61</td>
</tr>
<tr>
<td>Horizontal and</td>
<td></td>
<td>15</td>
<td>0.15</td>
<td>0.13</td>
<td>–</td>
</tr>
<tr>
<td>vertical blinds</td>
<td></td>
<td>30</td>
<td>0.30</td>
<td>0.27</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td>0.44</td>
<td>0.39</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>0.56</td>
<td>0.56</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
<td>0.64</td>
<td>0.61</td>
<td>–</td>
</tr>
</tbody>
</table>
The determination of the volume flow $\dot{V}_{AB}$ to be discharged via the discharge surfaces is based on the mass balance for the smoke layer described in Section 5.1.2. In summary, the following applies:

$$\dot{V}_{AB} = \dot{m}_{AS} \frac{T_{AB}}{\rho_{ZU} T_{ZU}}. \quad (55)$$

The determination of the plume mass flow $\dot{m}_{AS}$, which is conveyed at the height $h_{ER}$ of the smoke layer, is derived from

$$\dot{m}_{AS} = 0.19 \pi d_B h_{ER}^{3/2} \quad \text{for } h_{ER} \leq \sqrt{\pi} d_B \quad (56)$$

or

$$\dot{m}_{AS} = 0.071 \dot{Q}_K^{1/3} (h_{ER} - z_0)^{5/3} \quad \text{for } h_{ER} > \sqrt{\pi} d_B \quad (57)$$

This result, together with Equation (57), in the distance between the heat release plane of the fire and the ‘virtual origin’ from Equation (8), that is,

$$z_0 = 0.083 \dot{Q}_K^{2/5} - 1.02 d_B. \quad (58)$$

The heat release rates $\dot{Q}$ in Equation (58) and their convective portion $\dot{Q}_K = (0.7 \ldots 0.8) \dot{Q}$ (cf. Equation (8)) in Relation (57) are essentially dependent on the use of the room for which the smoke ventilation system is to be dimensioned.

Some reference values can be found in Table 3.

### Examples of maximum heat release rates

<table>
<thead>
<tr>
<th>Object, use</th>
<th>Maximum heat release (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC workstation, solid furniture (chipboard), in a room</td>
<td>2,500</td>
</tr>
<tr>
<td>PC workstation in an open-plan office, solid furniture (chipboard), partitioned with flammable screens</td>
<td>6,800</td>
</tr>
<tr>
<td>Passenger car in a public car park</td>
<td>2,200…5,500</td>
</tr>
<tr>
<td>Photocopiars</td>
<td>600…800</td>
</tr>
<tr>
<td>PC monitor</td>
<td>45</td>
</tr>
<tr>
<td>Wastepaper basket</td>
<td>30…45</td>
</tr>
<tr>
<td>Travel bag</td>
<td>55…100</td>
</tr>
</tbody>
</table>

Generally, the specific heat release rates vary for fires in the range $300 \text{ kW/m}^2 < \dot{q} < 500 \text{ kW/m}^2$. Thus, it follows for the area of the source of the fire

$$A_B = \frac{\dot{Q}}{\dot{q}}, \quad (59)$$

from which its diameter $d_B$ for use in plume equations can be determined.

The temperature $T_{AB}$ of the discharging smoke gas is determined on the basis of the heat balance equation (11). The heat loss flow necessary for this can be estimated from

$$\dot{Q}_V \approx \delta \dot{Q}_K. \quad (60)$$
The loss factor $\delta$ can be derived from Figure 29 relative to the footprint of the room in question.

![Figure 29](image)

**Figure 29.** Factor $\delta$ to estimate heat loss from smoke layer relative to the room size.

It should be noted that this factor is merely a rough approximation of the actual factors involved in the heat exchange processes in the smoke layer, because it reduces the complex conditions to the functional context $\delta = f(A_{\text{Room}})$. With the loss factor, the heat flow discharged from the room with the smoke (cf. Equation (13)) is subject to

$$\dot{Q}_{AB} = (1 - \delta) \dot{Q}_K,$$

(61)

and for the temperature $T_{AB}$, in analogy to Equation (15)

$$T_{AB} \approx \frac{(1 - \delta) \dot{Q}_K}{\dot{m}_{AB} c_p} + T_{ZU},$$

(62)

In the evaluation of this equation, the result derived from Equations (56) or (57) must be applied to the mass flow to be discharged for reasons of the mass balance ($\dot{m}_{AB} = \dot{m}_{AS}$).

The required aerodynamic discharge surface $A_{AB,ae}$ can be determined from Equation (53) on the basis of the available data. The size of the smoke ventilation equipment to be installed then results from

$$A_{AB} = \frac{A_{AB,ae}}{c_{v,AB}},$$

(63)

where the flow rate coefficient $c_{v,AB}$ represents an equipment-dependent variable that is determined according to EN 12101-2.

As part of the dimensioning, one must determine the size of the reflow surface, which is derived from

$$A_{ZU} = \frac{\dot{m}_{ZU}}{u_{ZU} \rho_{ZU}}.$$

(64)

### 5.2.2 Dimensioning of mechanical smoke control systems

The dimensioning of mechanical smoke control systems for simple spatial geometries is essentially the same procedure as for the designing of natural smoke control systems. The smoke gas volume flow to be discharged is determined according to equation (55) by means of the dependencies for the plume mass flow $\dot{m}_{AS}$ described in connection with this equation (56) or (57) and for the temperature $T_{AB}$ (Equation (62)).

Once the smoke gas volume flow to be discharged has been determined, the number of required extraction points in the room’s ceiling must be determined.
As for a volume flow to be discharged through a single extraction point, there is a limitation, because excessive extraction at a single location creates a funnel-shaped inflow that sucks in the air from the low-smoke layer (plug-holing, cf. Figure 30).

\[ \dot{V}_{AB,i,max} = 4.16 \gamma \Delta h_{RS}^{5/2} \sqrt{\frac{T_{RS} - T_\infty}{T_\infty}}, \quad (65) \]

where

- \( \dot{V}_{AB,i,max} \) is the maximum volume flow in m³/s that can be discharged through one extraction point.
- \( \gamma \) is the dimensionless factor for the position of the extraction vent, \( \gamma = \begin{cases} 1 & \text{for } \Delta r \geq D_{AB} \\ 0.5 & \text{for } \Delta r < D_{AB}, \end{cases} \)
- \( D_{AB} \) is the diameter of the extraction vent in m.
- \( \Delta r \) is the distance between the axis of the extraction vent and the nearest wall in m.
- \( \Delta h_{RS} \) is the distance between the lowest point of the extraction vent and the layer boundary in m.
- \( T_{RS} \) is the temperature in the upper (smoke) layer in K.
- \( T_\infty \) is the temperature in the bottom (low-smoke) layer in K.

Application of Equation (65) requires the condition

\[ \frac{\Delta h_{RS}}{D_{AB}} > 2 \quad (66) \]

In this context, the following applies to the maximum volume flow that can be discharged through a single extraction point (also see Figure 31).
If the extraction volume flow determined from Equation (55) exceeds the value calculated through Equation (66), then

\[ n = \left\lceil \frac{\dot{V}_{AB}}{\dot{V}_{AB,i,max}} \right\rceil \]  

(67)

must be applied to determine the number of required extraction points. Where it follows that more than one extraction point will be necessary, the distance of two extraction points must meet the condition

\[ S_{min} \geq 0.9 \sqrt[3]{\dot{V}_{AB,i}} \]  

(68)

where

- \( S_{min} \) is the minimum distance between two extraction points according to Figure 31 in m
- \( \dot{V}_{AB,i} \) is the volume flow to be discharged at the \( i \)th extraction point (\( i = 1 \ldots n \)) in m³/s

Knowing the smoke extraction volume flow may help to dimension a duct system to be installed, thus allowing for smoke extraction fan(s) to be selected. The temperature to be considered in determining the temperature category of the fan is derived when adapted from Equation (62)

\[ T_{AB} \approx \frac{\dot{Q}_{K}}{m_{AB} c_{p}} + T_{ZU}, \]  

(69)

with the heat loss flow \( \dot{Q}_{V} \) (cf. Equation (60)) being neglected, because the fire event may be directly below the extraction point.

Finally, the vent surface in the outer walls of the room necessary for the required re-flow air is determined from

\[ A_{ZU} = \frac{\dot{V}_{AB}}{u_{ZU}}. \]  

(70)

When evaluating this equation, the supply air speed must be specified, which should not exceed a value of \( u_{ZU} = 1 \) m/s (cf. Section 5.2.1).

### 5.2.3 Dimensioning of pressure differential systems

Pressurisation systems are intended to limit the spread of smoke by means of pressure differentials, i.e., maintaining a positive pressure within the protected spaces. In order to achieve this goal and enable safe evacuation as well as to support firefighting, all components of the system shall be properly selected and sized. Moreover, interaction of key components shall be evaluated at the design stage. It shall also be mentioned that most of the design calculations are performed for the steady state and isothermal conditions. Therefore, it is recommended to perform more advanced calculations, e.g., use computational fluid dynamics (CFD) tools or zone modelling in order to assess effectiveness of the pressure differential system (PDS) for non-isothermal, dynamic conditions.
In order to follow actual changes resulting from the revision of \[11\], it is recommended to refer to the pressure differential kits (PDK) assumed to be a defined combination of components capable of producing and controlling overpressure within the protected space.

For more information concerning the influence of the ambient conditions on the operation of the pressure differential system, please refer to the proper chapters of this Guidebook.
5. Dimensioning methods and how these are applied to systems

Design assumptions of the pressure differential system (PDS) shall take into consideration requirements of the fire scenario, i.e., list of the pressurised spaces, evacuation scenario etc.

Class of the pressurisation system shall refer to the requirements of the standard \([11]\) and national regulations. Actual version of the \([11]\) standard defines six different classes A–F, however, it is considered to reduce this number to the two classes, i.e., A – evacuation and B – evacuation and firefighting.

Among others, the most important design parameters are common for any pressure differential system. The most important design parameters are listed below:

- \(Dp_{\text{NOM}}\), the pressure difference across a closed door between the pressurised space and the accommodation area, Pa

This value is in fact pressure differential across the door between the pressurised and accommodation. Recommended value of the overpressure may vary depending on the type of the protected space, however, in most cases is selected from the range of 30–60 Pa. Recommended tolerance of the minimum value of the overpressure is +/-10%. Maximum value of the overpressure results mostly from the maximum door opening force corresponding to the pressure differential and door size.

- \(v_{\text{MIN}}\), the airflow through the doorway between the pressurised space and the accommodation on the fire floor, m/s

Depending on the pressure differential system class, minimum airflow shall be in the range from 0.75 m/s up to 2.0 m/s in accordance with \([11]\) and in the range from 1.0 m/s up to 2.0 m/s in accordance with \([12]\).

---

**Figure 32.** Fire storey plan – pressure criterion (all doors closed).

**Figure 33.** Fire floor plan – airflow criterion (escape or firefighting). ① Pressurised stairs; ② Pressurised firefighting lobby; ③ Pressurised firefighting lift shaft; ④ Corridor (unpressurised horizontal escape route); ⑤ Air release vent (to provide air release path); ⑥ Fire compartment (accommodation)

- \(F_{\text{MAX}}\), maximum allowable door opening force, N
The system shall be designed so that the force on the door handle shall not exceed 100 N.

The maximum pressure differential $P_{\text{MAX}}$ across a door opening into a pressurised space should be determined as a function of the door configuration using the following equation:

$$ P_{\text{MAX}} = \frac{2 \cdot (100 - F_{dc}) \cdot (W_d - d)}{D_A \cdot W_d}, \text{Pa} $$ (71)

where

- $F_{dc}$ is the force needed to be applied at the door handle to overcome the inherent resistance of the door to opening without a pressure differential applied to the door, N
- $W_d$ is the door width, m
- $d$ is the distance from the door handle centre to the nearest vertical edge of the door, m
- $D_A$ is the door area, m$^2$

For the most common door size with the area of approx. 2.0 m$^2$ and typical door closer maximum pressure differential across a door opening into the pressurised is approx. 70 Pa.

In order to enable proper operation of the pressure differential system, it is indispensable to guarantee fast and stable pressure differential regulation. Each pressure differential system operates in two modes, i.e., pressure criterion and airflow criterion. Supply rates for both criterion may vary significantly. Depending on the applied components pressure differential, regulation can be done by means of mechanical barometric damper and constant capacity supply fan (the simplest pressure differential kit) or motorised damper and variable capacity supply fan etc.

In some cases, to provide directed airflow through the protected space, an additional air release vent with a fixed free area $A_{AD}$ shall be provided. Such a component shall be located in the upper part of the protected space, e.g., stairwell or lift shaft, to enable ventilation of the protected space. The free area of the air release vent shall be calculated taking into consideration total cubature of the protected space to achieve the required air exchange rate.

Total effective flow area $A_{\text{TOT}}$ of the air leakages of a given protected space, e.g., stairs, firefighting lobby, lift shaft, can be calculated using the following equation:

$$ A_{\text{TOT}} = A_{DO} + A_{WA} + A_{CE} + A_{PV} + A_{AD} + A_{OT}, \text{m}^2 $$ (72)

where

- $A_{DO}$ is the total effective leakage area of all doors, m$^2$
- $A_{WA}$ is the total effective leakage area through the walls, m$^2$
- $A_{CE}$ is the total effective leakage area through the ceiling, m$^2$
- $A_{PV}$ is the total effective area of the pressure operated air relief damper, m$^2$
- $A_{AD}$ is the total effective area of the fixed air relief vent (opening), m$^2$
- $A_{OT}$ is the total effective area of other leakages (if any), m$^2$

Effective area of the parallel or series leakage paths can be calculated using the following equations:

- $A_{eP}$, the effective leakage area of the $N$ parallel paths
5. Dimensioning methods and how these are applied to systems

\[ A_{ep} = A_1 + A_2 + A_3 + \cdots + A_N, \text{m}^2 \] (73)

- \( A_{es} \), the effective leakage area of the \( N \) series paths

\[ A_{es} = \left( \frac{1}{A_1^2} + \frac{1}{A_2^2} + \frac{1}{A_3^2} + \cdots + \frac{1}{A_N^2} \right)^{\frac{1}{2}}, \text{m}^2 \] (74)

For many pressure differential systems, only two paths in series are the most popular case in which:

\[ A_{es} = \frac{A_1 \cdot A_2}{(A_1^2 + A_2^2)^{\frac{1}{2}}}, \text{m}^2 \] (75)

Total effective area of the pressure operated air relief damper can be calculated using the following equation:

\[ A_{PV} = \frac{Q_{AC} - Q_{PC}}{C \cdot p_{MAX}^{\frac{1}{2}}}, \text{m}^2 \] (76)

where

- \( C \) is the pressure loss coefficient

Based on numerical simulations and experimental results, \( C = 0.60 \ldots 0.90 \), recommended value is 0.83 \(^{[11]}\).

\[ Q_{TOT} = C \cdot A_{TOT} \cdot p_{NOM}^{\frac{1}{2}}, \text{m}^3/\text{s} \] (77)

where

- \( C \) is the pressure loss coefficient

Based on numerical simulations and experimental results, \( C = 0.60 \ldots 0.90 \), recommended value is 0.83 \(^{[11]}\).

\[ A_{TOT} \] is the total effective flow area of the air leakages, m²

\[ p_{NOM} \] is the nominal design pressure differential, Pa

Based upon experience for pressure criterion (all door closed), it is recommended that the total air supply rate should be determined by adding at least 50% to the calculated leakage rate, however, for modern air tight buildings, this correction factor can be neglected. To cover ductwork losses, total air supply rate shall be determined by adding 15% to the calculated leakage rate.

In order to provide proper operation of the pressure differential system (pressure criterion and airflow criterion), air release path from the fire storey shall be provided. The free area of the air release shafts can be calculated using the following equations:

- \( A_{VA} \), required area of the vent per storey, m²

\[ A_{VA} = \frac{Q_{AR}}{2.5}, \text{m}^2 \] (78)

where

- \( Q_{AR} \) is the air release airflow rate (required in order to provide design airflow through the open door to the fire room, m³/s)

\[ A_{VS} \] is the required area of the gravitational air release shaft, m²
\[ A_{VS} = \frac{Q_{AR}}{2.0}, \text{m}^2 \] (79)

where

- \( Q_{AR} \) is the air release airflow rate (required in order to provide design airflow through the open door to the fire room, \text{m}^3/\text{s})
- \( A_{VE} \) is the required area of the mechanical air extraction shaft, \text{m}^2

\[ A_{VE} = \frac{Q_{AR}}{8.0}, \text{m}^2 \] (80)

where

- \( Q_{AR} \) is the air release airflow rate (required in order to provide design airflow through the open door to the fire room, \text{m}^3/\text{s})

Air can be supplied to the protected space either with concentrated air supply or with multiple injection. In buildings less than 11 m in height, a single air supply point for each pressurised stairwell is acceptable. In buildings 11 m or more in height, air supply points shall be evenly distributed throughout the height of the stairwell, and the maximum distance between air supply points shall not exceed six storeys. The supply point shall not be located within 3 m of the final exit doors. For lift shafts, one injection/supply point shall be provided for each lift shaft up to 30 m in height. Each lobby shall be provided with one injection/supply point. Air intake shall be provided for drawing air in from outside the building in such a way that it is not contaminated by smoke from a fire within the building.

**PLEASE NOTE:** Air can be supplied to the protected spaces in a different manner if confirmed using numerical analysis, e.g., CFD simulations.

Air supply ducts shall be properly sized and air velocity in the ducts shall not exceed 10 m/s. Air velocity supplied to the protected space shall not exceed 5.0 m/s. If possible, it is recommended to locate air supply points above the occupied zone where evacuation is carried out. The free area of the air supply shaft can be calculated using the following equations:

- \( A_{AS} \), required area of the air supply shaft, \text{m}^2

\[ A_{AS} = \frac{Q_{TOT}}{10}, \text{m}^2 \] (81)

where

- \( Q_{TOT} \) is the total airflow into the protected space, \text{m}^3/\text{s}
- \( A_{AP} \) is the required area of the air supply point, \text{m}^2

\[ A_{AP} = \frac{Q_{TOT}}{N}, \text{m}^2 \] (82)

where

- \( Q_{TOT} \) is the total airflow into the protected space, \text{m}^3/\text{s}
- \( N \) is the total number of the air supply points

Airflow resistance of the air supply ductwork shall be calculated for design size and layout of the ductworks, taking into consideration design average air velocity in the ductwork.

Pressure differential kits and key components of the pressure differential system shall be selected based on the formulas listed above. Appropriate selection of the pressure differential kits and pressure regulating devices shall be considered as a key factor influencing proper operation of the pressure differential system.
At the design stage it is highly recommended to perform additional calculations in order to confirm effectiveness of the pressure differential system, taking into consideration the influence of the stack effect and wind pressure forces. The pressure differential system shall be capable of producing stable pressure distribution within the protected space in order to maintain design pressure differentials keeping escape routes smoke free and meeting airflow criterion. For buildings taller than 60 m, special provisions for stairwells and lift shafts shall be made. It is recommended either to apply active controlled pressurisation systems or divide the stairwell into sections (partitioning) not taller than 60 m. For more information concerning phenomena that may significantly influence proper operation of the pressure differential system, please refer to the proper section of this Guidebook.
6 Boundary conditions for smoke management

6.1 General information on the boundary conditions

Further boundary conditions both in the interior of the building and outside of the building will have to be taken into account and/or observed for smoke to be conveyed in a directed manner from the origin to the location of the smoke outlet, and for the fundamental principles of smoke control to be effective.

Smoke management also requires that, in the event of a fire, targeted measures be taken directly at the smoke extraction system and/or other systems that affect smoke control. In the simplest case, this may involve automatically created smoke extraction vents in the affected fire compartment or very complex fire control systems with up to hundreds of controls relative to the position of the fire (floor level, fire or smoke compartments, etc.), the type of current use within the building (such as during or outside of events) or relative to the external boundary conditions, such as direction of the wind, wind speed or external temperature.

Particularly in buildings with a large surface area, such as industrial warehouses, venues where people gather (e.g., theatres), sales outlets (e.g., shopping malls) and many others, the uncontrolled spread of smoke can be countered only by way of a clear partitioning of the surfaces into stand-alone smoke compartments. It is not necessary for smoke compartments to match the fire or fire control compartments, which may be considerably bigger in size. Smoke compartments may be room-enclosing (doors and gates, etc.) or subspaces, open at the bottom and connected to each other, within a larger spatial complex. Sometimes fire compartments can be easily divided into individual smoke compartments by means of smoke curtains. Smoke curtains can be installed as fixtures or be part of the building structure (e.g., closed binder-like roof beams or girders) or as moveable smoke curtains according to EN 12101-1 that are dropped or rolled down only in the event of a fire. It is also customary to create smoke compartments by means of automatically closing doors and gates.

Smoke control measures can be effective only in the affected smoke compartment, or they may affect all smoke compartments within a fire compartment. Generally, this depends on the smoke control strategy and smoke control method, that is, whether, for example, natural smoke extraction and supply vents are activated only in the affected smoke compartment or whether extensive controls for smoke control dampers of a mechanical smoke control system across several smoke compartments are combined with a wind-direction-based activation of the supply in remote smoke compartments.

The design of smoke compartments does not only depend on building regulations, which often provide for a size restriction, but also on the building geometry (such as elongated, L- or H-shaped buildings, or the structure of girders, etc.) as well as on the position and possible size of reflow vents and on the wind effects acting on discharge and reflow vents.
6. Boundary conditions for smoke management

6.2 Supply air, replacement air, make-up air

The smoke mass flow discharged from the fire compartment must be replaced by fresh air / make-up air in line with a fundamental law of physics. The reflow of fresh air may be natural through openings to the outside (directly in the external wall or via corridors or ducts connected to the outside) and/or mechanical on the basis of fans. In the case of low-smoke layers, fresh air must be introduced in such a manner that the smoke layer is not upset by the inflowing fresh air. One can do away with air supply close to the floor and with low-impulse supply where a smoke dilution system is used.

Fresh-air supply must be activated at the same time as the smoke extraction to meet the continuity requirement \( \dot{m}_{\text{Smoke}} = \dot{m}_{\text{Fresh air}} \).

When it comes to layer desmoking, which places great emphasis on keeping the bottom layer free of smoke because of emergency escape routes, there are special requirements regarding the introduction of fresh air, depending on the type of smoke extraction (natural or mechanical), which can be summarised as follows:

a) Close to the floor with sufficient distance from the smoke layer,
b) Low-pulse with low flow speed,
c) Flow should not be directed to the smoke layer where possible,
d) Inflow points should be distributed across the smoke compartment surface area.

Additional information on the individual items is provided below

Regarding a) There should ideally be a constant flow across the floor space by way of an upward piston flow (can be implemented only in extremely rare cases, and if so, only through mechanical means given the high-pressure loss). A constant, linear inflow from all sides of the smoke compartment (natural and mechanical) with evenly distributed displacement outlets (mostly mechanical) has also proved beneficial. The distance from the bottom smoke boundary must be sufficiently large where the inflow is primarily horizontal (windows, doors, wall openings, displacement outlets, etc.). Flow experts recommend a distance of at least one metre, even though some regulations, such as DIN 18232-2, also allow for smaller distances.

Regarding b) Generally, a maximum inflow speed of approximately 1 m/s is recommended, with a minimum reflow surface area one and a half times the size of the desmoking area in the case of natural smoke control. The inflow speed refers to the flow effect in the room (and not, for example, to the flow speed within the perforations in a perforated plate used to homogenise the flow), and the surface area specification in the case of natural reflow refers to the aerodynamically effective surface area, rather than the geometric, open surface area.

Regarding c) Doors generally create an inflow that is parallel to the floor, as do pivot windows. Bottom-hung windows with a tilting sash that opens towards the interior, however, create an upward inflow. As a result, the incoming fresh air may upset or even destroy the smoke layer even when the minimum distance from the smoke layer is observed. Top-hung windows that open to the outside and are near the floor can generally be used without disrupting the smoke layer.

Regarding d) If the air supply cannot be distributed evenly across the floor space of the...
smoke compartment, as is the case with the barrel-shaped displacement diffusers in Terminal T4 at Madrid airport (see Figure 34 and Figure 35), the outlets should be arranged in as linear a fashion as possible along the exterior walls of the smoke compartment.

**Figure 34. Principle of barrel-shaped displacement diffusers.**

Individual inflow openings, such as gates, create intensive jet flows that reach far into the room, causing the incoming fresh air to become mixed with the existing room air. Where a large room (fire compartment) is divided into several open smoke compartments connected with each other, such as by way of smoke curtains, it is usually recommended that the fresh-air reflow should be obtained from smoke compartments unaffected by a fire.

**Figure 35. Barrel-shaped displacement diffusers in Terminal T4 at Madrid airport.**

### 6.3 Influence of wind

About 98% of the time throughout the year, one must expect buildings to be affected by wind, which is why this factor must not be ignored, even though technical standards and national building regulations contain no or only few instructions about wind-related factors. The displacement effect of the building creates a pressure distribution, dependent on the direction of the wind, on the surface of the building envelope. At building openings (smoke extraction vents, supply vents, escape route egress, etc.), the wind-caused pressure of the adjacent facade areas takes effect. For example, if an opening is created on the building’s weather side (facing the wind), the excess pressure created by the wind there causes an inflow into the building. It is obvious that this opening cannot be used for natural smoke extraction. If this opening is intended as a supply vent, the wind will drastically increase the inflow speed, which can also harm the quality of the low-smoke layer. In other words, the effects of the wind on the building must be taken into account at the planning stage for all smoke control systems with natural smoke extraction and/or natural reflow, as well as for smoke displacement systems. Wind has a much more intensive effect on stand-alone buildings than on buildings within densely developed areas with equal heights.

Therefore, wind-based strategies must be developed and considered in designing natural smoke extraction and fresh-air supply (also in the case of mechanical smoke control). **Figure 36** shows the arrangement of natural smoke extraction and reflow vents for buildings with several smoke compartments and different wind directions. Further information can be found in the publications\(^{13,14}\).
To ensure that building openings can be opened relative to the wind direction, the wind direction acting on the building must be measured precisely. In addition, an activation matrix must be developed that takes into account the position of the fire/smoke compartment and the wind direction.

### 6.4 Temperature-related factors

Given the differences in air density in the building’s interior vis-à-vis the outside atmosphere, the external temperature generally plays a role that is not to be ignored where pressure differential systems for escape stairwells are concerned, both in respect of natural smoke ventilation and in respect of smoke displacement. While natural smoke extraction with low exterior temperatures is significantly supported by the temperature-based pressure differential already at the time of activation, such immense pressure differentials form at the doors leading to the escape stairwells of high-rise buildings that the doors may no longer open properly if systems are not designed or operated correctly. In a hall 13.5 m high, with an exterior temperature of −5°C, the pressure differential, solely due to the temperature differential between the interior and exterior, of $\Delta p_{th} = 15\, \text{Pa}$ (according to Equation (83)) already shows the same amount as a 2-m-thick smoke layer of $150^\circ\text{C}$ at the same exterior temperature.

$$\Delta p_{th} = \rho_{\text{air}} \cdot \left(1 - \frac{T_{\text{smoke}}}{T_{\text{air}}} \right) \cdot g \cdot h \quad (83)$$

where

- $\Delta p_{th}$ is the thermal pressure differential in Pa
- $\rho_{\text{air}}$ is the density of air in kg/m$^3$
- $T_{\text{smoke}}$ is the temperature of the smoke in K
- $T_{\text{air}}$ is the air temperature in K
- $g$ is the gravitational acceleration in m/s$^2$
- $h$ is the thickness of the smoke layer/height in m

**Figure 36.** Examples showing the arrangement of natural smoke extraction and reflow vents for buildings with several smoke compartments and different wind directions.
Taking into account the minimum surface area ratio for natural smoke extraction regarding the reflow area of $A_{in}/A_{out} = 1.5$, the creation of smoke extraction and reflow openings results in an inflow speed of $v_{in} = 2.23 \text{ m/s}$.

Pressure differential systems must be capable of managing a thermally based pressure differential of approximately $\Delta p = 130 \text{ Pa}$ in a building with a height, for example, of $H = 100 \text{ m}$ and an exterior temperature of $t_a = -5^\circ\text{C}$. Equation (83) is also used for the calculation.

### 6.5 Interfaces with other trades

All fire protection systems must function properly in the event of a fire. Smoke management systems represent only a part of all the fire protection systems in a building. Further systems that may be installed:

- Fire alarm systems,
- Fire extinguishing systems,
- Doors, gates and dampers to separate fire compartments,
- Voice alarm systems,
- Emergency lighting and escape route control,
- Fire-brigade lifts, etc.

Some fire protection systems may affect each other. For example, smoke extraction does not work if a gas extinguishing system for oxygen displacement is to be deployed in the same room, because smoke extraction would convey oxygen-rich fresh air to the source of the fire, which would render oxygen displacement ineffective. Smoke extraction and sprinkler systems may also interact with each other, for example, when the sprinkler heads are installed below natural smoke and heat exhaust vents. If smoke extraction is triggered by the parameter smoke, and the distance of sprinklers from the ceiling is far enough, it may be that the smoke discharge is activated so early that less hot gases reach the sprinklers, causing them to be triggered later. Conversely, the effect of the sprinklers cools down the smoke, causing a reduction in the driving pressure differential for natural smoke ventilation.

But smoke extraction systems do not only have interfaces with other fire protection systems, but also with systems and devices related to the normal use of the building, such as ventilation systems, sun protection systems or doors and gates that divide building and space sections into separate safety zones, such as at airports. Such devices (not part of fire protection systems) can impair the effectiveness of smoke extraction and smoke management devices substantially and must be activated and controlled accordingly in the event of a fire. Sun protection devices at doors and roof openings that are used for smoke extraction or reflow must be set to the neutral position so as to ensure an effective flow through such openings.

Ventilation systems that discharge air through the ceiling destroy the smoke layer when being operated and thus prevent the formation of low-smoke layers. However, if they are not in close proximity to the smoke compartment, they can deliver the supply air necessary for smoke extraction. In the case of low smoke temperatures, ventilation systems may contribute to smoke extraction, such as when coupled with the effect of the sprinkler system, if they are installed in the ceiling. But ventilation systems in adjacent smoke extraction compartments prevent or reduce the reflow of fresh air. The respective systems or system components must be activated and controlled in accordance with the smoke extraction and smoke management concept specific to the building. This may have a very complex
6. Boundary conditions for smoke management

structure where complex buildings are involved. Helpful instructions regarding the structure of a fire-event control matrix can be found, for instance, in VDI 6010 Part 2 or in the explanatory notes on fire protection 108-15, or regarding the often-required inspection of control functions, such as pursuant to, in VDI 6010 Part 3.
7 Ventilation systems in support of smoke control

7.1 Cold smoke extraction via ventilation system

Cold smoke extraction refers to the discharge of smoke gases whose temperature is only slightly different from that of ambient air and that, therefore, depend on mechanical discharge. Generally, one assumes for cold smoke a temperature below the triggering temperature of trigger devices (fusible links, thermal fuses) for fire dampers (72°C).

Very often, smoke discharge is required only as support for the fire brigade’s firefighting measures. It is therefore assumed that self-rescue is possible even without smoke discharge if the structural specifications, such as on structural partitioning as well as the type and number of escape/escape routes, are complied with. The volume flows required for such smoke discharge are significantly below the provisions contained in DIN 18232-5.

In the case of special structures with sprinkler systems, smoke extraction can then also be realised via the ventilation system. In the event of a fire, such a system will only ventilate and must ensure a sufficient volume flow. Supply air must be switched off or operated in such a manner that it, too, only ventilates in the event of a fire.

The exhaust air volume flow in the fire compartment can be increased further through additional measures:

- Increase of fan capacity in stages or via frequency inverter
- Volume flow controller in the fire compartment with forced control ON or de-energised ON
- Fire control of further ventilation dampers to concentrate exhaust air volume flow onto the fire compartment

The effectiveness of cold smoke extraction via the ventilation system is considered highly controversial. One must assume, in particular, that the temperature of the smoke gas layer can reach 200°C even in buildings with sprinkler systems. The ventilation system is not designed to handle such a temperature. In addition, especially fire dampers are shut automatically at a temperature of 72°C, thus limiting the options of cold smoke extraction.

Since supply air is switched off, or discharged as well, the necessary reflow is often not guaranteed, particularly so as it is supposed to act close to the floor and in a low-pulse manner so as not to disturb the smoke layer.
Cold smoke extraction via the ventilation system cannot be calculated in terms of time. Nor is it capable, in light of the feasible volume flows, to ensure constant, low-smoke layers. But it does delay the spread of smoke, thus allowing people additional time for self-rescue. As additional support for the fire brigade’s fire-fighting measures it is of limited use, because a full smoke filling must be assumed by the time the fire brigade arrives.

If one deviates from structural requirements, or if evacuation scenarios reveal that a sufficiently rapid evacuation cannot be ensured even when requirements are complied with, the design of the smoke control system must focus on the protection of personnel. In such a case, cold smoke extraction via the ventilation system would then be impossible.

### 7.2 Ventilation system in support of air supply

Standards on the dimensioning of mechanical smoke control systems stipulate low-pulse air reflow as close to the floor as possible in order to prevent any disturbance of the smoke layer. Some requirements call for a maximum speed of supplying air of 1 m/s. Some smoke extraction volume flows are considerable, and the requirements regarding reflow via the building envelope (windows, doors, other openings) are difficult to implement in terms of architecture.

As a result, it is quite common to use the supply air of the ventilation system for the reflow of the smoke extraction system. But the supply air outlets must not be located in the smoke layer. Source air and floor outlets would be particularly suited for this purpose. Alternatively, reflow may be realised also by way of supply air through adjacent smoke compartments. However, in such a scenario the supply air system would become part of the smoke extraction system, which means it must not be switched off or fail prematurely in the event of a fire.

![Image of ventilation system](source: Internet)

**Figure 38. Make-up air close to the floor via supply air outlets. (source: Internet)**

### 7.3 Ventilation system for smoke control via excess pressure

It may make sense to use the ventilation system for smoke control according to the displacement principle and on the basis of a special fire control matrix for large ventilation systems, in particular. In this case, the supply air fire dampers (FDs) can be closed in the area affected by the fire, while
the exhaust air FDs remain open until the thermal activation, which creates negative pressure. The FDs in the adjacent areas are controlled inversely, which means that the supply air FDs remain open, while the exhaust air FDs are shut. This creates excess pressure in those areas. The pressure conditions thus created produce an air flow towards the fire compartment, thus countering actively the spread of smoke. But attention must be paid to ensure that the allowable door-opening forces are not exceeded.

Such control of the ventilation system may represent an additional measure. It is not, however, a replacement for effective mechanical smoke control.

**Figure 39. Damper control; preventing the spread of smoke.**
8 Construction products for smoke management systems

8.1 Smoke control dampers

8.1.1 Typical application for smoke control dampers

Smoke control dampers are used to provide a controlled pathway through ducts, shafts or areas to allow the deliberate movement of heat and smoke away from a fire or smoke source. This way, it is not known until a fire or smoke incident starts which smoke control dampers are to open and which are to shut. They might respond to an automatic command or wait to be started or the states may be changed by a fire brigade.

Smoke control dampers may be single or multi-compartment. For single compartment applications, performance is required to 600°C and for multi-compartment applications, performance is required to a full fire test temperature (in excess of 825°C after 25 minutes).

The smoke control dampers are associated with ducts, shafts or walls and those which have to open will often then breach compartmentation. Thus, after such a breach, all the other dampers in a duct not in line with the exhaust path must be shut to maintain protection of compartmentation so that the fire or smoke does not break out of the duct. Effectively, the open path becomes part of the fire compartment.

As the path is to be maintained, it is generally required that actuators are of the ‘drive open drive closed’ type, so that the safety position (open or closed) cannot be changed just because of a loss of motive power.

Smoke control dampers should be installed using the instructions and information given by the manufacturer. Any deviation may mean that no responsibility may be taken by the manufacturer if the units fail in a fire situation, as the intention is that the smoke control dampers are installed as tested.

![Figure 40. ISO 834 Standard temperature vs. time curve.](image)

8.1.2 Standards for smoke control dampers

Product standard EN 12101-8

Smoke control dampers fall under the harmonised product standard EN 12101-8. This means that they require CE marking where they are covered by the scope of this standard. Third-party product certification is required as the AVCP system stated is system 1.

Test standard EN 1366-10

Products may be tested in conjunction with smoke control ductwork or in association with typical compartment boundaries such as floors and walls. Each boundary type and each sealing method requires classification.
There are test regimes for single and multi-compartment applications and for products that are automatically triggered by smoke alarms or others that may be required to change state later into a fire or smoke incident. There is an alternative to test for multi-compartment products with a functionality HOT test to 400°C. All tests require the dampers to prove maintenance of opening as well as closing.

**Classification standard EN 13501-4**
This standard describes the classes that the smoke control damper may be applied to in light of testing and is qualified by the third-party notified body in a classification report. Details are given on the times for integrity (E), insulation (I) and reduced smoke leakage (S) that the dampers are required to achieve. Further information is given on vertical or horizontal installation, side of exposure, pressure of exposure, automatic or manual intervention and the day-to-day application dealt with in terms of the number of operations.

**EXAP standard**
At the time of writing, no EXAP standard is available, so this makes assessment difficult or perhaps impossible, but at some point, a standard will be published.

**Standard specification**
Smoke control dampers shall meet the requirements of EN 12101-8 in their application in smoke control ducts or their positioning in other ducts, shafts and walls.

**8.1.3 Smoke control dampers – design and application details**
Appropriate components of the required classification must be installed correctly at the right location to create a functioning, efficiently optimal overall plant for effective smoke management.

This must generally be done in accordance with the relevant manufacturer’s documents:
- assembly and installation instructions
- operation and maintenance instructions
and the associated proof of performance. Reading the related product standard EN 12101-8 is also recommended.

It is important to know in this context that the smoke control dampers may be installed and used only if they successfully passed the inspection under EN 1366-10.

Apart from the classifications E, EI, EIS and the different fire resistance times, this includes also the following characteristics:
- Mounting position (horizontal or vertical; in or on smoke extraction ducts, in walls or ceilings)
- Mounting location (single or multiple compartments)
- Number of position changes of the damper blade (on/off)
- Expected maximum pressure conditions to name only a few.

**Single compartment and multi-compartment**
The building object in question must be divided, in terms of fire protection, into single compartments and multi-compartments. The easiest way to do this is to start at the smoke control fan and follow the smoke control duct. Each final compartment is called a single compartment.

Multi-compartments are sections that smoke control ducts pass through. Where hot fire gases are to be discharged, the fire is to be prevented from being spread to unaffected compartments.
The manufacturer of smoke control dampers makes this distinction by way of the construction, design, the choice of different base materials (physical properties, quality, dimensions, etc.).

The situation for smoke control ducts is similar. There are line sections for single compartments (600°C lines) and for multi-compartments (fire-resistant lines).

**Figure 41. Example for mechanical smoke and heat extraction (EN 12101-8).**

**Key:**

1. Fire compartment; 2. Smoke reservoir; 4. Air inlet (make-up air); 5. Smoke barrier; 6. Powered smoke control fan; 7. Smoke control dampers for single compartments (EN 12101-8 and EN 1366-10); 8. Smoke control ducts for single compartments (EN 12101-7 and EN 1366-9); 9. Smoke control ducts for multi-compartments (EN 12101-7 and EN 1366-8); 10. Smoke control dampers for multi-compartments (EN 12101-8 and EN 1366-10) mounted inside or outside of wall or floor; 11. Smoke control dampers for multi-compartments (EN 12101-8 and EN 1366-10) mounted on the surface of the duct; 12. Electrical equipment.

**Notes:**

- Single and multi-compartment application;
- Smoke control dampers that are built and classified for multi-compartments can also be used in applications for single compartments. The reverse is not possible.
Automatic activation (AA) and manual intervention (MA)
This involves the activation of smoke control dampers. If a smoke control damper is also to be activated and/or controlled manually in the event of a fire, a smoke control damper of MA classification must be used. This allows the specialist staff some time to override the initial damper position in order to track the damage progression or to partition unaffected compartments subsequently.

If manual intervention is not to be used at all and activation will be triggered only through an automatic fire alarm system, smoke control dampers with AA classification can be used. In case of fire, these dampers move into the required position once and remain there.

The manufacturer of the smoke control dampers makes this distinction by way of the design of the damper (materials, etc.) as well as by way of creating thermal shielding or insulation around the damper drive (thermal enclosure). This is the only way to ensure reliable control of the smoke control damper even at elevated temperatures.

In the actual structural implementation, one must also choose the correct type of electrical supply line of appropriate qualification. Refer to Section 11.4 for more information.

AA and MA
Smoke control dampers that are built and classified for manual activation can also be used in applications with automatic activation. The reverse is not possible.

Installation of smoke control dampers
One must distinguish between horizontal (Figure 42) and vertical (Figure 43) alignment.

Figure 42. Horizontal installation (horizontal mounting position) of smoke control dampers; damper axis is horizontal. 1. Installed in a vertical duct, 2. Installed on the surface of a horizontal duct (bottom), 3. Installed on the surface of a horizontal duct (top).

Figure 43. Vertical installation (vertical mounting position); damper axis varies (horizontal or vertical). 4. Installed in a horizontal duct, 5. Installed on the lateral surface of a vertical duct (left), 6. Installed on the lateral surface of a vertical duct (right), 7. Installed on the lateral surface of a vertical duct (front/back), 8. Installed on the lateral surface of a horizontal duct (front/back).
8. Construction products for smoke management systems

**Figure 44.** Smoke control dampers in single compartments.

**Figure 45.** Smoke control dampers in multi-compartments.
Overview of smoke control dampers

<table>
<thead>
<tr>
<th>Controls</th>
<th>Single Compartment</th>
<th>HOT 400</th>
<th>Multi Compartment</th>
</tr>
</thead>
</table>
| **Automatic activation (AA)** | - 600°C Damper with Actuator  
- Actuator without thermal protection | - per definition, this damper does not exist | - Standard temperature curve (fire curve) with Actuator  
- Actuator without thermal protection |
| Fire test: OPEN Command after 90 s | | | |
| **Manual intervention (MA)** | - 600°C Damper with Actuator  
- Actuator with thermal protection | - Fire damper modified as HOT 400 damper  
- Actuator with thermal protection | - Standard temperature curve (fire curve) Damper with Actuator  
- Actuator with thermal protection |
| Fire test: OPEN Command after 20 min | | | |
| HOT 400: Cycling at 400 °C | | | |

*Figure 46. Examples of different classifications and possible designs.*

### 8.2 Fire dampers

#### 8.2.1 Typical application for fire dampers

Fire dampers are used to maintain compartmentation where a duct passes through a compartment wall or floor. They have a fusible link to make sure they close at elevated temperatures (normally 72°C). To prevent smoke migration, they may have a smoke leakage classification and in this case, would normally close under the control of smoke or fire detectors. Motorized fire dampers (powered units) usually close automatically on loss of power supply or in response to an alarm signal (NC to OPEN).

Fire dampers should be installed using the instructions and information given by the manufacturer. Any deviation may mean that no responsibility may be taken by the manufacturer if the units fail in a fire situation, as the intention is that the dampers are installed as tested.
8. Construction products for smoke management systems

8.2.2 Standards for fire dampers

**Product standard EN 15650**
Fire dampers fall under the harmonised product standard EN 15650. This means that they require CE marking where they are covered by the scope of this standard. As with the AVCP system stated in system 1, third party product certification is required. It also gives information on the number of operations if this is a requirement.

**Test standard EN 1366-2**
Products are tested in conjunction with typical compartment boundaries such as floors and walls. A classification is required for each type of fire boundary construction and sealing-in method. In addition, products usually need to demonstrate performance from both sides, as it cannot be predicted which side the fire is coming from.

**Classification standard EN 13501-3**
This standard describes the classes that the fire damper may be applied to in light of testing and is qualified by the third-party notified body in a classification report. Details are given on the times for integrity (E), insulation (I) and reduced smoke leakage (S) that the dampers are required to achieve. Further information is given on vertical or horizontal application and side of exposure.

**EXAP standard EN 15882-2**
Assessments of certain changes to product design are allowed under this standard. It does not generally extend to the application in different supporting constructions or sealing methods outside of that tested. These assessments may not be done by manufacturers or installers and must be made by a notified body that will then provide an extended field of application report defining what has been agreed and this will allow CE marking of the revised products.

**Standard specification**
Fire dampers shall meet the requirements of EN 15650 in their application in the protection of compartmentation where duct and other air transfer penetrations are made in compartment boundaries (walls or floors).

8.3 Smoke control ducts

8.3.1 Typical application for smoke control ducts
Smoke control ducts are used to provide a contained pathway to allow the deliberate movement of heat and smoke away from a fire or smoke source. Multi-compartment smoke control ducts will often breach compartmentation. It is imperative that the fire or smoke does not break out of the duct. Effectively, the contained path becomes part of the fire compartment.
Smoke control ducts may be single or multi-compartment. For single compartment applications, performance is required to 600°C and for multi-compartment applications, performance is required to a full fire test temperature (in excess of 825°C after 25 minutes).

For some of the above reasons, there are additional requirements for smoke control ducts over that for fires resisting ducts. These are that the cross section must be maintained without collapse and that multi-compartment smoke control ducts must have an insulation classification.

Smoke control ducts should be installed using the instructions and information given by the manufacturer or the company that has performed the fire resistance initial type testing. Any deviation may mean that no responsibility may be taken by the manufacturer if the units fail in a fire situation, as the intention is that the ducts are installed as tested.

Test standards EN 1366-1 and EN 1366-9

The test for multi-compartment smoke control ducts is shown in EN 1366-8 and the test for single compartment smoke control ducts is shown in EN 1366-9. The latter has no requirement for insulation. Testing is performed at 500 pa pressure difference.

The tests for fires resisting ducts to EN 1366-1 shall be performed and classified at 300 Pa before the smoke control duct testing is undertaken on the product.

Products are tested in conjunction with typical compartment boundaries such as floors and walls. A classification is required for each type of fire boundary construction and sealing-in method. In addition, products usually need to demonstrate performance from fire inside and from fire outside, as it cannot be predicted from where the fire is coming from.

Classification standard EN 13501-4

This standard describes the classes that the smoke control duct may be applied to in light of testing and is qualified by the third-party notified body in a classification report. Details are given on the times for integrity (E), insulation (I) and reduced smoke leakage (S) that the duct is required to achieve. Further information is given on vertical or horizontal application and exposure from outside and inside.

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8.3.2 Standards for smoke control ducts

Product standard EN 12101-7

Smoke control duct sections made in a factory fall under the harmonised product standard EN 12101-8. This means that they require CE marking where they are covered by the scope of this standard. As with the AVCP system stated is system 1, third party product certification is required.

Smoke control ducts manufactured / built / ‘installed’ on site do not fall under this standard, as products assembled on sites do not come under the CPR.
8. Construction products for smoke management systems

**EXAP standard**
At time of writing, no EXAP standard is available, so this makes assessment difficult or perhaps impossible, but at some point, a standard will be published.

**Standard specification**
Smoke control ducts shall be installed following the company performing the fire resistance initial type testing’s information with particular regard to the installation / sealing at compartment boundaries. Testing of smoke control ducts shall be in accordance with EN 1366-8 or EN 1366-9 for multi-compartment and single compartment applications as relevant. Where applicable, the smoke control duct sections shall meet the requirements of EN 12101-7.

8.4 Fire resisting ducts

8.4.1 Typical application for fire resisting ducts
Fire resisting ducts are used to provide a contained pathway for air through a building. Fire resisting ducts will often breach compartmentation. They will be used in specific applications where the use of fire dampers at compartment boundaries are not required or specifically forbidden. They are also used in cases where ducts cross escape routes where extra protection is needed. Some applications require insulation and some do not and in some cases this is country-specific. Smoke control ducts need further testing above this testing.

Fire resisting ducts should be installed using the instructions and information given by the manufacturer or the company that has performed the fire resistance initial type testing. Any deviation may mean that no responsibility may be taken by the manufacturer if the units fail in a fire situation, as the intention is that the ducts are installed as tested.

![Figure 50. Typical smoke control duct sections, fire-resistant.](image)

8.4.2 Standards for fire resisting ducts

**Product standard EN 12101-7**
Still under development, but it will be available at some point. From a year after its publication, fire resisting duct sections made in a factory fall under this harmonised product standard. This means that they will then require CE marking where they are covered by the scope of this standard. As with the AVCP system stated will be system 1, third party product certification will be required.

Fire resisting ducts manufactured / built / ‘installed’ on site do not fall under this standard, as products assembled on sites do not come under the CPR.

**Test standards EN 1366-1 and EN 1366-8**
The tests for fire resisting ducts to EN 1366-1 are performed and classified at 300 Pa. Products are tested in conjunction with typical compartment boundaries such as floors and walls. A classification is required for each type of fire boundary construction and sealing-in method. In addition, products usually need to demonstrate performance from fire inside and from fire outside, as it cannot be predicted from where the fire is coming from.
Classification standard EN 13501-3
This standard describes the classes that the fire resisting duct may be applied to in light of testing and is qualified by the third-party notified body in a classification report. Details are given on the times for integrity (E), insulation (I) and reduced smoke leakage (S) that the duct is required to achieve. Further information is given on vertical or horizontal application and exposure from outside and inside.

EXAP standard EN 15882-1
Assessments of certain changes to product design are allowed under this standard. It does not generally extend to the application in different supporting constructions or sealing methods outside of that tested. These assessments may not be done by manufacturers or installers and must be made by a notified body that will then provide an extended field of application report defining what has been agreed and this will allow CE marking of the revised fire duct sections.

Standard specification
Fire resisting ducts shall be installed following the company performing the fire resistance initial type testing’s information with particular regard to the installation / sealing at compartment boundaries. Testing of fire resisting ducts in accordance with EN 1366-1. Where applicable, the fire resisting duct sections shall meet the requirements of EN 12101-7.

8.5 Smoke curtains
Smoke curtains limit the spread of fire gases to one fire compartment and allow for the creation of smoke compartments. This allows for more effective smoke management.

Smoke curtains (e.g., as beams or girders) can be fixed components of the building or moveable, such as textile curtains. Fixed smoke curtains must be dimensioned such that their height exceeds the calculated smoke layer thickness.

Figure 51. Smoke curtains (principle).
Moveable smoke curtains are generally covered. In the event of fire, they move to a specified height, in other cases all the way down to the floor. Smoke curtains in escape routes are frequently segmented and allow for the passage of people.

Some moveable smoke curtains are also certified for use as fire barriers.

8.6 Smoke control fans

8.6.1 Typical application for smoke control fans

Smoke control fans are used in a variety of smoke control systems. They are the motive power moving air, heat and smoke through or out of any system. The design will predict the temperatures required for fans to work and they should be selected accordingly.

8.6.2 Standards for smoke control fans

Product standard EN 12101-3

Smoke control fans fall under the harmonised product standard EN 12101-3. This means that they require CE marking where they are covered by the scope of this standard. As with the AVCP system stated is system 1, third party product certification is required.

The fans are tested at the temperature for which they are designed and classified accordingly. This is done by passing heated air through them for the described period and checking various parameters and performance.

Test standard

Test standard is included in the product standard above.

Classification standard EN 13501-4

This standard describes the classes that the smoke control fan may be applied to in light of testing and is qualified by the third-party notified body in a classification report. Details are given on the times for Functionality (F) that the fans are required to achieve.

EXAP standard

Limited EXAP guidance is given in the product standard above and is still under the control of a notified body.

Standard specification

Smoke control fans shall meet the requirements of EN 12101-3, having a classification that meets the requirements for their application in the smoke control system specified.

8.7 Mobile smoke control fans

8.7.1 High-performance fans (fire brigade’s aerators)

The effective use of mobile smoke control fans requires blow-in vents in addition to smoke extraction vents / air release openings. They must be arranged in such a manner that mobile smoke control fans can be set up and operated effectively.

Normally high-performance fans are part of the modern equipment and supporting aids for trained firefighters. Correct and proper use can improve working conditions and thus give rescue teams more time. Smoke gases can be cooled and discharged from the building. Wrong and incorrect use, however, will have adverse effects. That is, adverse effects for the emergency personnel, the building and also adjacent properties. The noise created by certain models may also have adverse effects on the communications of the emergency personnel.
Some pros for use of mobile smoke control fans:

- Improves operating conditions for fire-extinguishing and rescue personnel (air quality, temperature, visibility, etc.)
- Lowers smoke gas temperatures in the affected building
- Delays the flashover
- Minimises damage to the affected building
- Improves visibility within the affected building
- Can be used in a flexible manner by the fire brigade, depending on the situation on the ground
- Large-surface supply air vents can be serviced by several aerators (availability must be clarified with the respective fire brigade)

Some cons for use of mobile smoke control fans:

- Considerable, general turbulence (not only smoke gases) in the affected building must be taken into account
- Substantial noise, mostly in the entrance area, causes communication problems
- Mistakes in deployment can cause the fire to spread further
- Adjacent properties, position, direction, etc. should be examined carefully during deployment
- Deployment planning must factor in the local, exterior pressure conditions
- Exhaust air vents with appropriate discharge surfaces must be open at the correct location, as close to the source of the fire as possible

National regulations and standards apply to the use and deployment of mobile smoke control fans.
9 Standardisation of selected building products

The legislation for smoke and fire-related products in each country should be checked as there are differing requirements in each country under their relevant building regulations. As for instance, some countries require insulation characteristics, others do not.

CE marking is simply one way to prove a product meets building regulations and it might be possible to prove this in different and additional ways, particularly if dampers are very big or it is a one-off application to meet a new / different engineering challenge. In some cases, CE marking is quite limited in its applicability.

However, CE marking is a requirement of the Construction Products Regulation (CPR), where a harmonised product standard exists. The CPR is a different piece of pan-EU legislation and completely different and not to be confused with a country’s building regulations.

It is generally a way to make trade simple between EU countries, so that there does not have to be constant checking and there is an apparent level of standard requirements. If the product falls within the scope of the harmonised standard it is required to be CE marked simply to put the product on the market anywhere in the EU or countries seeking affiliation. This includes your own country, if it is within the EU. The concept is to make sure that a standard level of initial type testing (ITT) and factory production control (FPC) is set up, with ongoing Assessment and Verification of Constancy of Performance (AVCP), including further auditing, FPC, testing, etc. Harmonised standards for most smoke and fire-related building products require AVCP system one or above. This means third-party product certification by a notified body, a satisfactory quality system for FPC and ITT. Self-certification for smoke and fire-related building products is therefore generally not allowed.

Certain products such as ducts may be required to be CE marked where they are constructed in a factory, but apparently are not required to be CE marked if installed / constructed on a site, however, they could be if certification was put into place.

As ranges and products are developed, they still need to be CE marked. To try and make this easier and in theory reduce excessive testing, the assessment of test results and changes must follow the extended field of application (EXAP) standards so that CE marking scope may be extended. Again, self-certification is not allowed, and assessment to this standard and the resulting report must be by a notified body.

Certain countries also have existing documentation requirements for some of the products that still need to be met over and above CE marking, such as the French NF certification, which is to ensure good operation and maintenance details, with very clear checking of electrical requirements and safety.

Other countries such as Germany and Finland require much more detailed reaction to fire details in theory to reduce fire loads in the vicinity of products, but this requires more third-party intervention and is still subjective. In addition, some countries such as Germany require hygiene information with evidence of checking too.
10 Fire alarm systems

Fire alarm systems are used in modern buildings to detect fires (smoke) early.

A fire can be detected in an early phase of development by way of modern smoke detectors. Some manufacturers have even started providing a false alarm guarantee.

Fire alarm systems also alert and ensure the automatic control of further fire protection systems, in addition to the early detection of a fire. Toxic gases pose a direct health risk to people, but hydrogen chloride (HCl) can also cause substantial property damage to machinery and damage to electronic components.

Fire alarm systems that are not designed or built correctly can seriously thwart the protection objective. It is therefore very important for all stakeholders to know and apply the different technical terms involved in designing a fire alarm system.

10.1 Protection objectives of fire alarm systems

The protection objective of fire alarm systems has not really changed over the course of their varied development.

The main tasks of fire alarm systems are the discovery and reporting of a fire and the controlling of fire protection systems.

This results in the following requirements:

• Rapid information to and alerting of people affected
• Detection of a fire at an early stage
• Automatic activation of fire protection and operating systems; and
• Alerting the fire brigade and/or other assistance personnel

10.2 Scope of a fire alarm system

A clear specification of the aforementioned protection objectives notwithstanding, each technical system can be designed and built differently.

This is why the objective and type of detection must be specified correctly in the planning of a fire alarm system.

An automatic fire alarm system alerts and controls automatically, without requiring additional commands or actions.

As regards setup and operation, fire alarm systems can range from one with a single manual call point and local alert to systems with automatic fire alarms, manual call points and a link to the local fire brigade.

In other words, when ordering an automatic fire alarm system, it may be possible that a system with manual call points only is delivered. It then ensures the automated process of activating further tasks of the fire alarm system.

An automatic fire alarm system, like an automatic fire-extinguishing system without human intervention, detects fires, sounds the alarm and handles the further tasks of a fire alarm system. These systems are always coupled with automatic fire detectors.
10.3 Fire detection

Where fire detection is concerned, one must distinguish between manual and automatic detection.

In the context of activating natural or mechanical smoke control systems, the distinction between smoke and heat detectors is particularly important, because the different detection and/or response times result in different design parameters for the smoke control system.

As for the planning and development of detectors, reference is made to the national guidelines, which contain all information on planning, setup and operation.

10.4 Monitoring scope

There are four different monitoring categories for fire alarm systems in Europe:

- Category 1: Complete area
- Category 2: Partial area
- Category 3: Coverage of escape routes
- Category 4: Equipment protection

It is therefore necessary to specify the monitoring coverage as well as the type of fire detection. Some areas may be excluded, such as toilets or false ceilings.

10.5 Fire alarm concept

Planning on the basis of a fire alarm concept is recommended, particularly where only a partial area is monitored. This used to be called a fire protection concept, but this term is more accurate as it concerns the designing of the fire alarm system.

The fire alarm concept defines the requirements with respect to the fire alarm system.

These include, in particular:

- Designation of safety areas and monitoring coverage, which should, but does not have to, be identical to the fire compartments.
- Information on the type and scope of alerting and particularly the alarm zones, which also do not have to be identical to the safety areas or fire compartments
- Position of the central fire alarm system or centres and type of accessibility
- Type of activation of fire protection closures, fire-protection and operating facilities
- Alarm organisation of the user, instructed and/or knowledgeable personnel, and measures when parts of the fire alarm system are taken off-line, such as during maintenance and inspection.

The fire alarm concept indicates the setup of a fire alarm system, such as the one shown in Figure 54.

10.6 Activation of fire protection devices

The activation of fire protection devices, frequently referred to as fire control, includes, for example, the reliable triggering and/or activation of:

- Automatic fire extinguishing systems
- Smoke control systems
- Lift systems
- Switching off ventilation systems

One must always also specify the quality of activation for the planned activation, particularly if it cannot be derived from the protection objective. Further fire protection devices, even as secondary controls, can be activated regardless of monitoring tasks, in contrast with the specified activation quality and monitoring of the transmission.
paths of alarm transmitters, fire brigade key depots, fire brigade display panels, etc.

This is particularly the case when this involves controls not required by building authorities.

Fire controls, if they are part of a fire alarm system, must be realised by means of specified interfaces harmonised with each other.

This includes electrical data, the type of signal transmission and, in particular, the monitoring of transmission paths, including fault notification and the system’s behaviour in the event of a fault.

The following data are defined at the fire alarm system for the general interfaces for activating other systems:

<table>
<thead>
<tr>
<th><strong>Activation</strong></th>
<th>through current amplification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Actuation voltage (from the activation device)</strong></td>
<td>(12 ± 1.8) V or (24 ± 3.6) V DC</td>
</tr>
<tr>
<td><strong>Internal resistance of the load</strong></td>
<td>200 Ω to 1000 Ω</td>
</tr>
<tr>
<td><strong>Duration of activation</strong></td>
<td>1 s to 6 s or sustained</td>
</tr>
<tr>
<td><strong>Line resistance per conductor</strong></td>
<td>≤ 50 Ω</td>
</tr>
<tr>
<td><strong>Reset current</strong></td>
<td>≤ 2.5 mA</td>
</tr>
<tr>
<td><strong>Reset time</strong></td>
<td>≥ 1 s</td>
</tr>
<tr>
<td><strong>Monitoring current</strong></td>
<td>≤ 10 mA</td>
</tr>
</tbody>
</table>

*Figure 54. Setup of a fire alarm system.*
11 Activation of components for smoke control

11.1 Fire dampers

Fire dampers prevent the spread of fire and smoke through ventilation systems. They close permanently upon reaching the thermal triggering temperature. As concerns the prevention of flashover, the OFF position (closed blade) of the fire damper is always considered a safe state. The OFF position upon reaching the triggering temperature is deemed intrinsically safe.

However, the following cases should be noted:

11.1.1 Smoke-based activation

With motorised fire dampers, there is an option allowing for the remote triggering of fire dampers by means of smoke-based activation devices. Smoke-based activation is often a fixed part of fire protection concepts. But the intrinsic safety of the fire damper only refers to its thermal activation. Remote triggering by means of a smoke-based activation device, therefore, must be ensured by way of sufficiently reliable activation.

11.1.2 Fire dampers are not supposed to close without reason

Ventilating systems ensure the hygienic air exchange and temperature control of rooms. Sometimes they also maintain defined pressure conditions in buildings. This is especially true of laboratories, hospitals or also cleanrooms. In such cases, the closing of fire dampers without reason (false alarm, interruption of supply voltage) must be prevented at all cost. This, too, requires reliable controls.

11.1.3 Fire dampers must not close prematurely

The failsafe OFF position of fire dampers is especially problematic if other fire protection measures are impeded as a result of the fire dampers closing prematurely or without reason. This applies in particular to cold smoke extraction via the ventilation system and to the use of supply air as part of the reflow for smoke extraction systems. In this case, the closing of fire dampers would be nothing more than the last resort to prevent a flashover. Otherwise, the damper must remain open due to its function.

11.2 Smoke control dampers

Under normal conditions, smoke control dampers are closed and open in the affected fire compartment. The smoke control dampers in adjacent compartments must remain closed to prevent a flashover and to allow for the smoke extraction volume flow to be concentrated in the affected area. Thus, the smoke control damper has two safety positions (ON and OFF or OPEN and CLOSE respectively).

11.3 Smoke protection dampers

Other ventilation dampers can also be activated to prevent the spread of smoke. Smoke protection dampers are quite common, but not standardised in Europe. Smoke protection dampers are cut-off devices to prevent smoke from being spread through ventilation ducts. Usually they are designed as tight-sealing, multi-leaf dampers. As a rule, they cover larger cross-sections than fire dampers, for instance. They are equipped with a spring return actuator,
which is controlled by a smoke-based activation device. But smoke protection dampers are not designed, or certified, for high temperatures. Therefore, they cannot be used to function as fire dampers or smoke control dampers. Conversely, however, fire dampers can function like smoke protection dampers if they are equipped with a smoke-based activation option.

11.4 Functional integrity

Functional integrity is a term mainly applied to electrical circuit systems. This means that safety devices required under building regulations must remain functional over a sufficiently long period of time when being affected by an external fire and also in interaction with other technical systems.

The duration of functional integrity is frequently regulated in a generalised manner.

Thus, as a rule, mechanical smoke control systems and smoke control by pressurisation systems are subject to 90 minutes of functional integrity; fire control with respect to passenger lifts and fire alarm systems, 30 minutes.

In many cases, these requirements may be reduced without any loss of safety.

Smoke control dampers of the MA operating mode, for example, can be wired in E30, because their actuators have to remain functional only for up to 25 minutes after the outbreak of a fire (Standard temperature / time curve). Smoke control dampers of the AA operating mode can be connected without functional integrity, because they are triggered by smoke detectors and because it is ensured that the smoke control dampers have assumed their safety position before electrical circuits fail.

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**Figure 55. Example of wiring from VDMA 24200-1.**

1. Fire protection damper.
2. Smoke control damper.
3. Communication module with thermal protective housing.
4. Communication module without thermal protective housing.
5. Damper actuator without thermal protective housing.
6. Damper actuator with thermal protective housing.
The functional integrity requirement will depend on the damper with the higher requirement, that is, as a rule, on the smoke control damper, where fire protection and smoke control dampers are developed via one supply line. On the assumption that a fire always breaks out in only one area, setup with functional integrity in the respective area to be desmoked will be sufficient.

11.5 Functional safety

Functional safety is the part of overall safety that depends on the system delivering correct responses to its input state (cf. EN 61508 Part 1, 2005, p. 7). According to EN 61508 Part 1, two types of requirements must be met to achieve functional safety. On the one hand, this involves requirements concerning the safety function itself, derived from a risk analysis (e.g., the smoke control damper must open within a defined amount of time after a fire has been detected). On the other hand, there are requirements regarding safety integrity, that is, the probability of a function being executed satisfactorily. This is done on the basis of a risk assessment.

**Figure 56** shows the failure tolerances for a safety function that is operated at a low demand rate (low-demand systems), thus indicating that a fire occurs rarely. System-based fire protection is generally subject to SIL requirements of up to SIL-2. A SIL-2 requirement means that it is accepted that the system (e.g., smoke control system) fails once in one hundred to one thousand fire events.

<table>
<thead>
<tr>
<th>Safety integrity level</th>
<th>Operating mode with low demand rate (average probability of failure of the planned function upon demand)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>( \geq 10^{-4} ) to ( &lt; 10^{-3} )</td>
</tr>
<tr>
<td>3</td>
<td>( \geq 10^{-5} ) to ( &lt; 10^{-4} )</td>
</tr>
<tr>
<td>2</td>
<td>( \geq 10^{-6} ) to ( &lt; 10^{-5} )</td>
</tr>
<tr>
<td>1</td>
<td>( \geq 10^{-7} ) to ( &lt; 10^{-6} )</td>
</tr>
</tbody>
</table>

**Figure 56.** Safety integrity levels with probabilities of failure at a low demand rate.

**Figure 57** shows an example of a risk graph for determining the requirements regarding the functional safety of a system.

SIL (Safety Integrity Levels) can be derived directly from the risk graph shown. They represent the accepted probability of failure of the system in an actual event (here: fire).

**Figure 57.** Example of a risk graph. C. Extent of damage in the event of failure. F. Stay parameter. P. Emergency response. W. Probability of occurrence.
11.6 Conventional and bus control

Components for controlling the smoke control system can be activated and controlled conventionally or by means of bus systems.

Often conventional control refers to the radial wiring from the source (e.g., control cabinet) to the drain (e.g., smoke control damper). The switching on or switching off of the supply voltage generates an activation command. The respective damper positions are also signalled via separate electrical circuits.

Conventional control is increasingly being replaced by bus control, especially where a larger number of components to be activated is concerned. This requires that the components to be activated can be addressed. As a rule, a free wiring topology is now possible. This lowers the wiring costs drastically, reduces fire loads and often allows for the uncomplicated transmission of additional component parameters. As a result, system safety is improved, and it also allows for conclusions to be drawn about necessary maintenance work. At the same time, the transmission paths are monitored.

Figure 58. Conventional control and activation (principle). Source: VDMA 24200-1.

Figure 59. Control in bus technology (principle). Source: VDMA 24200-1.
12 Acceptance and recurring inspections

12.1 Individual inspections

12.1.1 Inspection of documents provided

Concerning systems subject to inspection, the documents created and to be provided must be inspected in accordance with the ‘four-eye principle’. The following main points must be considered as well as inspected for mutual consistency and their actual implementation on site:

- Approval documents listing the protection objectives and fire protection certificates
- System-specific dimensioning in consideration of the aforementioned protection objectives
- Plans and diagrams of the planned systems, including essential boundary conditions regarding systems’ effectiveness
- Functional descriptions of the systems implemented
- Commissioning documents and measurement reports of the installers
- Documents regarding building automation
- Maintenance certificates and maintenance cycles for the planned systems

12.1.2 Inspection of mechanical smoke control systems (SHEVS)

When inspecting individual systems, SHEVS in this case, it is necessary first to check the components of the system for consistency with the requirements under the approval documents. This means that consistency with the protection objectives must be determined on the basis of the documents submitted under Section 12.1.

Using the available assessment bases, one must check whether the planning and executing stakeholders have implemented the protection objectives in accordance with the building permits. This process involves risk analyses and safety concepts. It must be determined whether the essential requirement classes have been verified for all individual components of the system in the documents.

In the following, the smoke control fan must be inspected. The suitability of the installation site must also be assessed. Attention must be paid to the requirements regarding the fire resistance duration of components, closures and ducts as well as the prevention of third-party installations, fire loads, etc. The installation site is generally inspected by way of a plausibility check, because the person inspecting the system is generally not an expert for structural fire protection. This may require cooperation with those in charge of structural fire protection.

Furthermore, it is important to check that the smoke control fan does not pose a risk for other areas by spreading the fire. Where fans are set up in a building, one must ensure that secondary fires do not break out as a result of smoke spreading, particularly at discharge vents. The fans used must be appropriate for the intended application. In particular, it is necessary to check the type approvals on the smoke control fans. For example, compliance with the temperature class, thermal external protection and installation conditions must be given. The electric motor protection of a smoke control fan must be bridged in the event of a fire, so that the fan can continue operating for as long as the machine has not yet failed completely.
Functional tests must be conducted on the smoke control fan itself: direction of rotation, the functioning and locking of repair switches, as well as measurement of volume flows and power consumption. The measurement methods under EN 12599:2012 are to be applied in this case.

As for commissioning and acceptance measurements, measuring errors and deviations at the measuring point must be determined accurately so as to evaluate the measurement results. When measuring air volumes, it should be noted that air is measured in a cold state (ambient temperature). In other words, measurements are not taken in the rated operating state (hot smoke). This is why the target air volumes must be determined by calculation or simulation, always at a regular design temperature of 20°C. In assessing effectiveness, one must keep in mind that the measured air volumes are consistent with the required air volumes due to the temperature change in the course of an actual fire.

It is also important to note that many SHEVS require an emergency power supply. As a rule, the person inspecting mechanical smoke control systems does not have the necessary training for inspecting the emergency power supply. Therefore, a qualified inspector must be assigned to the inspection of the emergency power supply.

The inspection of SHEVS also involves inspections of smoke control ducts, smoke control dampers as well as smoke extraction, discharge (air release openings), supply air and fresh air vents. The proper distance between the discharge and fresh air vents must be checked to prevent smoke from being sucked in again.

There is now a distinction between smoke control ducts that can be used within a fire compartment and those used outside a fire compartment. Smoke control ducts outside a fire compartment must meet a classification requirement, because they are supposed to prevent secondary fires as they transport smoke through the building to be protected.

Smoke control dampers must be inspected, in particular, to verify that their installation within the system is consistent with the respective type approval. In this case, one must distinguish between smoke control dampers with automatic activation (AA) or manual activation (MA).

It is important that the inspector conducts an individual assessment based on the system concept, given the different inspection criteria for smoke control dampers, to determine whether each damper is suitable for the intended application based on the smoke control concept. As a result, the inspector must be provided with the relevant certificates by those involved in performing and planning the work.

Smoke control dampers must also be inspected in full with respect to their installation in the smoke control duct. It is further recommended for practical reasons that smoke control dampers be inspected in full at regular intervals due to their importance to the building’s operation.

As far as the inspection of supply air is concerned, one must determine whether supply air is introduced into the fire compartment by means of natural supply air vents or mechanical systems (supply air systems). The use of overflow vents from other areas is also quite common, which must be inspected with particular care. In the case of mechanical air supply, one must ensure that air is introduced into the bottom part of the fire compartment without any draught to prevent the supply air from being mixed.
with smoke gases. But natural supply air or overflow vents must also comply with the planned limit values relative to size and the smoke extraction air volume. Clear compliance with the protection objectives of the SHEVS is generally required. An essential criterion of particular importance to the inspection of these system components is the specification regarding low-smoke layers.

The complete inspection of the system may require a smoke test on the basis of the known boundary conditions, such as fire load and temperature. An essential criterion in the inspection of the systems is the effectiveness and operational safety of the building automation and necessary activation controls, such as fire alarm systems.

12.1.3 Inspection of natural smoke ventilation systems (NSHEV)

When inspecting NSHEV systems, one must first determine whether a system is, indeed, intended for smoke extraction and whether it meets the criteria of such a system. Oftentimes, natural openings for smoke extraction are designated as NSHEV by those in charge of the execution, even though such openings do not meet the required criteria of such system.

In the case of NSHEV, this mainly concerns the size of discharge vents for smoke extraction and the size of supply air vents. As the inspection of supply air is concerned, along the lines of SHEVS, one must determine whether supply air is introduced into the fire compartment by means of natural supply air vents or mechanical systems (supply air systems). The inspection of the supply air inflow is as critical as it is for SHEVS when it comes to the arrangement of overflow vents and the draught-free introduction of air into the fire compartment. Any measurement of supply air volumes in connection with mechanical supply air systems is subject to the criteria for air volume measurement under EN 12599:2012 already mentioned in Section 12.1.2.

NSHEV systems also often require an emergency power supply.

12.1.4 Inspection of pressure differential systems (PDS)

Acceptance and inspection to determine the performance of PDS are carried out at the end of construction measures, because the building must be virtually complete at the time of the PDS acceptance. Moreover, safety systems like PDS must be inspected at regular intervals according to national and, perhaps, regional building and/or inspection regulations also during the building’s operation.

Prerequisites for conducting inspections

The following conditions must be met in order to conduct inspections on pressure differential systems in buildings:

• Operational readiness of all systems involved
• Pressure differential system(s) with all components
• Fire alarm system (where signals are transmitted)
• Emergency power supply (where pressure differential systems are supplied via emergency power)

Completion of the building with respect to the following details:

• Stairwell with all doors adjacent to it
• Installation and adjustment of doors, door seals and door closers
• Installation and activation of discharge vents and dampers through walls or ducts towards the building’s exterior (facade or roof)
• Installation of all components affecting pressure loss in the flow paths of the pressure ventilation systems (weather protection grilles, intake grilles, outlet grilles, dampers, vents, outlet hoods, etc.)
• Installation and activation of all overflow vents (with and without check valves)
• Submission of essential documents
• Building permit, construction certificate or other regulatory requirements regarding pressure ventilation
• Fire protection concept, PDS concept incl. control and regulation concept
• PDS system description with description of functions and regulation, pictorial and system schematic, performance data, maintenance documentation
• Building plans (floor plans and cross-sections of the building)

Conducting the inspection
The inspection consists of a visual, functional and performance inspection.

Visual inspection
• How and where is fresh-air intake realised?
• Can smoke be drawn in as well or not?
• Is the system equipped with a duct smoke detector in the intake?
• Which component of the pressure differential system is located where? (intake, dampers, ducts, fan(s), discharge (air release openings), pressure regulation, etc.)
• How and where have the systems been installed?
• Fan in the stairwell, in a separate, isolated room, in a basement room, in a utility room, in the underground car park or outside the building?
• Is fire protection ensured for systems and ducts?
• Ducts of 90 minutes quality where they intersect with other smoke or fire compartments?

• Fire protection for the site where fans are installed
• Overflow dampers with/without fire protection with/without check valve, with/without damper actuator?

Functional test
The extent of the functional test depends on the system’s complexity. This is why only a few examples of questions are provided here.

• Does the system start up properly upon activation?
• Activation through fire alarm system (FAS) (Triggered by fire alarm on each floor)
• Activation through detectors (smoke parameter or pushbutton) that are part of PDS
• Activation of each sensor to verify whether the system starts automatically
• If the system works in accordance with the system description (e.g., flushing phase at 100% fan capacity and 100% damper opening followed by pressure regulation, activation of discharge vents, activation of dampers, etc.)
• Does the smoke detector in the intake duct switch off the system and close the intake dampers?
• Does the system switch properly to emergency power if the mains power supply fails?
• Is the smoke extraction vent at the top of the stairwell released if pressure control fails?
• Are all activation events carried out properly? (specific floor-by-floor activation with air release on the floor affected by the fire, general activation of pressure control without floor-based air release, activation of ground floor system only, activation of all systems, etc.)
• Are the required discharge vents activated (e.g., in the case of control dependent on the direction of the wind)?
**Performance inspection**
The extent of acceptance inspections of pressure differential systems differs, depending on whether the inspection involves smaller buildings or high-rise buildings. A fire alarm is generally triggered on each of the floors in smaller buildings (up to approximately six floors), and the performance data will be recorded. For high-rise buildings, the full performance data will usually be measured only on three different levels.

However, the door-opening forces while the PDS is operating are checked at all escape doors on all floors between the accommodation and the stairwell exit in order to ensure that the stairwell remains accessible also outside the floor where the fire occurs. A fire alarm is triggered on the respective floor to check the performance data. The performance data will be checked under the required boundary conditions (closed/open exit door, closed/open door(s) outside the floor where the fire occurs, etc.).

**Pressure differences between protected area and unprotected area**
The pressure differential, for example, between the stairwell and/or lobby and accommodation is checked by means of a suitable and calibrated differential pressure sensor while the door leading to the unprotected area is closed (static system operation). The sign must be noted when measuring the pressure (higher pressure in the area to be protected).

**Door opening forces**
Door opening forces are measured by means of a suitable and calibrated scale, with the door being pushed towards the stairwell or pulled from the side facing the stairwell, at the centre of the door handle or at the door leaf around the door handle.

Random tests of door opening forces without operating PDS are recommended. The inspector should have relevant target values at hand and check for plausibility.

**Volume flow / flow velocity**
The flow velocity is determined as a mean value calculated from eight measuring points arranged across the open door cross-section. All doors between the area to be protected and the air release (usually away from the unprotected area) are opened fully and propped open. Alternatively, a suitable measuring device that calculates mean values automatically may be ‘waved’ back and forth in the door cross-section at a constant speed. The volume flow is determined from the mean velocity and the open door surface through which the flow passes.

**Time-based performance data**
Meeting the requirements regarding flow velocity or volume flow and door opening forces must not only be seen as a static parameter for all PDS systems. Instead, it is a time-critical factor relative to door movement and active control of the PDS. For example, if all other doors are open and the last door in the flow path between the stairwell and ambient is opened, as happens also when a person tries to escape, the volume flow will initially have to build and is not immediately available for pushing back any existing smoke. Similarly, upon closing the door, a higher excess pressure is created due to the operating state of the PDS, which results in increased door opening forces. Figure 60 shows a schematic of pressure and volume flow over time relative to the opening of a door.

The time of volume flow development \( \Delta t_v \) and/or pressure reduction \( \Delta t_c \) upon completion of the door movement are also specified for pressure differential systems pursuant to EN 12101-6\(^{19} \) and must also be
verified when inspecting the performance data in the completed building.

Figure 60. Pressure and volume flow over time relative to the opening of a door.

where

\[ \dot{V}_{\text{min}} \] is the min. volume flow rate
\[ \Delta p_{100N} \] is the pressure difference at 100 N door open force
\[ \Delta p_c \] is the pressure difference at closed door
\[ \Delta p_o \] is the pressure difference at opened door
\[ \Delta t_o \] is the time to reach min. volume flow rate
\[ \Delta t_c \] is the time to reach pressure difference at 100 N door open force

**Evaluation of results**

- Evaluation of the boundary conditions (meteorological conditions, conditions inside the building, such as ventilation systems, etc.) based on performance data identified
- List of deficiencies (missing door closers, door opening forces that are too high due to closer or insufficient door adjustments, etc.)

**Final assessment on:**

- Requirements met yes/no
- Follow-up inspection necessary yes/no

12.2 Interaction test, integrated system test

Modern, complex structures are characterised by their mixed use and size as well as by their being equipped with a variety of safety systems. There are two situations where a building’s full functionality must be ensured:

- its regular utilisation and the safety function under building regulations.

People are at the centre of a building’s use. They must feel comfortable and safe within it. This requires appropriate fire protection concepts and a related fire control matrix to implement the protection objectives specified in approval documents and regulations. Various European countries have their specific regulations regarding such inspections.

These involve tests that are variously known as integrated system test or interaction test.

The integrated system test goes far beyond the fire protection requirements of systems subject to inspection.

**Documentation**

The inspection documentation must contain at least the following:

- Building and system designations
- Date, time period and type of inspection conducted
- Specification of the required performance data
- System condition
- Meteorological environmental conditions during the inspections (exterior temperature, direction and amount of wind, information regarding the sun, rain, snow, etc.)
- Specification of all performance data obtained (actual data)
- Comparison of target and actual data
The interaction test checks safety-related systems for ensuring fire protection; these systems are subject to inspection. Inspections in connection with integrated system tests or interaction tests are conducted in accordance with various test conditions. One such special test condition is the full disconnection of the object from general power supply. With this boundary condition in place, the functions of the individual technical systems already inspected must be effective and reliable in terms of operation when interacting with each other. There may be special scenarios where the system must be fully operational both during a power failure and during power recovery.

Planning involves the identification of sources that generate an alarm, such as fire alarms, fire-extinguishing systems and similar fire-detecting components. As a further step in the process, so-called drains are identified. These are generally technical systems that must be activated/controlled and that must be able to carry out their assigned tasks in the event of a fire (such as PDS, SHEVS and NSHEV).

As part of the planning actions, the possible sources whose activation is to result in identical activation patterns are combined, and the required activation pattern of individual technical systems (drains) is determined. In their functions and operations, the systems must not have adverse effects on the protection objectives of any other systems affected. This is an essential criterion for conducting an interaction test.

The group of sources is called the test group that activates the same activation pattern in the drains, and this interaction is referred to as the activation scenario. In preparation of an integrated system test or interaction test, the respective test scenarios are determined from the different activation scenarios. This means that a specific source (such as a fire alarm) is identified to activate a complete activation scenario. This is what is known as the ‘test scenario’. The tester of the integrated system test or interaction test must specify for different test scenarios the test conditions under which tests are to be carried out. Test conditions may specify energy supply through mains power supply, through emergency power supply or a so-called ‘black circuit’ (for a black building test) during the testing and similar boundary conditions.

An express recommendation for the integrated system test and interaction test is that the testers who have inspected individual systems be involved in the interaction test.

### 12.3 Operation and maintenance procedures

Generally, a sound fire protection concept contains appropriate elements from all three fire protection systems.

Depending on the specific project, these are organisational and technical fire protection measures, in addition to the architectural ones.

The fire protection concept forms the foundation for ensuring that the structure is designed and built in a manner that, in the event of a fire:
- The load capacity of the building is maintained for a specified amount of time;
- The development and spread of fire and smoke in the building is limited;
- The spread of fire to adjacent buildings is limited;
- The occupants of the building are able to leave it or can be rescued by other measures without injury;
- The safety of the rescue teams is taken into account.
These goals can only be ensured for the entirety of the use phase if there is due attention paid to professional maintenance of the building.

It is assumed that only components (construction products) and systems that were developed for the specific application are selected and installed in accordance with the concept.

The functions should be inspected on a regular basis and the results documented once facilities have been commissioned successfully with all required, integral tests and an initial acceptance performed, which is generally required by local authorities. The manufacturer / supplier of the component needs to describe the type of inspection and how it is performed in their document. It should also include the intervals for functional testing.

The system should be inspected again after changes, expansions or conversions have been made.

Any defects detected need to be corrected as soon as possible. And in the meantime, there should be effective compensating measures taken with the same protection goals. Often, an appropriate solution is organisational measures.

The owner/operator of the building is in charge of making sure that the measures taken (technical systems, organisational instructions, etc.) are functional and effective over the long term.

12.4 Hot smoke tests

Hot smoke tests are generally used for the following:

- Documenting the fire detection time
- Verification of functionality and correct interaction of all safety devices involved in smoke control in the event of a fire
- Determining and assessing the spread of smoke under various fire conditions (low-smoke layers, smoke flows, targeted smoke control and smoke extraction, visibility on escape routes, fresh air supply, etc.) for the purpose of evaluating the effectiveness of smoke control measures
- Familiarising fire brigade, emergency personnel and operating personnel with fire events and their consequences

12.4.1 Protection objectives

The protection objectives and performance characteristics of smoke control systems are specified by the fire protection concept, the smoke management concept and regulatory provisions to evaluate the results of hot smoke tests. The methods employed in carrying out hot smoke tests must be appropriate to meet the respective requirements regarding proof (functional check, qualitative assessment or quantitative assessment of effectiveness).

12.4.2 Requirements concerning hot smoke test method

As extensive studies have shown, the method employed in carrying out hot smoke tests for the purpose of assessing smoke management measures must be capable of simulating the typical characteristics of an actual fire (generally also ‘design fire’ regarding proof of smoke control). As such, a realistic simulation of the smoke gas plume is of primary importance. The hot fire gases rising above the source of the fire create a highly turbulent convection air flow in the shape of a plume. The production rate of the smoke gas volume flow essentially depends on the fire intensity and the flow length, i.e., on the height of the
smoke gases measured from the source of the fire to the bottom smoke layer boundary and/or ceiling height. The fire intensity, for its part, determines the smoke gas temperature and, in the event of a fire, is derived from the heat release per surface, the so-called specific heat release rate and the speed at which the fire spreads, resulting in the fire development coefficient. Both the heat release and the burn area change in the course of the fire and are thus time-based parameters. Furthermore, the burn area defines the boundary surface of the smoke plume, where friction causes ambient air to be mixed into the plume, and thus also the total smoke volume and smoke temperature that reach the bottom boundary of the smoke layer. Therefore, hot smoke tests are not only conducted, for example, in accordance with VDI 6019-1.

As for quantitative tests of smoke layers and the spread of smoke, the hot smoke tests can often be carried out only with significantly less heat release than is the case for the fire scenarios underlying the design due to spatial conditions. Apart from the requirements under VDI 6019-1 for acceptance-related fire tests, the various physical modes of action of smoke extraction will then have to be taken into account for the different smoke extraction methods. Since mechanical smoke control systems always convey almost the same volume flow regardless of the smoke gas temperature, assessing the effectiveness of the smoke control system requires that in hot smoke tests for acceptance, it is always the same smoke gas volume that is introduced into the smoke layer that would also be introduced by the design hostile fire. If the smoke gas volume flow of the acceptance fire test is significantly smaller (e.g., design fire 1 000 kW and acceptance fire 100 kW), the discharged volume flow of the mechanical smoke control system, prior to the fire tests, must be reduced by the same ratio as that between the volume flow generated by the acceptance fire and the volume flow generated by the design fire. It must be noted in this context that the key physical parameter is the smoke gas volume flow and not the smoke gas volume flow introduced into the smoke layer. Alternatively, scaling calculations must be worked out prior to the hot smoke tests in order to be able to perform a comparative assessment of the height of the low-smoke layer obtained over time in the applied hot smoke test with a deviating level of heat release in proportion to the design fire.

Since the natural smoke / air release exhibits other mechanisms – the smoke / air release in this case is generally characterised not only by the smoke exhaust vent surface, but also by the smoke layer thickness and smoke gas temperature as well as the pressure loss due to the reflow – the effects of hot smoke tests with reduced heat release rates are also different. In other words, if an acceptance fire generates less smoke gas as a result of less heat release (in the above example, acceptance fire 100 kW, design fire 1 000 kW), with the smoke gas being heated to a substantially smaller extent due to a heat output that is smaller by a factor of ten, the results of the acceptance fire tests must be corrected through computational fire protection engineering methods (e.g., simulation calculations) in order to be able to evaluate the smoke layer thickness and height of the low-smoke layer created in the actual design fire. Only then can a statement be made as to whether the protection objectives have been achieved through the hot smoke tests with reduced heat release rates.

One must add to the above factors a third mechanism that must account for the particles introduced into the smoke layer
relative to the particles created in the hostile fire where smoke volumes are introduced into the low-smoke layers in the area of the escape routes to be protected that necessitate an assessment of visibility (also see Section 3.1).

Thus, hot smoke tests should be conducted in such a way that the fire scenarios that underlie the design of smoke control systems are implemented as accurately as possible upon acceptance. Heat release rates may be limited by the reaching of maximum allowable temperatures in the smoke layer so as not to damage the technical devices in the building.

Externally generated white fog is generally added to the smoke gas plume for the purpose of making it visible and also detectable through optical means. The fog fluid used should not contain any toxic substances so as not to pose a health risk to the observing personnel, nor should it cause precipitation, such as on valuable surfaces.

12.4.3 Extent of measurement and observation

During the hot smoke tests, the temperature of the rising smoke gases should be monitored, while checking and controlling heat release in such a manner that critical temperatures are not exceeded at the structure or the technical devices. Heat release, particle release, smoke layer development, temperatures, spread of smoke and, if necessary, visibility must be recorded and documented in a time-based manner during the hot smoke test.

Visibility on escape routes should be measured and assessed, at least visually, for example, with respect to the escape route signs. This should be documented by way of photos and videos.

For documentation purposes, video cameras should be placed at multiple locations to record the progression of the fire and spread of smoke. A report on the hot smoke tests should be prepared that contains at least the following information:

- Description of the smoke control system assessed
- Requirements under the fire protection and/or smoke management concept
- Regulatory and/or building law requirements
- Protection objectives and performance characteristics of smoke control systems to be assessed
- Description of the hot smoke test method employed
- Assessment of design fire
- Documentation of the completed fire test showing the development of heat release, smoke production and particle release over the testing period
- Documentation of the boundary conditions within (e.g., ventilation systems, compartments, etc.) and outside the building (e.g., direction and amount of wind, temperature, etc.) during the hot smoke test
- Documentation of control processes during the hot smoke test
- Documentation of the spread of smoke (by way of photos, videos, descriptions, etc.), temperatures, height of low-smoke layer, visibility, factors influencing the smoke layer, etc. in a time-based fashion over the testing period
- Assessments regarding the function chain, effectiveness of the smoke control system, compliance with protection objectives and requirements
Annex 1. Pressure differential systems (PDS) – additional information

Pressure differential systems (PDS) are installed to prevent the inflow of smoke in safety staircases, their lobbies as well as in fire-brigade lift shafts and their lobbies.

The typical spread of smoke across lobby doors, which connect the corridor of a floor of origin to a stairwell, is shown in Figure 61. In the upper door area, smoke flows from the corridor into the stairwell, while air from the stairwell is conveyed to the corridor at floor level. This is caused by the temperature difference between the two room areas. The intensity of such exchange flow increases as the temperature differential rises. The mean flow speed of the smoke in the door cross-section can be estimated by

\[
\bar{u}_R = 1.98 \sqrt{h_T \left(1 - \frac{T_V}{T_F}\right)}
\]

(84)

where

- \(\bar{u}_R\) is the mean flow speed of the smoke in m/s in the door cross-section,
- \(h_T\) is the clear door height in m
- \(T_F\) is the mean temperature in K in the corridor,
- \(T_V\) is the mean temperature in K in the lobby.

Figure 61. Spreading of smoke from a floor into the stairwell with open lobby doors, without PDS (schematic outline). ① Stairwell; ② Lobby (airlock); ③ Corridor (Accommodation).
Figure 62 shows the evaluation of (84) for different door heights.

A PDS prevents the inflow of smoke into the stairwell by creating a blocking flow in the door cross-sections. As part of the process, a fan conveys air to the stairwell that flows on through the lobby to the corridor when the lobby doors on the floor are open.

The flow speed \( u_{\text{Block}} \) of such blocking flow must assume values that are greater than the mean outflow speed of the smoke, determined according to Figure 62, so that the smoke can be effectively prevented from entering the stairwell.

The floor must have an outflow to the outside to maintain the blocking flow created by the PDS.

The blocking-air volume flow that must be conveyed through a lobby on the floor (with the doors open) depends on the existing door cross-sections. It results from

\[
\dot{V}_{\text{Block}} = u_{\text{Block}} \cdot b_T \cdot h_T
\]  
(85)

Where

- \( u_{\text{Block}} \) is the mean speed of the blocking flow in the area of the door cross-sections in m/s;
- the condition \( u_{\text{Block}} \geq \bar{u}_R \) with \( \bar{u}_R \) operates according to Equation (84);
- \( b_T \) is the clear door width in m
- \( h_T \) is the clear door height in m

This is the minimum air flow that the PDS fan must convey to the stairwell. To this one must add a differential volume flow that is lost through leaks in the building and cannot be utilised for the flow of air of the floor.

Figure 62. Mean flow speed of the smoke in door cross-sections.

Figure 63. Smoke control by pressurization system for a stairwell (principle).
Typical leaks include cracks or gaps in the design of the external facade, as well as joints of doors and windows. The determination of the total leakage volume flow is described in standard EN 12101 Part 6. It also contains tables showing reference values for the air leak rates of individual components, such as walls, ceilings, windows and doors (cf. Figure 64).

The primary leaks of a stairwell are the lobby doors of all floors as well as the door leading outside, which must usually be smoke-shielding and self-closing. There are generally standard requirements regarding the tightness of such doors. These allow for air leak rates from approximately 20 m³/h to 30 m³/h with a differential pressure of 50 Pa. The leak rates to be expected in real installation situations, however, may assume much higher values (cf. Figure 65).

When determining the air leak flows, one must take into account, regarding the exit door, that it may be open.

The air conveyed into the stairwell by the PDS fan, if the lobby doors on the floor are closed, must be discharged via a pressure relief unit, so that the pressure in the stairwell remains limited to a value that allows for the lobby doors to be opened by persons escaping from the respective floor. A useful parameter for evaluating the pressure is the required door opening force $F_T$.

In general, this is subject to a limit value of $F_{T,\text{max}} = 100$ N. Regarding Figure 66, the door opening force results from an equilibrium of moments around the door hinge from

$$ F_T = \frac{F_P b_1 + C_S}{b_2} \quad (86) $$
where
\[ F_p \] is the force on the door leaf produced by the differential pressure between the lobby and floor in N
\[ b_1 \] is the distance between the hinge and point of application of the force \( F_p \) in m
\[ C_S \] is the self-aligning torque of the door closer in Nm
\[ b_2 \] is the distance between the hinge and point of application of the door opening force \( F_T \) (door handle centre) in m

\[ F_p = (p_V - p_F)b_T h_T = \Delta p b_T h_T. \quad (87) \]

And the combination of Equations (86) and (87) yields the differential pressure following a slight transformation

\[ \Delta p = \frac{F_T b_2 - C_S}{b_T h_T b_1}. \quad (88) \]

The maximum allowable differential pressure \( \Delta p_{\text{max}} \) between the lobby and the floor finally results when the allowable limit value \( F_{T,\text{max}} \) is used for \( F_T \). According to an initial estimate, where \( b_1 = b_T/2 \) and \( b_2 = b_T \) are set,

\[ \Delta p_{\text{max}} = \frac{2}{b_T h_T} \left( F_{T,\text{max}} - \frac{C_S}{b_T} \right). \quad (89) \]

Among other things, the allowable differential pressure is essentially dependent on the self-aligning torque of the door closer. Such door closers have been classified in seven sizes in EN 1154. The classes are used to assign to different door sizes the required opening and closing forces (cf. Table 4).

**Table 4. Closing and opening forces of door closers pursuant to EN 1154 (excerpt).**

<table>
<thead>
<tr>
<th>Door closer parameter</th>
<th>Recommended door leaf width</th>
<th>Closing force between 0° to 4°</th>
<th>Opening force between 0° to 60°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mm)</td>
<td>min. (Nm)</td>
<td>max. (Nm)</td>
</tr>
<tr>
<td>1</td>
<td>750</td>
<td>9</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>850</td>
<td>13</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>950</td>
<td>18</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>1100</td>
<td>26</td>
<td>37</td>
</tr>
<tr>
<td>5</td>
<td>1250</td>
<td>37</td>
<td>54</td>
</tr>
<tr>
<td>6</td>
<td>1400</td>
<td>54</td>
<td>87</td>
</tr>
<tr>
<td>7</td>
<td>1600</td>
<td>87</td>
<td>140</td>
</tr>
</tbody>
</table>

**Figure 66. Balance of forces when determining the door opening force.**
If these values in Equation (89) are taken into account, the condition described in Figure 67 will apply to the maximum allowable differential pressure rates across lobby doors.

Pressure relief units have as their central element a damper equipped with a spring system or powered by a pressure-controlled actuator. This damper opens if the pressure in the stairwell rises above a set limit value upon closing of the lobby doors and then aligns the volume flow that passes through it to such limit value. The damper closes if the pre-pressure in the stairwell drops below the limit value upon opening the lobby doors on the respective floor.

The pressure constellations in a stairwell can be controlled by the pressure relief unit. However, they also depend on the climatic environmental conditions as well as on the geometry of the stairwell.

As concerns the geometry of the stairwell, it bears mentioning that the air flow through the stairwell causes pressure losses that, in this case, can be described formally by

\[ \Delta p_{TR} = \zeta'_{TR} \bar{V}_{TR}^2 \]  \hspace{1cm} (90)

where

- \( \Delta p_{TR} \) is the pressure loss that occurs in Pa as the air flow passes through the stairwell or a section of the stairwell
- \( \zeta'_{TR} \) is the pressure loss rate in Pa s²/m⁶
- \( \bar{V}_{TR} \) is the volume flow that passes through the stairwell and/or the section of the stairwell observed in m³/s

The pressure loss rate \( \zeta'_{TR} \) in Equation (90) is essentially co-determined by the geometric conditions within the stairwell.

As a result of the pressure loss, the differential pressure between the stairwell and the external environment depends on the vertical position. The resulting pressure gradient in a stairwell with isothermal conditions \( (T_{TR} = T_{\infty}) \) is shown in Figure 68.
The figure shows the supply air flow $\dot{V}_{ZU}$ being routed to the stairwell’s base area by the PDS. When the lobby doors of the respective floor are closed, and assuming that there are no leaks in the stairwell, $\dot{V}_{AB} = \dot{V}_{ZU}$ applies to the outflowing air flow above the pressure relief unit.

As a result of the pressure loss caused by the air flow passing through the stairwell from position ① to position ②, the pressure at the stairwell base is higher than in the stairwell’s upper section. Therefore, this results in differing values for the differential pressure via the lobby doors of two floors at different heights – in Figure 68 they are floors A and B with the differential pressures $\Delta p_A = p_A - p_\infty$ and $\Delta p_B = p_B - p_\infty$.

Since these differences in pressure increase towards the stairwell base, the required door opening forces also increase in the same direction (cf. Equation (90)), which means that the maximum allowable force $F_{T,max}$ may be exceeded.

To counter this fact, it makes sense, especially for taller buildings, to introduce supply air through several points, distributed across the height of the stairwell.

**Figure 68.** Pressure gradient in a stairwell when operating a PDS, neglecting any leakage losses (isothermal conditions).
The resulting pressure gradient is shown, by way of an example, in Figure 69: two supply air vents are used in this case, with each one conveying half of the total volume flow into the stairwell.

Since the supply air flow transported through the bottom part of the stairwell is diminished, so is the resulting pressure loss in this area (cf. Equation (90)). This is why the differential pressure $\Delta p_A$ via the lobby doors of floor A near the area of the stairwell also decreases compared to the situation represented in Figure 68.

The pressure gradients in a stairwell previously discussed were based on the assumption of isothermal conditions, i.e., $T_{TR} = T_\infty$.

In the case of $T_{ST} \neq T_\infty$, however, an additional pressure component must be taken into account that results from the temperature dependency of density. Figure 70 shows a typical gradient of the stairwell pressure in winter ($T_{TR} > T_\infty$), with the other conditions from Figure 69.

---

**Figure 69.** Pressure gradient in a stairwell when operating a PDS with two blow-in vents, neglecting any leakage losses (isothermal conditions).
The higher temperature in the stairwell causes the density $\rho_{TR}$ of the air in the stairwell to be lower than the density $\rho_\infty$ of the ambient air.

This difference in density results in a (geodetic) differential pressure that is superimposed on the pressure gradient that occurs under isothermal conditions in the stairwell.

The smaller density (in winter) in the stairwell is the reason why the geodetic pressure $\rho_{TR} g (z_2 - z_1)$ increases less from the stairwell’s upper section (point 2) towards the stairwell base (point 1) than does the corresponding ambient pressure $\rho_\infty g (z_2 - z_1)$.

With sufficiently substantial temperature differentials, this may cause the pressure in the lower section of the stairwell to drop below the ambient pressure. Consequently, differential pressure relative to a floor (A) in this area will then become negative. Smoke may penetrate the stairwell if the lobby doors on that floor are opened.

Figure 70. Pressure gradient in a stairwell when operating a PDS with two blow-in vents, neglecting any leakage losses (winter situation: $T_{TR} > T_\infty$).
One action to shift pressure in the stairwell to values that are above ambient pressure everywhere is to raise the pressure loss that is created when the air flow passes through the stairwell. The following applies to such pressure loss:

\[
\Delta p_{TR} = \zeta_{TR} \frac{\rho_{TR} u_{TR}^2}{2} = \zeta_{TR} \frac{\rho_{TR}}{2} \left( \frac{\dot{V}_{TR}}{A_{TR}} \right)^2
\]

(91)

where

- \( \zeta_{TR} \) is the pressure loss coefficient of the stairwell
- \( \rho_{TR} \) is the density of air in the stairwell in kg/m³
- \( u_{TR} \) is the mean air flow speed in m/s
- \( \dot{V}_{TR} \) is the volume flow in m³/s that is conveyed through the stairwell or a section of the stairwell
- \( A_{TR} \) is the floor space of the stairwell in m²

The pressure loss \( \Delta p_{TR} \) can be influenced by the pressure differential system by varying the air flow speed \( u_{TR} \).

During winter it makes sense to use at first the blow-in vents in the stairwell for air supply, which are primarily found at the stairwell base. It may also be necessary to increase the volume flow conveyed by the pressure differential system.

The situations described for winter also apply in reverse to summer (\( T_{TR} < T_\infty \)). In this case, it may be necessary to feed in supply air in the upper section of the stairwell. A pressure relief unit at the stairwell base may also be helpful.

The facts discussed show that a pressure differential system may have to be controlled relative to the temperature differential \( \Delta T = T_\infty - T_{TR} \) with respect to its volume flow and the supply air position(s) in the stairwell. The probability for this increases as the height of the stairwell increases.

Regarding the pressure loss coefficient \( \zeta_{TR} \) occurring in connection with equation (91), initial measurements taken by Ostertag et al. are available that were obtained by means of model experiments.

During these experiments, the stair width \( b_{Stair} = 1.25 \text{ m}, 1.5 \text{ m} \), the width of the stairwell \( b_{Well} \leq 0.55 \text{ m} \), the floor height \( h_{Floor} = 2.8 \text{ m}, 4.2 \text{ m} \) and the blockage ratio of the railings \( 0\%…100\% \) varied.

To represent the results, an effective surface \( A_{eff} = A_{TR}/\sqrt{\zeta_{TR}} \) has been defined that varies in the range \( 2 \text{ m}^2 < A_{eff} < 4 \text{ m}^2 \) under the aforementioned general conditions.

Apart from the pressure distribution in the stairwell when the lobby doors are closed, one must also consider the pressure gradient when the lobby doors are open. In particular, the pressure loss created when the blocking-air volume flow pursuant to Equation (85) passes through the floor must be smaller than the differential pressure between the stairwell and the environment when the lobby doors are closed.

The total pressure loss when the air flow passes through the floor is also substantially determined by the pressure loss and the surface of the discharge to the outside. This surface must be of adequate size in dimensioning the system. One must also ensure, as concerns its positioning, that the function of the pressure differential system is not impacted negatively by any wind factor. Facade sections where a lot of dynamic
pressure may occur are not suited for the positioning of discharge surfaces.

Given the varied number of factors that can affect pressure conditions in stairwells, it is recommended that the pressure differential system especially for very tall buildings should be dimensioned on the basis of computational fluid dynamics (CFD).
Annex 2. Pedestrian flow movement during fire evacuation

General principal of travel speed analysis

The main indicator of motional activity of a crowd moving simultaneously on the same route in the same direction as its reaction to the conditions of the environment is the speed of the human flow. It is well-known that the velocity of the human flow \( V \) depends on the type of routes \( j \), the density of flow \( D \) and the level of emotional state \( e \). In other words, the velocity is the function of these factors and its value at the i section of the route can be represented as \( V_{j,Di}^e \). The purpose of the field observations and these experiments is to establish the relation between the human flow velocity and other multiple factors. The flow velocity is defined by the mean values of individual travel speed \( V_n \) of \( N \) people moving on a particular section of route, i.e.:

\[
V_{j,Di}^e = \frac{\sum_{n=1}^{n} V_n}{N}
\]  

(92)

More than seventy series of observations of human flow in various types of buildings on the different route types (horizontal, door openings, stairs ascent and descent) were carried out and special experiments were conducted at the beginning of the 1980s in Russia. These results are shown in Figure 71, Figure 72 and Figure 73. The total number of values of ‘the travel speed – the density’ was about 25,000.

All this data as well as similar data found in foreign studies and known in Russia by that time Figure 74 was dispersed in numerous literary publications and scientific reports and was never analysed side-by-side. The need to analyse it together arose due to the development of the State Building Code at the end of the 1970s – ‘SNiP II-2-80 Fire Safety of Buildings and Structures’. They prescribed to establish estimated relations between characteristics of human flows for each route type for forecasting human flow movement during evacuations in new buildings.

Figure 71. Empirical relationships between travel speed of human flow and density, which were obtained at the end of the 1970s (horizontal plane). Type of buildings: 1, 5) Theatres, cinemas; 2) Universities; 3) Industrial; 4, 13, 14) Transport structures; 6) Sports; 7) Other; 8) Trade; 9) Schools: senior group; 10) Schools: middle group; 11) Schools: young group; Streets: 12) Shopping street; 15, 16, 18) transport junction; 19) Industrial units; 20, 21) Underground stations; 22, 23) Experiment.
Empirical relationships between travel speed of human flow and density, which were obtained at the end of the 1970s (stairs downwards). Type of buildings: 1) Multipurpose; 2, 3) Sports; 4) Universities; 5) Schools: middle group; 6) Schools: young group; 7, 8) Streets: transport junction.

The multitude of empirical relationships $V_{j,D} = \varphi(D)$ for each route type provoked an attempt to try and unite them. As the sample of observable values $V_n$ in each density interval was known for each series of field observations, that is why numeral characteristics of distributions for the respective sampling population were defined for each of them: the mean value $m(V_{j,D})$ and the dispersion $S^2_{V_D}$.

The nature of empirical distributions is illustrated by the bar charts given in Figure 75.

The presence of all those characteristics gives an opportunity, based on the statistical analysis, to unite various series to a general sample. According to the methodology of mathematical statistics, to achieve this purpose they have to be homogeneous, i.e., they should not have significant differences in mean values and dispersions at all the density intervals.

The given analysis in general does not provide any basis for the correct unifying of statistical data of separate series to establish general relationship $V_{j,D} = \varphi(D)$. Meanwhile, even a quick look at the charts showing empirical relations is enough to understand that they illustrate the general tendency of a change in the velocity of human flow movement when its density is increased. Here we clearly have ‘a feeling’ that there is a certain ‘inner law paving its way through the randomness and regulating it’.

This figurative expression helps enable better understanding that each series of field observations and experiments is one of isolated cases of a random process manifestation; that is a human flow by its nature. Consequently, a mathematical expression of relations between its parameters should be sought for in the class of random rather than determinate functions.
Figure 74. Relationship between travel speed of human flow and density according to international authors’ data (numbers on the curves correspond to the references on the right part of the picture).

Figure 75. Histograms and polynomial distributions of travel speed value in various density intervals on horizontal route (dot line – median, solid line – mean values).

Such an understanding of a process and the required form for its mathematical description leads to an understanding that there is a need for a change in the methodology of processing empirical data. The essence of this changes can be expressed briefly in terms of the theory of probability and mathematical statistics: ‘It is pointless to hunt after the equations that would give exact equality for each pair of numbers \((X_i, Y_i)\). The later mistake is what most experimenters are apt to commit – having plotted several obtained points, they take as a graph of \(y\) against \(x\) a smooth curve passing through those plotted points! Thus, the method of interpolation from the given points cannot be applied in the theory of random values\(^{29}\). Such method with its ‘preciseness’, in fact, ‘tones down’ the expression of the desired ‘inner law’ manifesting itself though accidents. The mathematical formula that we fit to approximate empirical data ‘only then gets a real value when it is adequate to the inner relations between the inner phenomena or at least expresses those relations with a sufficient degree of approximation. That is why, when plotting a regression line, a researcher should clearly see the inner relations that can determine the relationship in this precise form\(^{30}\).

None of the studies describing the movement of people in a flow succeeds in finding ‘the inner relations’ that can determine the relation between the velocity and density of human flow in the form of mathematical expression. At best we can observe some attempts\(^{31}\) to take into account the influence of physical state of the people comprising the flow and their psychological state by way of calculating the empirical coefficient of ‘the flow composition’ and the conditions of movement. Those coefficients are calculated as the ratio of average values of flow velocity obtained during the series of observations to the average values
of velocity in the other series carried out earlier and taken for no clear reason as the main one. Apparently, this approach does not explain ‘the inner relations’ determining the nature of the relation between these parameters but just demonstrates the understanding of a need to somehow reflect their influence on the formation of the desired relations.

**An impact of flow density on travel speed**

An impact of random realisation of the movement process makes it difficult to identify underlying essence of relationship between parameters.

The fact that travel speed detected during all field observations is formed not only under the influence of density, but also as a result of the emotional and psychological state of the people have in the observed situation, for example, comfortable movement after the theatre play or increased activity during rush hour in the morning in the public transport. Consequently, the way to neutralise this factor should be found.

The classification of the movement of people during changing the flow density (Table 5 in accordance with 32) pointed to such capability.

The physical nature of different travel speed depends on two factors: the length of the step and the movement pace. The density of the flow from this point of view has an effect in that it deprives a pedestrian of a space necessary to walk with a full step. However, with a density of people in a flow about 1 pers/m², there is some space for walking with the full step but a person is proceeding with a speed less than the speed of free movement when there are no other people around. In this interval of density, the distance between people forced to decrease the speed of a person because it limits a person’s capacity to maneuver with an intention to overtake or avoid a collision with the other people. If, on the other hand, he decides to overtake a preceding person, he will have to either increase his speed significantly or conversely slow down abruptly to avoid a collision or go ahead, all this would provoke physical and psychological rebuff from the people around and will not be enjoyable for the overtaking person himself. It is apparent that the density of the flow is perceived by a person not only as the limitation of the physical space but as something more complex – a set of physical and psychological factors whose intensity of impact on a person increases as the flow density grows and it is not clear to what extent.

**Table 5. Classification of movement with increasing density of flow.**

<table>
<thead>
<tr>
<th>Density, persons/m²</th>
<th>Individual</th>
<th>Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–0,05</td>
<td>Free movement</td>
<td>Free movement in a flow</td>
</tr>
<tr>
<td>0,05–1,5</td>
<td>Without contacting obstacles</td>
<td>Without contacting obstacles</td>
</tr>
<tr>
<td>1,5–4</td>
<td>With force impact</td>
<td>With force impact</td>
</tr>
<tr>
<td>4–7</td>
<td>Body compression</td>
<td>Body compression</td>
</tr>
<tr>
<td>7–9</td>
<td>Body deformation</td>
<td>Body deformation</td>
</tr>
<tr>
<td>&gt; 9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The listed effects of human impacts that are associated with density changing show that density is a synthesising factor of different aspects of environment impact on people. Actually, it is impossible to determine the physical impact of this factor: whether – ‘the number of visible heads in front of’, or – invisible below the chest area of unoccupied way, whether – ‘something’ physical non-specific, which, however, identifies the certain physical reaction – changing travel speed in the flow. From this point of view, we can say that the density of human flow is relative, convenient for researchers, physical ‘carrier’ of complex psycho-physical environment effects.

The name itself ‘free individual movement’ suggests that in this interval the density \( (D_0) \) has no effect on travel speed. On the interval from 0 to \( D_0 \), the velocity of people in the flow \( (V_{j,0}) \) depends on a physical ability and emotional and psychological state, because ‘a person even without psychological pressure from others people infects with their behaviour submit and follows it’\(^\text{33} \).

This fairly obvious conclusion allows us to determine at least statistical tendency of density influence on travel speed, introducing \( \Delta V^e_{j,Di} \) that reflects travel speed changes in various density intervals:

\[
\Delta V^e_{j,Di} = V^e_{j,0} - V^e_{j,Di} \quad (93)
\]

Apparently, the absolute values of the variable \( \Delta V^e_{j,Di} \) depend on the emotional state of people and will differ in different series of field observations with the same values of flow density. In order to bring out one general trend of a speed change under the impact of density, one has to resort to relative values:

\[
R^H_{j,Di} = \frac{V^e_{j,0} - V^e_{j,Di}}{V^e_{j,0}} = \varphi (D) \quad (94)
\]

This gives us an opportunity to get an understanding of a general trend in a reaction \( (R) \) of people to the increasing impact of human flow density. From the formulas (93) and (94) it follows that the common relation of travel speed can be written as:

\[
\Delta V^e_{j,Di} = V^e_{j,0} (1 - R^H_{j,Di}) \quad (95)
\]

Empirical values of \( R^H_{j,Di} \) were determined at all the intervals of human flow density for all the field series.

One has to look for a relation \( R = \varphi(D) \) in the context of one of the psychophysical laws describing the quantitative relationship between physical characteristics of a stimulus and the intensity of a sensation as a response to this stimulus. As the result of the analysis of the most general psychophysical laws (the Weber–Fechner law\(^\text{34} \) and Steven’s law\(^\text{35} \)), the Weber–Fechner law was used to approximate empirical relationship \( R^H_{j,Di} = \varphi(D) \). This choice was justified because it was proved\(^\text{36} \) that it is true for the cases where the increment size of the impact is not clearly perceivable and only its general level has a practical value, just as in human flow:

\[
R^R_{j,Di} = a_j \ln \frac{D_i}{D_{0j}} \quad (96)
\]

Here the coefficient \( a_j \) is interpreted as the indicator of adaptation of the mixed human flow to the movement of the J-type route. The example of approximation of empirical values of \( R \) obtained on the basis of a series of field observations on horizontal routes is given on Figure 76. The values of \( a_j \) and
$D_{0j}$ for various route types are presented in Table 6.

The evaluation of correlation tightness between the given values was performed using theoretical correlation relation, whose values were: for horizontal routes within buildings – 0.99; for horizontal routes outside the buildings – 0.984; stairs descent – 0.985; stairs ascent – 0.996. Determination coefficient (square of theoretical correlation ratio) shows that at a fixed level of emotional state, more than 97% of total variance of travel speed on all kinds of routes is determined by the density of human flow.

This approach enables us to describe the relationship between the parameters of the human flow as a stochastic process in the form of elementary random function.

$$V_{Dj}^e = V_{0,j}^e \left[1 - a_j \ln \frac{D}{D_{0j}} \right]$$ (97)

<table>
<thead>
<tr>
<th>Route type</th>
<th>$a_j$</th>
<th>$D_{0j}$, person/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal outdoors</td>
<td>0.407</td>
<td>0.69</td>
</tr>
<tr>
<td>Horizontal indoors</td>
<td>0.295</td>
<td>0.51</td>
</tr>
<tr>
<td>Door aperture</td>
<td>0.295</td>
<td>0.65</td>
</tr>
<tr>
<td>Stair downwards</td>
<td>0.400</td>
<td>0.89</td>
</tr>
<tr>
<td>Stair upwards</td>
<td>0.305</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Elementary random function is the product of a random value of free travel speed of human flow on a non-random function (in the parentheses) that describes the effect of its density.

**Travel speed and emotional state of people**

Statistical analysis showed that at the first interval of density, travel speed values are homogeneous and might be combined. Moreover, travel speed values might be grouped into three-four speed intervals of free movement. An analysis of the experiment conditions suggests the identity of the psychological stress of the situations. However, we can’t say more because the scaling of psychological tension of the situation is limited by a scale: comfortable movement, movement under normal conditions and in conditions of an approaching emergency (because of an absence of observations in real emergency situations).
Physical activity indicators and emotional state levels that were scaled in relative units and can be obtained from data\textsuperscript{37} that psychologists used for information emotional states modelling. However, there is no sufficient data to establish the relation between speed and the degrees of psychological tension of evacuees.

The scale of levels can be represented in relative units (from 0 to 1) and has the following conceptual description. The first stage (0 < \( e \) < 0.3) is connected with the development of weak signals about a possible danger. At this stage, the body is adjusting, preparing to face with an expected danger. The second stage (0.3 < \( e \) < 0.7) should be called ‘energetic actions’ because this stage is associated with a state of heightened activity that goes along with the behaviour aimed at eliminating the danger. When it is not possible to eliminate the danger and there is a sense of helplessness in the face of impending danger, the third stage comes (0.7 < \( e \) < 1). This stage is characterised by a lack of activity and beyond-control listlessness.

However, there is no sufficient data to establish this correspondence as regards movement of people in situations having various degrees of psychological tension.

Nevertheless, it is obvious that in the statistical distribution, the maximum values of travel speed are more associated with the people who are in an increased emotional state. This led to an idea to use statistical theory of extreme sample values for predicting their possible meanings in the extreme, not observable, but possible situations (emergency situations). It should be considered that the maximum value of the sample cannot exceed twice its mean value\textsuperscript{38}.

The example of established categories of movement of mixed human flow on the horizontal routes is shown on Figure 78. The intervals of categories of movement of mixed composition human flow on all types of routes were calculated (Table 7).

![Figure 77. The influence of emotional state on the level of activity: 1) Attention; 2) Management; 3) Movement.](image)

![Figure 78. The relation between free travel speed and emotional state level: 1) Horizontal plane, door opening and stairs downwards; 2) Stairs upwards.](image)
Annex 2: Pedestrian flow movement during fire evacuation

Thus, all the values that compose formula (97) are determined. Their values for the category of heightened activity are used in normative documents in Russia both for the purposes of standardisation of evacuation parameters in case of fire\textsuperscript{39,40} and planning evacuation routes and exits in the Construction Standards and Regulations\textsuperscript{41,42}.

It is interesting to analyse the manifestation of the established relations of human flow speed changes that depend on the flow density in the international studies. However, it is rather difficult to accomplish this due to the lack of exact data as well as due to the uncertainty surrounding the methods used to carry out field observations and statistical processing of the results. It is absolutely obvious that the graphs given on Figure 74 might be inaccurate due to the quality of the published diagrams.

However, it is obvious that they demonstrate both qualitative and quantitative similarity to empirical relations established in Russia. Thus, the data obtained by Japanese researchers during field observations can be approximated by the established relations (97) with a high degree of accuracy with the values $V_{j,0}^e = 80 \text{ m/min}$ and $d_j$ and $D_{0,j}$ for horizontal routes equal to the data given in Table 6; whereas the data of observations in the London Underground (up to 5 per/m²) is described by the very similar relationship ($V_{j,0}^e = 88 \text{ m/min}$) that was established during the extensive studies at the stations and transfer hubs of the Moscow underground transport system\textsuperscript{43,44}:

$$V = 106.2 \cdot \left[1 - 0.4 \ln \frac{D}{0.56}\right].$$

**An application of established law for vulnerable populations**

According to the World Report on Disabilities, the total number of disabled people in the world is about one billion. Obviously, the distinct physical peculiarities of disabled people affect their mobility abilities. In the result of special study\textsuperscript{45,46}, disabled people were divided on four groups according to their movement characteristics: M1 – healthy adults and people with hearing limitations; M2 – elderly people, disabled people with artificial limbs, with loss of sight, people with mental problems; M3 – disabled people with travel aids such as sticks, crutches. M4 – people moving on manual wheelchairs. It was established that the parameters of their movement are described by the same relationship (97) but with different values of the variables (Table 8). This data is included in the Russian Building Code SNiP 35-01-2001 ‘Accessibility of Buildings and Structures for the People with Disabilities’.

**Table 7. Categories of movement, emotional state level, and unimpeded travel velocity.**

<table>
<thead>
<tr>
<th>Categories of movement</th>
<th>Level of emotional state</th>
<th>Unimpeded travel velocity, $V_0$, m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Horizontal route, door opening, stairs downwards</td>
</tr>
<tr>
<td>Comfortable</td>
<td>0.00</td>
<td>&lt;49.0</td>
</tr>
<tr>
<td>Quiet</td>
<td>0.45</td>
<td>49.0 – 66.0</td>
</tr>
<tr>
<td>Active</td>
<td>0.68</td>
<td>66.0 – 90.0</td>
</tr>
<tr>
<td>Of increased activity</td>
<td>0.70</td>
<td>90.0 – 120.0</td>
</tr>
</tbody>
</table>
Special attention was also paid to research the pedestrian movement of children and adolescents of various ages. The movement of people studying at university in normal conditions was analysed in the studies 47,48. This data was included in the general empirical database (see Figure 71) and was also analysed separately49. The data under conditions similar to an emergency was observed during experiments50,51.

The pedestrian movement of young kids (3–7 years old) is of a particular interest52,53. First of all, because as a result of the field observations and game experiments with children, the significant database was collected – about 4000 counts of travel speed-density relations. These values were obtained in junior, middle and senior age groups with different levels of their emotional state and during the movement on horizontal routes through doorways, upstairs and downstairs. Secondly, because at this age a psychophysiological model of the own body is formed, called in psychophysiology ‘body scheme’. This ‘body scheme’ is ‘orienting’ on the movement task under certain conditions and makes it possible for other parts of the body to feel the speed in a sensory form. At this stage, the main motor skills are formed and motion experience is being accumulated. However, even at this age (Table 9), the relations between the parameters of human flow are governed by the same relations (97) when the values of theoretical correlative ratio are higher than 0.95.

Thus, the analysis of differentiated relations between characteristics of the human flow for various age groups, which is typical for buildings of different functional usage, shows that they have a common relationship that can be described as function (97).

Conclusions
An analysis and generalisation of multi-thousand statistical data of various series of observations and experiments of pedestrian flow movement revealed that pedestrian flow should be considered as a random process (in terms of the theory of probability). Instead of a set of separate empirical relations (92), the general law for \( V = f(D) \) as a random function was established [formulae (97)]. This relation – due to its high validity – has been used for more than 30 years for evacuation routes design, evacuation time calculation and fire risk assessment.
Annex 2: Pedestrian flow movement during fire evacuation

Table 8. The values $a_j$ and $D_{0j}$ for different mobile groups of disabled people (for fire evacuation conditions).

<table>
<thead>
<tr>
<th>Mobility group</th>
<th>Parameters</th>
<th>A value of parameters depending upon route type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Horizotal</td>
</tr>
<tr>
<td><strong>M2</strong>: Elderly people, disabled people with artificial limbs, with loss of sight, people with mental problems.</td>
<td>$V_0$, m/min</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>$a_j$</td>
<td>0.335</td>
</tr>
<tr>
<td></td>
<td>$D_0$, pers/m²</td>
<td>0.675</td>
</tr>
<tr>
<td><strong>M3</strong>: Disabled people with travel aids such as sticks, crutches.</td>
<td>$V_0$, m/min</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>$a_j$</td>
<td>0.350</td>
</tr>
<tr>
<td></td>
<td>$D_0$, pers/m²</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>M4</strong>: People moving on manual wheel-chairs</td>
<td>$V_0$, m/min</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>$a_j$</td>
<td>0.399</td>
</tr>
<tr>
<td></td>
<td>$D_0$, pers/m²</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Note 1. M1 group – healthy adults and people with hearing limitations. The parameters of their movement age given in Table 6.

Note 2. Recent studies revealed that this classification needs further research. For instance, filed studies and statistical data treatment showed that elderly people should be classified in at least four groups: 1) without movement aids; 2) with 1 handhold; 3) with 2 handholds; 4) moving on a wheelchair without assistance.

Table 9. The values $a_j$ and $D_{0j}$ for pre-school children (for fire evacuation conditions).

<table>
<thead>
<tr>
<th>Mobility group</th>
<th>Parameters</th>
<th>A value of parameters depending upon route type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Horizotal</td>
</tr>
<tr>
<td>Pre-school children</td>
<td>$V_0$, m/min</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>$a_j$</td>
<td>0.275</td>
</tr>
<tr>
<td></td>
<td>$D_0$, pers/m²</td>
<td>0.78</td>
</tr>
</tbody>
</table>
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