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István Mihály[1]

Estimating the Air Leakage Rate of Smoke Control Doors for Calculations Procedures, Part 1

Abstract

The extent of smoke spread during building fires is critical, as it can adversely affect both evacuation and firefighting intervention. Smoke migration can occur through structural gaps, therefore this possibility should be minimised. One way to exclude smoke is to pressurise the structure, and an important starting parameter for the design of this is to know the leakage areas. The need for knowledge of the size of structural gaps has been high since the inception of design methods. This article aims to identify the potential for improving the calculation procedures by using the results of measurements on existing smoke control doors in pressurised vestibules. In this section, the author presents the relevant literature on the leakage area of the openings and the air flow coefficient of the openings. It describes the measurement method for determining the air flow through doors and structures and the calculation procedure currently used.

Keywords: smoke control door, leakage area, air flow coefficient, stairwell pressurisation, fire safety design

Introduction

When a fire occurs in a building, it produces heat and toxic gases that can damage the people in the building, the objects in the building and the structure of the building.[2] The immediate release of large quantities of smoke that obstructs visibility and breathing must be given particular attention and combated from the start.[3] It can be seen that providing protection against heat and smoke is one of the main pillars of occupant's

[1] Certified Fire Protection Specialist, Judicial Expert, CEO, Brandplan Kft.; PhD student, Ludovika University of Public Service, Doctoral School of Military Engineering, e-mail: m.istvan@brandplan.hu
[2] Beda 2011: 94–98.
[3] Blume–Hegger 2021: 459–499.

safety. In order to achieve life safety objectives, the evolution of smoke must be limited or effective drainage of the resulting combustion products must be ensured.

Smoke may leak through open doors or windows, gaps around closed doors, cracks of structures, ventilation ducts or grills, shafts and other boundaries. The amount of the air leakage through the doors is influenced by several factors. Examples include the type of door and the pressure differential across the door, which causes air to leak through gaps and openings between the door and the frame.[4] Smoke can quickly spread to other areas of the building, which can impede evacuation from the building, among other things.[5]

The pressurisation created by mechanical fans can be used to control the movement of smoke through the barriers like doors. Air flow through the doors and the gaps of the structures keeps smoke from entering the higher pressure space. If the door is open and the air flow is sufficiently high, the backflow of smoke can be prevented.[6] In other words, the required overpressure and air volume are two important design parameters that have a decisive influence on the efficiency of the systems.

The creation of overpressure between two sides of a structure is typically provided by a mechanical fan.[7] To achieve overpressure, it is necessary to be able to determine the amount of air to be supplied. If the amount of air supplied is insufficient, the correct overpressure will not be created between the two sides of the structure. In this case, the smoke may infiltrate through the gaps into the lower pressure space. On the other hand, if the amount of air supplied is too large, an overpressure may develop that makes it difficult to open the doors or may even cause structural damage.

In the design process, it is crucial to know the amount of air that will flow through the structures at a given pressure and thus to determine the amount of air to be supplied with sufficient accuracy. Calculation methods provide a means of estimating this value by knowing the gap sizes of the structures. Since doors play a particularly important role in leakage losses, it is important to know the gap dimensions as accurately as possible.[8]

In many cases, smoke-protected spaces are separated from other spaces by so-called smoke control doors with a self-closing mechanism and restrict the entry of smoke at ambient or elevated temperatures.[9] Given the existence of test standards for these doors, it can be assumed that their air tightness is different from that of conventional doors and that their gap size can be estimated more uniformly if they passed the standard test.

In this paper, the author presents the literature on the air leakage of doors in the design process of positive pressure ventilation (called also pressurisation systems or pressure differential systems), and then describes two measurement methods for measuring the air tightness, and two calculation methods for estimating the amount of air leaking through door gaps.

4 Younes et al. 2011: 267–302.
5 Achakji 1987: 1.
6 Klote–Milke 1992: 39.
7 Klote–Milke 2002: 88.
8 Gross 1991: 171–177.
9 Gross 1981: 1–3.

Literature review

All countries have national regulations to minimise the risk of fire in buildings.[10] The use of positive pressure ventilation for smoke control as well as heat and smoke extraction started in the U.K. and Australia in the 1950s.[11] The idea of pressurising stairwells to provide a tenable environment within egress routes during building fires was first advanced in the late 1960s. ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Smoke Control Manual was the first document on the subject specifically intended for use by designers.[12]

Early research has already highlighted that the leakage characteristics of walls and doors are particularly important, and more information is needed on the effective crack areas of installed leaf doors.[13] Even in a closed room, there is always some ventilation around doors, windows and through gaps in structures.[14]

Tamura's paper describes a computer study of smoke movement based on measured air leakage characteristics in office buildings. The equivalent leakage area for stairwell doors was 0.0185 m^2.[15] Soon afterwards, Hobson and Stewart carried out air leakage measurements on thirty doors with rebated frame. The results of the air leakage tests on the installed doors showed that the typical equivalent leakage area for single-leaf doors was 0.01–0.02 m^2.[16] This value was in good agreement with Tamura's previous result.

BS5588-4, published in 1978, made a distinction according to the opening direction of the doors.[17] The typical leakage area values given by the standard for single-leaf doors in rebated frame opening into a pressurised space were 0.01 m^2. For single-leaf doors in rebated frame opening from a pressurised space, this value was 0.02 m^2. Both values were given for a crack length of 5.6 m for doors 2.0 m high and 0.8 m wide.[18] The 1998 (2004) edition of the standard contained an informative annex with air leakage data for doors, but still recommended a value of 0.01 m^2 for single-leaf doors opening into a pressurised space and 0.02 m^2 for single-leaf doors opening from a pressurised space.[19]

Klote et al. gave flow areas of gaps values for single-leaf doors in tabular form, which can be used in the orifice equation with a flow coefficient of 0.65. For doors 2.13 m high, 0.914 m wide and 44.5 mm thick, the typical value is 0.0073–0.0428 m^2 depending on the thickness of the gaps above and below the door.[20]

In Annex A of the 2005 edition of EN 12101-6, the recommended air leakage data for doors opening into or out of the pressurised space were also 0.01–0.02 m^2.[21]

10 Majorosné Lublóy et al. 2023: 4.
11 Usemann 2003: 416.
12 Klote 1987.
13 Barrett–Locklin 1969: 299–310.
14 Bedford–Chrenko 1974: 233.
15 Tamura 1970.
16 Hobson–Stewart 1972: 47.
17 British Standards Institution 1978: 13–15.
18 Butcher–Parnell 1979: 145–146.
19 British Standards Institution 1998: 66–67.
20 Klote et al. 2012: 116–122.
21 CEN 2005: 88–91.

In the modernisation of the standard, the methods for designing pressure differential systems have been transferred to EN 12101-13, which also recommends values of 0.01–0.02 m^2 depending on the opening direction of single-leaf doors to be taken into account when estimating the air leakage through closed doors.[22]

There is another approach. The air leakage coefficient and gap length can be used to characterise the air flow through the gaps in the openings. The problem is that there is little literature data available on the values of air leakage coefficients.[23]

This is also the basis of the Fire Protection Technical Guideline in the field of Protection against Heat and Smoke Spread (TvMI), which proposes a method for determining the amount of air leakage through S_a/S_{200} smoke control doors.[24] The calculation procedure according to the TvMI is derived from the national fire protection regulations issued by Decree 9/2008 (II. 22.) ÖTM.[25]

In Hungary, the National Fire Safety Code defines the cases in which it is necessary to install a smoke-free staircase.[26] The safety level defined in the National Fire Safety Code can be achieved by applying the technical solutions and calculation methods developed in the Fire Protection Technical Guidelines.[27] A major part of designers and experts use the technical solutions proposed in the fire protection technical guidelines in their work.[28] It is important to give preference to systems that do not require physical intervention.[29]

The air leakage coefficient was also a traditional parameter for air leakage through windows and doors in Poland, defined as the amount of air entering a window 1 m in length at a pressure difference of 1 daPa in 1 hour.[30]

In Table 1, the author summarises air leakage coefficient values from various literature sources. The table clearly shows the variation in the air volume values theoretically required to maintain a given pressure differential depending on the literature sources.

The fire prevention solutions presented in this publication provide an opportunity to prevent or reduce the harmful effects of a possible fire on health.[31] The examination of the harmful effects shows similarities with the consequences of toxic combustion products produced in an industrial environment like chemical warehouses.[32] Additional technical solutions can be fire protection signalling systems, the development of which provides many new solutions in the field of property protection and fire protection.[33] Finally, we can learn important practical lessons for the development

22 CEN 2022: 66–72.
23 Baumann 2011.
24 National Directorate General for Disaster Management 2025: 51–52.
25 Decree 9/2008 (II. 22.) of the Minister for Local Government and Regional Development.
26 Decree 54/2014 (XII. 5.) of the Ministry of the Interior.
27 Act XXXI of 1996.
28 Bérczi–Badonszki 2021: 66–96.
29 Bérczi 2025: 19–23.
30 Lis–Lis 2021.
31 Almási et al. 2023.
32 Berger et al. 2024.
33 Tóth 2005.

of fire protection authority activity when dealing with the policing issues of event order security.[34]

Table 1: Air leakage coefficient of doors from various sources

Reference	Air leakage coefficient of doors [m3/hmPa2/3]		Air flow through door gaps at 25 Pa and 6.0 m gap length [m3/h]	
	With threshold	**Without threshold**	**With threshold**	**Without threshold**
Recknagel et al.35	9	3	467	156
Várfalvi36	8	1	415	52
Barna37	6	2	311	104
Gábor–Zöld38	4	1.5	207	78
Hobson–Stewart39	7.4	3.9	380	200
Liddament40	5.22 (weather-stripped)	5.67 (unsealed)	268	291
TvMI 3.641	1.11 (for Sa and Sm/S200 rated doors)		58	
ME-04–132–8442			184	

Source: compiled by the author

Estimating the amount of air flowing through door openings is an important factor in the design of positive pressure ventilation.

A review of the literature suggests that estimates of the effective leakage area for single-leaf closed doors have been in the order of 0.01–0.02 m^2 since early research. Recent studies on single-leaf smoke control doors have shown that the effective leakage area of single-leaf smoke control doors is independent of the opening direction and smaller than previous values reported in the literature.[43]

[34] Kanyó–Vásárhelyi 2019.
[35] Recknagel et al. 2000: 882–891.
[36] Várfalvi s. a.
[37] Barna 2015.
[38] Gábor–Zöld 1981: 130–131.
[39] Hobson–Stewart 1972: 47.
[40] Liddament 1986: 6.25.
[41] National Directorate General for Disaster Management 2025: 51.
[42] ÉSZK 1984: 6–7.
[43] Mihály et al. 2025.

Another method used to calculate the amount of air flow through closed doors is the air flow coefficient, which can be used to calculate the amount of air flowing through the closed door as a function of the length of the door slots.

Materials and methods

Description and characteristics of the subject of the study

In a previous study by Mihály et al., air leakage was measured from the smoke control doors of a mid-rise residential building, from which the effective leakage area of the doors could be calculated. The horizontal structures bounding the vestibule are reinforced concrete slabs, while the vertical structures are reinforced concrete and masonry. The lobby is 1.32 m × 2.18 m, with a ceiling height of 2.57 m, and the interior walls are plastered and painted white.

There are two doors per level to the vestibules, one to the vestibule and one from the vestibule. The doors with self-closing mechanism were made in 2013 and according to the available documents have Sm smoke control characteristics. The width of the door gaps to the lobby was 0.98 m and the height was 2.073 m. The width of the door gaps from the lobby was 0.92 m and the height was 2.05 m.

Due to door use, the actual air leakage through doors can vary greatly over the years.[44] This finding also suggests that tests should be carried out on structures already installed.

The pressurisation of the vestibules was ensured by an axial fan on the roof with a separate air duct. The design air flow rate of the fan was approximately 2,300 m^3/h according to the manufacturer's data sheet. The air was supplied to the vestibule from below the ceiling via a manually adjustable valve plate mounted on the side wall. The amount of air supplied could be varied by manually adjusting the valve plate.

Measuring air permeability with a Blower Door instrument

The pressure method is a pressure measurement method developed by the Department of Building Engineering at the Lund Institute of Technology and others to measure the compactness of a whole building.[45] The Blower Door instrument is used to measure air tightness. The principle of operation is to install an adjustable fan in a door or window frame and record the volume of air required to maintain a given pressure differential.[46] Figure 1 shows a Blower Door instrument installed in a door frame during the measurement process. If the flow characteristics, flow coefficient and exponent

[44] Cho et al. 2010: 3.
[45] Kronvall 1980a: 62.
[46] Sherman 1995.

of a building element, e.g. doors and windows, are known, the infiltration caused by the element can be calculated as a function of the pressure difference.[47]

According to the standard for determining the air permeability of buildings, there are several ways to create negative or positive pressure in the building envelope to perform measurements. One possible way is the blower door assembly, but for some buildings, the use of a building ventilation system fan is also possible to determine the air permeability.[48]

Figure 1: Blower Door instrument installed in a door frame
Source: compiled by the author

47 Ridley et al. 2003.
48 CEN 2016: 17–18.

Mihály et al. used a Duct Blaster B fan and a DG-1000 micromanometer with a maximum flow rate of 2,500 m^3/h at 50 Pa. The accuracy of the DG-1000 digital pressure and flow meter is 0.9% of the pressure value or 0.12 Pa (whichever is greater) under typical conditions of use, with a resolution of 0.1 Pa up to 1,000 Pa.[49]

In preliminary tests, the instrument was installed in a vestibule door and the differential pressure and air flow rate values were recorded.

Many infiltration models are based on an empirical (power law) relationship between flow and pressure differential through a crack or opening in the building envelope.[50] The flow of air through openings or ducts and the associated relationship is a well-studied phenomenon.[51] Physically, it is assumed that the exponent should have an expected value between 0.5 (for orifice flow) and 1.0 (for fully developed, long-tube laminar flow).[52]

Measuring air permeability with funnel and vane probe

EN ISO 9972 describes in an information annex the equipment used for pressurising buildings. The air permeability can also be tested using fans that are part of the heating or ventilation and air conditioning system of the building.[53]

If the supply system in the vestibule can provide the air volume required to perform the test at the specified pressure differentials, it may be suitable for determining the air permeability.

This requires an adjustable valve plate to control the amount of air supplied. In addition, a suitable and sufficiently accurate instrumentation to measure the amount of air discharged through the disc valve. An instrument for this purpose may be, for example, a funnel with a vane probe (Figure 2). By manually adjusting the disc valve during measurements, it is possible to establish the pressure levels and, with a sufficient seal between the funnel and the wall, to measure the amount of air flowing out with high accuracy.

The result of the series of measurements is a pressure and flow volume value pair that can be used to characterise the air tightness of the structures.

49 Mihály et al. 2025.
50 Ridley et al. 2003.
51 Klems 1983.
52 Zheng–Wood 2020.
53 CEN 2016: 18.

Figure 2: Measurement with funnel vane probe
Source: compiled by the author

Use of the recommendation for estimating air leakage through doors according to EN 12101-13

The informative annex to EN 12101-13 proposes calculation methods for estimating the air flow through different structures, e.g. windows, doors, walls, floors.
The standard recommends that when air flows through an opening, the flow can be expressed as a function of the area of constriction and the differential pressure across the opening according to equation (1).[54]

$$Q_{OPENING} = C_v \times A_{OPENING} \times \sqrt{\frac{2}{\rho}} \times (\Delta P)^{\frac{1}{R}} \qquad (1)$$

where

$Q_{OPENING}$ – is the airflow through the relevant opening (m^3/s)
C_v – is the coefficient of discharge (0.6–0.9); in the absence of additional data, 0.65 should be used for the calculations of the Pressure Differential System
$A_{OPENING}$ – is the opening area (m^2)

[54] CEN 2022: 64.

ΔP – is the pressure difference across the opening (Pa)
ρ – is the density of air (kg/m[3]); use 1.2 kg/m[3] as typical
R – is the coefficient of flow (for wide cracks may be taken to be 2.0, narrow leakage paths R is 1.6)

Using equation (1), if the leakage area and pressure difference are known, the amount of air flowing through the gap can be estimated. In another approach, knowing the amount of air flowing through the gap and the pressure differential forcing the air, the gap area can be estimated. The standard suggests tabular values for estimating the leakage area of different doors, walls and floors. For walls and floors, it is proposed to take the value of R as 1.6, and for doors as 2.

By combining the constants in equation (1), equation (2) is used to estimate the flow through gaps in closed doors, while equation (3) is used to estimate the flow through walls and floors.

$$Q_{DOOR\ CLOSED} = 0.839 \times A_{DOOR\ CLOSED} \times \Delta P^{\frac{1}{2}} \quad (2)$$

$$Q_{FL/W} = 0.839 \times A_{FL/W} \times \Delta P^{\frac{1}{1.6}} \quad (3)$$

where
$Q_{DOOR\ CLOSED}$ – is the airflow through the gap of the closed door (m3/s)
$A_{DOOR\ CLOSED}$ – is the leakage area of closed door (m2)
ΔP – is the pressure difference (Pa)
$Q_{FL/W}$ – is the airflow through the gap of floors or walls (m3/s)
$A_{FL/W}$ – is the leakage area of floors or doors (m2)

From equations (2) and (3), the estimated leakage areas can be expressed in terms of the differential pressure and the volumetric flow rate according to equations (4–6).

$$A_{FLOOR} = \frac{Q_{FLOOR}}{0.839 \times \Delta P^{\frac{1}{1.6}}} \quad (4)$$

$$A_{WALL} = \frac{Q_{WALL}}{0.839 \times \Delta P^{\frac{1}{1.6}}} \quad (5)$$

$$A_{DOOR\ CLOSED} = \frac{Q_{DOOR\ CLOSED}}{0.839 \times \Delta P^{\frac{1}{2}}} \quad (6)$$

where
A_{FLOOR} – is the leakage area of floors (m2)
Q_{FLOOR} – is the airflow through the gap of floors (m3/s)
ΔP – is the pressure difference (Pa)

A_{WALL} – is the leakage area of walls (m2)
Q_{WALL} – is the airflow through the gap of walls (m3/s)
$A_{DOOR\ CLOSED}$ – is the leakage area of closed door (m2)
$Q_{DOOR\ CLOSED}$ – is the airflow through the gap of the closed door (m3/s)

In the above calculation, if the air volume flow rate can be measured for a given pressure difference across walls and floors (for example, by taping door gaps), then the total gap area of walls and floors can be estimated. If a further measurement is made by removing the adhesive tape from the door under test, the volumetric flow rate measured in this situation can be corrected by the air flow rate determined on the walls and floors. The leakage area of the door can then be estimated. This is possible because these components form a branch with flow resistances parallel to their flow characteristics, and both resistances are affected by the same pressure differential.[55]

Use of the recommendation for estimating air leakage through doors according to TvMI

When designing a smoke-free stairwell according to TvMI, the gap loss of closed opening structures must be taken into account when calculating the air volume to be introduced into the stairwell using formula (7).[56]

$$\dot{V} = c \cdot \Delta p^n \cdot l \qquad (7)$$

where

$\dot{V}$– air leakage from the closed opening structure (m^3/h)
c – 1.11 (for S_a and S_{200} rated openings)
Δp – the pressure difference between the two sides of the opening (Pa)
n – 0.67 (for S_a and S_{200} rated openings)
l – the perimeter of the opening, in relation to the nominal size (m)

This relationship is similar to the formulas used in previous research to determine the amount of air flowing through window openings.[57]

By expressing equation (7) in terms of “c”, we can obtain the air leakage coefficient for the door, given the pressure difference between the two sides of the opening, the length of the opening gap and the amount of air flowing through the gap (8).

55 Kronvall 1980b: 91–96.
56 National Directorate General for Disaster Management 2025: 51.
57 Baumann 2011; Baumann 2005: 28–30; Mainka–Winkler 2010.

$$c = \frac{\dot{V}}{\Delta p^{n} \cdot l} \qquad (8)$$

where

$\dot{V}$ – is the airflow through the gap of the closed door (m^3/h)
c – is the air leakage coefficient ($m^3h^{-1}m^{-1}Pa^{\wedge -0.67}$)
Δp – is the pressure difference between the two sides of the opening (Pa)
n – 0.67 (for S_a and S_{200} rated openings)
l – the perimeter of the opening, in relation to the nominal size (m)

Summary

In this article, the author has shown that the spread of smoke during fires poses a risk when evacuating building occupants. Smoke propagation through gaps in structures, including flows through door gaps, plays a significant role.

A recent experiment has shown that the effective leakage area of single-leaf smoke control doors is smaller than the values reported in the literature.58 In this context, the author investigated the calculation procedure used in Hungary for the design.

In the next part of the paper, the author describes the measured determination of the leakage area and the air flow coefficient. The conclusions are drawn and suggestions are made for improving the values used in the design procedures. (8)

References

Achakji, George Y. (1987): *NRCC Experimental Fire Tower for Studies on Smoke Movement and Smoke Control in Tall Buildings.* Internal Report No. 512. Ottawa: National Research Council Canada Institute for Research in Construction. Online: https://doi.org/10.4224/20338144

Almási, Csaba – Kátai-Urbán, Lajos – Cimer, Zsolt (2023): ABV-felderítő eszközök bemutatása és fejlesztési lehetőségei. *Védelem Tudomány,* 8(Különszám), 195–205.

Barna Lajos (2015): Tüzelőberendezések égési levegő ellátása. Előadás. „A szén-monoxid mérgezések hatékony megelőzése" Országos szakmai konferencia, Budapest, 5 March 2015. Online: http://www.vedelem.hu/files/UserFiles/File/aktualis/20150403/04.pdf

Barrett, Richard E. – Locklin, David W. (1969): A Computer Technique for Predicting Smoke Movement in Tall Buildings. *Fire Technology,* 5(4), 299–310. Online: https://doi.org/10.1007/BF02600417

Baumann, Mihály (2005): Tüzelőberendezések légellátása. *Magyar Installateur,* 15(10–11), 28–30.

[58] Mihály et al. 2025.

Baumann, Mihály (2011): *Épületek légforgalma.* 17th "Building Services, Mechanical and Building Industry Days" International Conference, Debrecen, 13–14 October 2011. Online: https://www.e-gepesz.hu/files/cikk9422_EUG_Baumann.pdf

Beda, László (2011): Gondolatok az épületek tűzbiztonságáról. *Magyar Építőipar,* 56(3), 94–98.

Bedford, Thomas – Chrenko, Frank Ambrose eds. (1974): *Bedford's Basic Principles of Ventilation and Heating.* London: H. K. Lewis.

Bérczi, László – Badonszki, Csaba (2021): A tűzvédelmi tervezés fő tartópillérei a tűzvédelmi műszaki irányelvek. *Védelem Tudomány,* 6(2), 66–96. Online: https://ojs.mtak.hu/index.php/vedelemtudomany/article/view/13473

Bérczi, László (2025): Új kihívások és alternatív megoldások a tűzoltásban. *Tűzvédelem,* 32(2), 19–23.

Berger, Ádám – Kátai-Urbán, Lajos – Németh, Zsolt – Zsitnyányi, Attila – Kátai-Urbán, Maxim – Cimer, Zsolt (2024): Applicability of Design Methodology for the Remediation Bund of Flammable Dangerous Liquid Storage Tanks. *Fire,* 7(7). Online: https://doi.org/10.3390/fire7070246

Blume, Gary – Hegger, Thomas Fr. (2021): Rauch- und Wärmeabzug. In Fouad, Nabil A. (ed.): *Bauphysik Kalender 2021.* Brandschutz, 21. Jahrgang. Berlin: Ernst & Sohn GmbH & Co. KG, 459–499. Online: https://doi.org/10.1002/9783433610572.ch19

British Standards Institution (1978): BS 5588-4:1978 Fire Precautions in the Design and Construction of Buildings. Part 4. *Code of Practice for Smoke Control in Protected Escape Routes Using Pressurisation.* London: British Standards Institution.

British Standards Institution (1998): BS 5588-4:1998 + A2:2004 Fire Precautions in the Design, Construction and Use of Buildings. Part 4. *Code of Practice for Smoke Control Using Pressure Differentials.* London: British Standards Institution.

Butcher, Edward G. – Parnell, Alan C. (1979): *Smoke Control in Fire Safety Design.* London: E. & F. N. Spon Ltd.

CEN (2005): EN 12101-6:2005 Smoke and Heat Control Systems. Part 6. *Specification for Pressure Differential Systems.* Kits. Brussels: Technical Committee of the European Committee for Standardisation.

CEN (2016): *EN ISO 9972:2016 Thermal Performance of Buildings. Determination of Air Permeability of Buildings.* Fan Pressurisation Method (ISO 9972:2015). Brussels: Technical Committee of the European Committee for Standardisation.

CEN (2022): *EN 12101-13:2022 Smoke and Heat Control Systems.* Part 13. Pressure Differential Systems (PDS). Design and Calculation Methods, Installation, Acceptance Testing, Routine Testing and Maintenance. Brussels: Technical Committee of the European Committee for Standardisation.

Cho, Heejin – Liu, Bing – Gowri, Krishnan (2010): E*nergy Saving Impact of ASHRAE 90.1 Vestibule Requirements: Modeling of Air Infiltration through Door Openings.* Technical Report, PNNL-20026. Online: https://doi.org/10.2172/1017117

ÉSZK (1984): *ME-04–132–84 Füstmentes lépcsőházak követelményei.* Budapest: Építésügyi Szabványosítási Központ.

Gábor, László – Zöld, András (1981): *Energiagazdálkodás az építészetben.* Budapest: Akadémiai Kiadó.

Gross, Daniel (1981): *A Review of Measurements, Calculations and Specifications of Air Leakage Through Interior Door Assemblies.* Gaithersburg, MD: National Institute of Standards and Technology. Online: https://doi.org/10.6028/NBS.IR.81-2214

Gross, Daniel (1991): Estimating Air Leakage Through Doors for Smoke Control. *Fire Safety Journal,* 17(2), 171–177. Online: https://doi.org/10.1016/0379-7112(91)90040-6

Hobson, P. J. – Stewart, L. J. (1972): *Pressurisation of Escape Routes in Buildings. Fire Research Note No. 958.* Bracknell: Heating and Ventilating Research Association. Online https://publications.iafss.org/publications/frn/958/-1/view/frn_958.pdf

Kanyó, Ferenc – Vásárhelyi-Nagy, Ildikó (2019): Research for New Physical Ability Testing Method for Firefighters in the V4 Countries. *Műszaki Katonai Közlöny,* 29(1) 161–166. Online: https://doi.org/10.32562/mkk.2019.1.13

Klems, Joseph H. (1983): Methods of Estimating Air Infiltration Through Windows. *Energy and Buildings,* 5(4), 243–252. Online: https://doi.org/10.1016/0378-7788(83)90012-9

Klote, John H. (1987): *An Overview of Smoke Control Technology.* Gaithersburg, MD: National Institute of Standards and Technology. Online: https://doi.org/10.6028/NBS.IR.87-3626

Klote, John H. – Milke, James A. (1992): *Design of Smoke Management Systems.* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers – Boston, MA: Society of Fire Protection Engineers.

Klote, John H. – Milke, James A. (2002): *Principles of Smoke Management.* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Klote, John H. – Milke, James A. – Turnbull, Paul G. – Kashef, Ahmed – Ferreira, Michael J. (2012): *Handbook of Smoke Control Engineering.* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Kronvall, Johnny (1980a): *Airtightness. Measurements and Measurement Methods.* Stockholm: Swedish Council for Building Research.

Kronvall, Johnny (1980b): *Air Flows in Building Components.* PhD Thesis. Lund University.

Liddament, Martin W. (1986): *Air Infiltration Calculation Techniques.* An Applications Guide. Coventry: The Air Infiltration and Ventilation Centre. Online: https://www.aivc.org/resource/air-infiltration-calculation-techniques-applications-guide

Lis, Piotr – Lis, Anna (2021): The Required Amount of Ventilation Air for the Classroom and the Possibility of Air Infiltration through the Windows. *Energies,* 14(22). Online: https://doi.org/10.3390/en14227537

Mainka, Georg-Wilhelm – Winkler, Heiko (2010): *Influence of New External Protective Glazing on Historic Painted Windowpanes in Medieval Churches.* Online: http://eprints.sparaochbevara.se/610/1/31_Mainka%5B1%5D.pdf

Majorosné Lublóy, Éva Eszter – Major, Zoltán – Szép, János – Hlavička, Viktor – Biró, András (2023): *Méretezés tűzteherre az Eurocode szerint. Vasbeton, acél-, fa-, falazott és öszvérszerkezetek tervezése.* Budapest: TERC Kereskedelmi és Szolgáltató Kft.

Mihály, István – Bérczi, László – Bognár, Balázs – Kátai-Urbán, Maxim – Tóth, Levente – Kátai-Urbán, Lajos – Vass, Gyula – Varga, Ferenc (2025): Experimental Study to Determine the Leakage Area of Single-Leaf Smoke Control

Doors in the Design of Pressure Differential Systems. *Fire,* 8(1). Online: https://doi.org/10.3390/fire8010005

National Directorate General for Disaster Management (2025): *Tűzvédelmi Műszaki Irányelv [Fire Protection Technical Guideline]. Hő és füst elleni védelem [Protection against Heat and Smoke Spread].* TvMI 3.6:2025.02.01. Belügyminisztérium, Országos Katasztrófavédelmi Főigazgatóság. Online: https://www.katasztrofavedelem.hu/application/uploads/documents/2024-12/84963.pdf

Recknagel, Hermann – Sprenger, Eberhard – Schramek, Ernst-Rudolf (2000): *Fűtés- és klímatechnika 2000. I. kötet.* Budapest–Pécs: Dialóg Campus.

Ridley, Ian – Fox, J. – Oreszczyn, Tadj – Hong, Sung-Hugh (2003): The Impact of Replacement Windows on Air Infiltration and Indoor Air Quality in Dwellings. *International Journal of Ventilation,* 1(3), 209–218. Online: https://doi.org/10.1080/14733315.2003.11683636

Sherman, Max Howard (1995): The Use of Blower-Door Data. *Indoor Air,* 5(3), 215–224. Online: https://doi.org/10.1111/j.1600-0668.1995.t01-1-00008.x

Tamura, George T. (1970): *Computer Analysis of Smoke Movement in Tall Buildings.* Research Paper No. 452. Ottawa: National Research Council of Canada, Division of Building Research. Online: https://doi.org/10.4224/40000451

Tóth, Levente (2005): *CCTV magyarul.* Budapest: BM Nyomda Kft.

Usemann, Klaus W. (2003): *Brandschutzanlagen. In Brandschutz in der Gebäudetechnik. VDI-Buch.* Berlin–Heidelberg: Springer, 333–437. Online: https://doi.org/10.1007/978-3-642-19001-8_3

Várfalvi, János [s. a.]: *Ablakszerkezetek légáteresztése.* Online: http://152.66.45.150/EPFIZ/Ablakszerkezetek_legatreresztese.pdf

Younes, Chadi – Shdid, Caesar Abi – Bitsuamlak, Girma (2011): Air Infiltration through Building Envelopes: A Review. *Journal of Building Physics,* 35(3), 267–302. Online: https://doi.org/10.1177/1744259111423085

Zheng, Xiaofeng – Wood, Christopher J. (2020): On the Power Law and Quadratic Forms for Representing the Leakage-Pressure Relationship – Case Studies of Sheltered Chambers. *Energy and Buildings,* 226. Online: https://doi.org/10.1016/j.enbuild.2020.110380

Legal sources

1996. évi XXXI. törvény a tűz elleni védekezésről, a műszaki mentésről és a tűzoltóságról [Act XXXI of 1996 on Fire Prevention, Technical Rescue and Fire Brigades]. Online: https://njt.hu/jogszabaly/1996-31-00-00

9/2008. (II. 22.) ÖTM rendelet az Országos Tűzvédelmi Szabályzat kiadásáról [Decree 9/2008 (II. 22.) of the Minister for Local Government and Regional Development on the Issuance of the National Fire Protection Regulation]. Online: https://njt.hu/jogszabaly/2008-9-20-1V.2#CI

54/2014. (XII. 5.) BM rendelet az Országos Tűzvédelmi Szabályzatról [Decree 54/2014 (XII. 5.) of the Ministry of the Interior on the Issuance of the National Fire Protection Regulation]. Online: https://njt.hu/jogszabaly/2014-54-20-0A