Ekonomikas ministrija

CMB INŽENIERU KOMPETENCES CENTRS

Tiešsaistes apmācību seminārs būvspeciālistiem un projektētājiem

ID Nr. EM 2023/28

Rīga, 2023

Ekonomikas ministrija

CMB INŽENIERU KOMPETENCES CENTRS

Training seminar / Apmācību seminārs

"ĒKU DŪMU AIZSARDZĪBAS SISTĒMU PROJEKTĒŠANA"

DESIGN OF SMOKE PROTECTION SYSTEMS FOR BUILDINGS

September 21st, 2023

Wojciech Węgrzyński (Polija)

Agenda

9:30 – 10:00	Registration

10:00 – 11:40	• Introduction
	• Smoke protection:
	  • Smoke protection strategies;
	  • Types of smoke protection solutions;
	  • Methods, tools, standards and national legislation specific to the design of smoke protection solutions.
	• Q&A session

11:40 – 12:00	**Break**

12:00 – 13:30	• Natural draft smoke and heat ventilation systems, application and design examples:
	  • Examples of solutions with protection strategy - rescue of people
	  • Examples of solutions with a protection strategy - support of the fire-fighting process;
	  • Examples of solutions with a protection strategy - property rescue and/or process continuity;
	• Q&A session

13:30 – 14:10	**Break**
14:10 – 16:00	• Characterisation and comparison of the technical performance of the system elements; • Key design mistakes and stereotypes. • Forced draught smoke and heat ventilation systems - description of system design methods and results according to the protection strategies defined above. • Overpressure air systems - description of system design methods and best practices. • Methodology for smoke volume prediction; • Q&A session

Agenda/ 10:00 – 11:40

- Introduction
- Smoke protection:
  - Smoke protection strategies;
  - Types of smoke protection solutions;
  - Methods, tools, standards and national legislation specific to the design of smoke protection solutions.
- Q&A session

About me

Dr hab. Inż. Wojciech Węgrzyński, prof. ITB

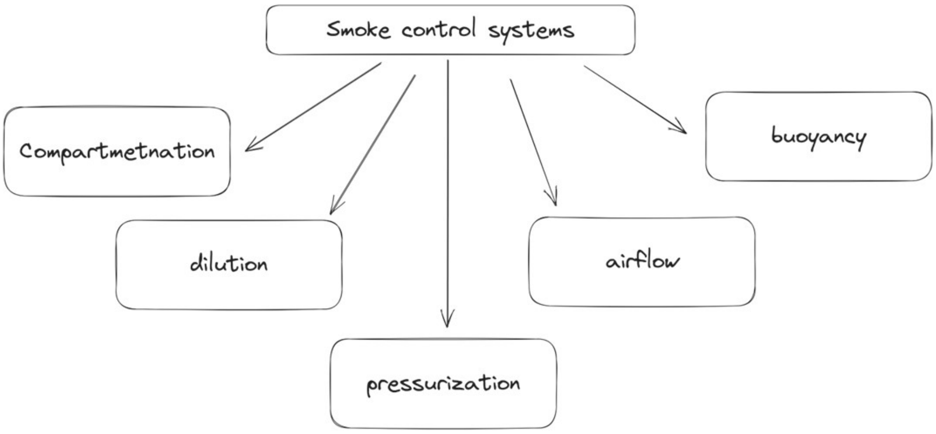
- **Scientist at ITB**: visibility in smoke, wind and fire coupled modeling, smoke control systems, compartment fires and fundamentals of fire phenomena.
- **Engineer at ITB**: smoke control in tunnels, car parks, malls. Hot smoke tests. Fire testing of fans, natural ventilators, full scale fire tests. Involved in 200+ projects and nearly every tunnel built/designed in Poland since 2010
- **Science propagator**: runs a fire science podcast at www.FireScienceShow.com with nearly 120+ episodes with science and industry leaders. Sponsored by OFR Consultants

About me

Dr hab. Inż. Wojciech Węgrzyński, prof. ITB

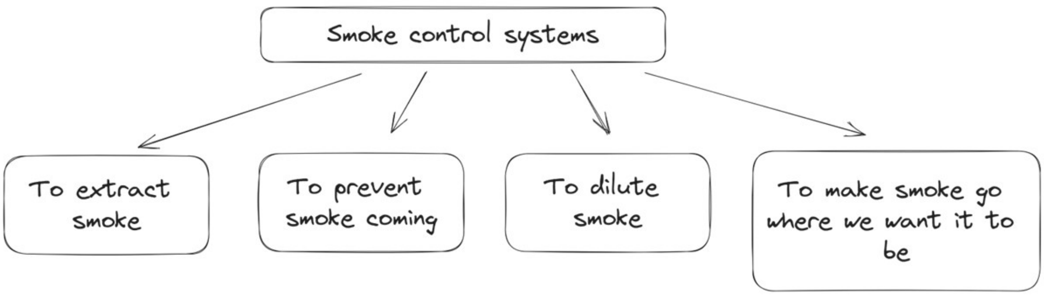
- 40 published peer-reviewed papers in renowned journals
- Director at SFPE Europe
- 2019 NFPA H.C. Bigglestone Award for work on Wind and Fire simulations
- 2020 SFPE 5 Under 35 Award
- 2020-23 OPUS19 grant on development of NSHEV systems
- Involved in design of 250+ buildings
- Runs a fire science podcast @ firescienceshow.com

Smoke control systems



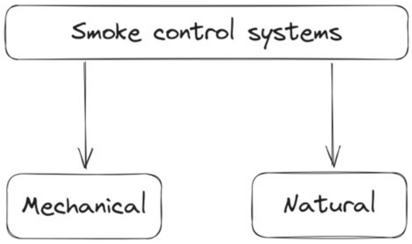
Distinction by Milke/Klote – Handbook of Smoke Control Engineering

Smoke control systems



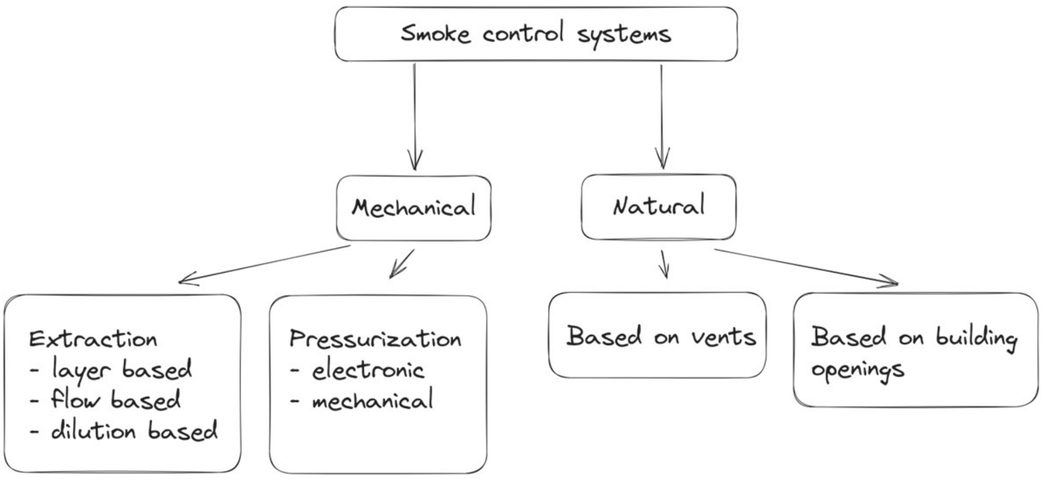
My distinction by what you want to achieve through smoke control

Smoke control systems



My distinction by how you achieve your goal

Smoke control systems



My distinction by how you achieve your goal

Mechanical vs natural ventilation

Mechanical ventilation

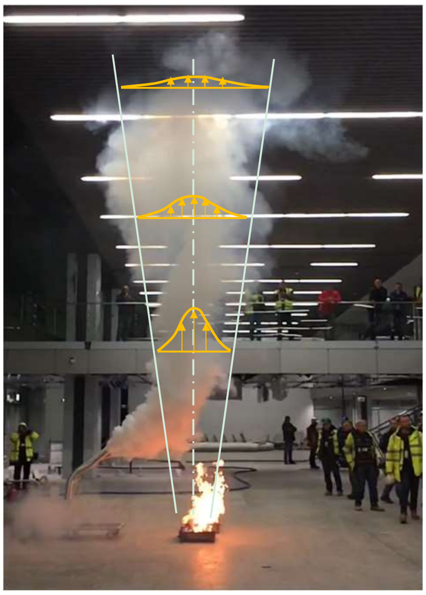
Natural ventilation

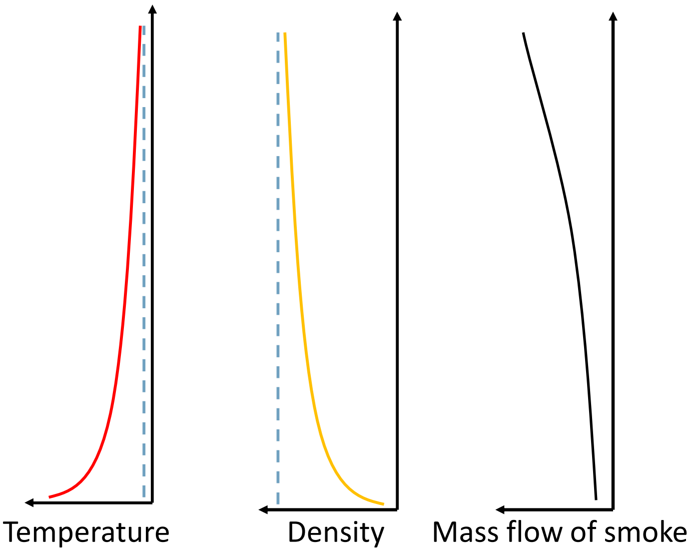
Goals of the design

Smoke control goals

- Safety of building occupants, users, visitors – safety of humans, directly connected to their ability to escape the building in very early stage of the fire
- Safety of firefighters – safety of the people entering the building at a later stage of the fire (potentially fully developed fire)
- Property safety – safety of the structure itself or the goods stored within, regardless of the duration of the fire

Smoke physics





Smoke physics

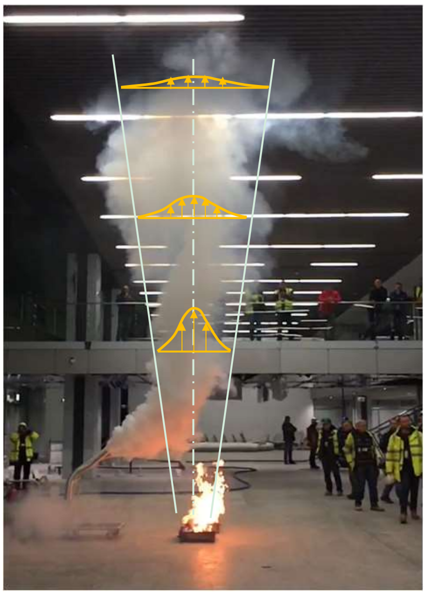
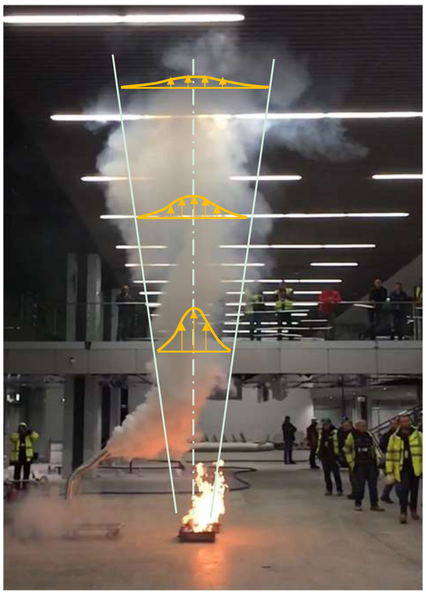


Table 1
Plume Models Used in Chosen Codes and Design Guidelines

Code or design guide	Type	Country of origin	Plume entrainment correlations (relevant section of the paper)
NFPA 92 [1]	National code	USA	Heskestad (2.5)
EN 12101-5 [22]	International code	EU	Thomas (2.2) and Heskestad (2.5)
TM19 [23]	Design guideline	UK	Heskestad (2.5) Thomas (2.2) as an alternative
NBS S21-208-1 [24]	National code	Belgium	Thomas (2.2)
BRE 368 [25]	Design guideline	Europe	Thomas (2.2) Zukoski (2.3)
BS 5588-7 [26]	Design guideline	UK	Redirect to BS EN 12101-5 [22]
BS 9999:2017 [27]	National code	UK	Redirect to BS EN 12101-5 [22]
AS 1668.3-2001 [28]	National code	Australia	Thomas (2.2)
Principles of Smoke Management [29]	Design guideline	USA	Heskestad (2.5)
Handbook of Smoke Control Eng. [30]	Design guideline	USA	Heskestad (2.5)

G. Vigne, C. Gutierrez-Montes, A. Cantizano, W. Węgrzyński, G. Rein, Review and Validation of the Current Smoke Plume Entrainment Models for Large-Volume Buildings, Fire Technol. 55 (2019) 789–816. https://doi.org/10.1007/s10694-018-0801-4.

Smoke physics



$$\dot{m}_p = 0.21 \left(\frac{\rho_\infty^2 g}{c_p T_\infty}\right)^{1/3} \dot{Q}^{1/3} z^{5/3} \quad (5)$$

This equation is also commonly shown in the form below where the ambient air properties are assumed to be $T_\infty = 293$ K, $\rho_\infty = 1.1$ kg/m^3, $c_p = 1.0$ kJ/kg K and $g = 9.81$ m/s^2.

$$\dot{m}_p = 0.071\, \dot{Q}^{1/3} (z)^{5/3} \quad (6)$$

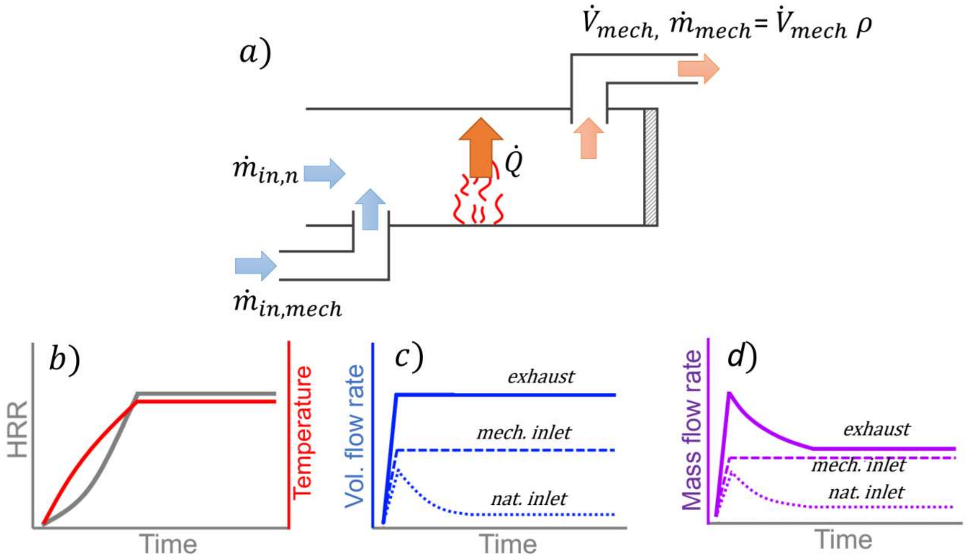
G. Vigne, C. Gutierrez-Montes, A. Cantizano, W. Węgrzyński, G. Rein, Review and Validation of the Current Smoke Plume Entrainment Models for Large-Volume Buildings, Fire Technol. 55 (2019) 789–816. https://doi.org/10.1007/s10694-018-0801-4.

Smoke physics

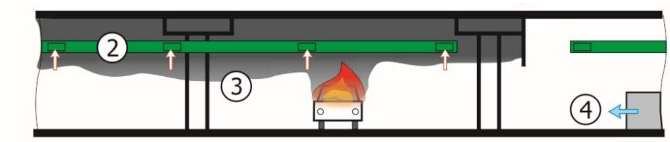
Upper layer

Bottom layer

Mechanical system physics

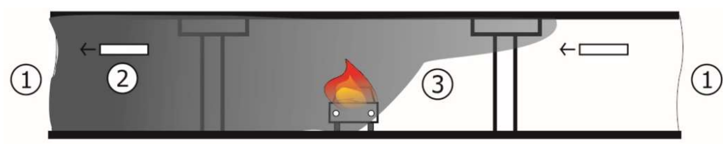


Layer vs airflow



(2) Extraction ducts, (3) smoke layer, (4) inlet points

Layer based system



(1) Reversible inlet/outlet locations, (2) jet-fans, (3) smoke stopped upstream,

Airflow based system

Layer vs airflow

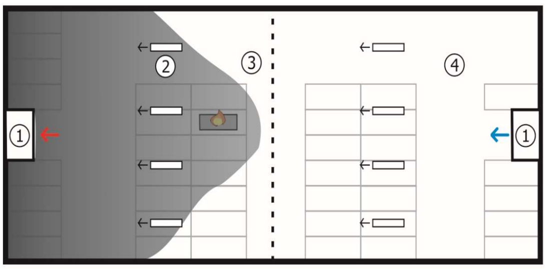
Layer based system

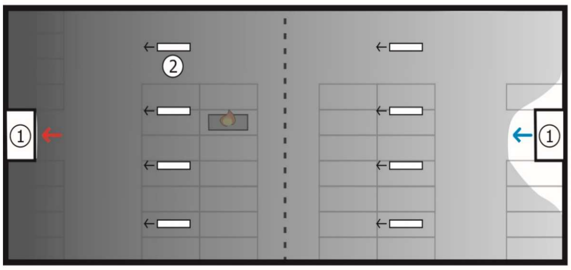
Airflow based system

Control vs clearance

Control system

Clearance system (dilution)





You have control over where the smoke goes

You accept the smoke fills your whole domain, maintain flow to provide dilution

Layer vs dilution

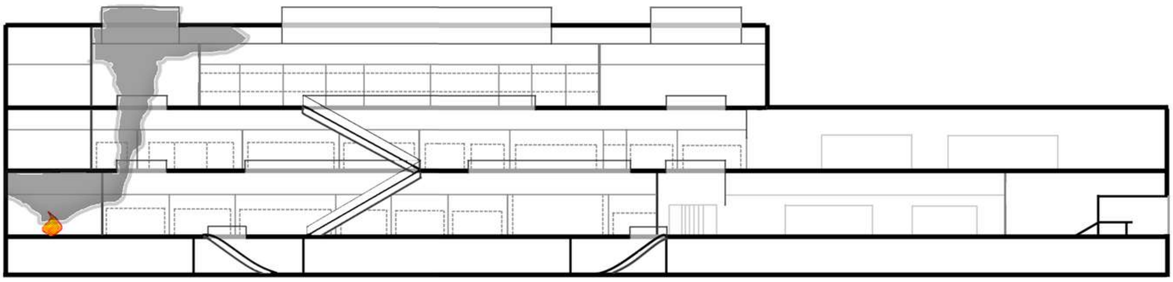
Layer based system

You keep the smoke in the predefined smoke layer

Dilution based system

You exchange the spoiled air multiple times per hour

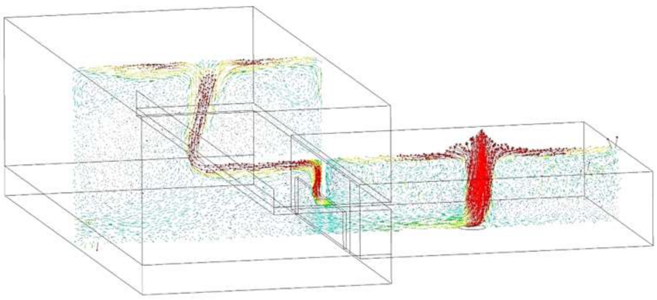
Complex architectures



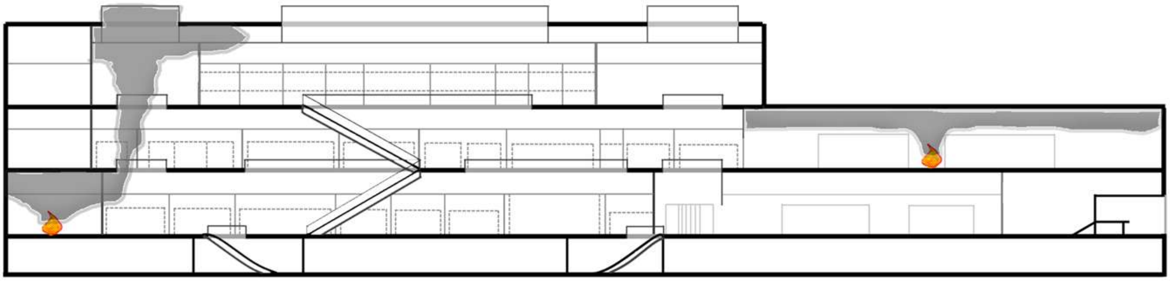
Common systems

In some buildinds the complexity and fragmentation of space makes it preferable to design smoke control in a larger space, to which adjacent compartments are ventialted into.

This is a common strategy in malls, airports, railway stations



Complex architectures



Common systems

In some buildinds the complexity and fragmentation of space makes it preferable to design smoke control in a larger space, to which adjacent compartments are ventialted into.

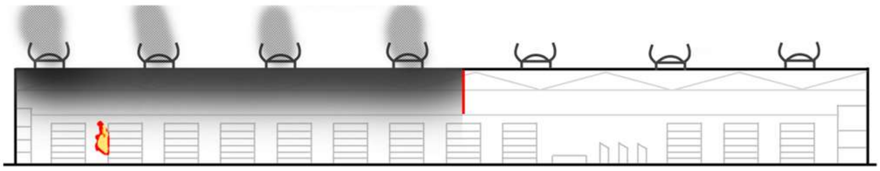
This is a common strategy in malls, airports, railway stations

Individual systems

Usually, it is preferable to remove the smoke from the volume of its origin.

This is the common strategy for large shopping units, offices, corridors, car parks, warehouses and other large single volume spaces

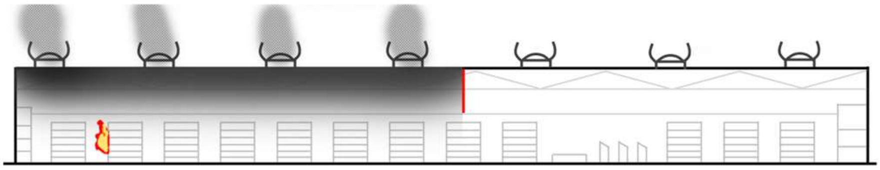
Smoke control zones



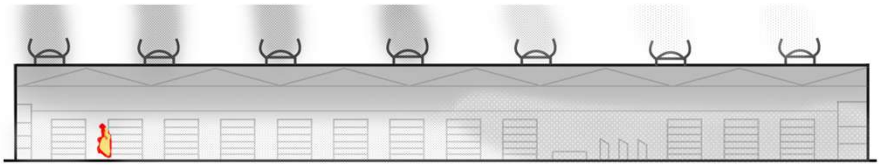
Smoke control zones

To maintain smoke control efficient, one must prevent excessive cooling of smoke (and following loss of buoyancy). This means there exists an upper limit of how big the smoke reservoir can be – usually a „golden number" is between 2000 – 2600 sqm.

Smoke control zones

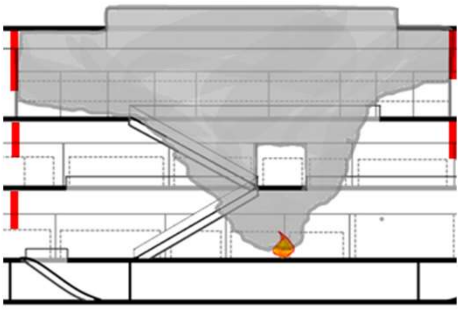


Smoke control zones – what happens if this fails?



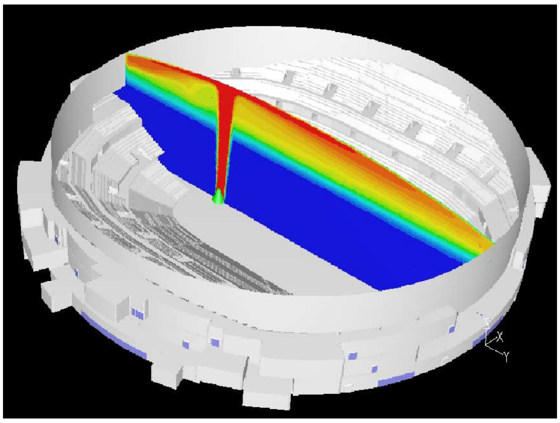
If you spearation into control zones is unsuccesfull you risk smoke filling the entire present volume. This smoke is cold, has no buoyancy and is very difficult to be removed from the building.

(too) complex architecture

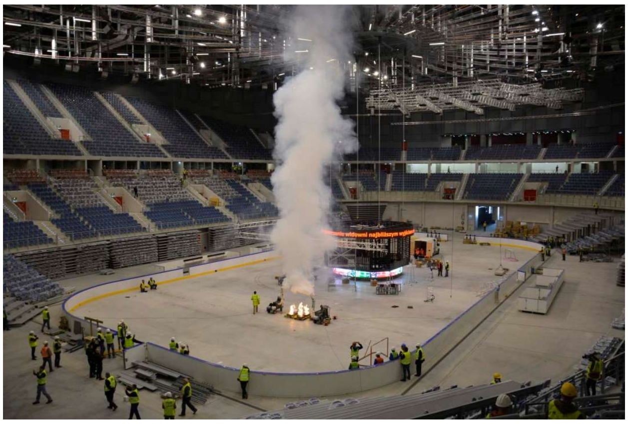


Plume theory and simple models stop being applicable at highly complex architecture, where smoke changes its direction multiple times. For cases like this you need a smart engineer and computer models.

Computer modeling tools



Computer model prediction



Full scale fire test

The expected workflow

In performance based design of smoke control system you would hope for this:

Problem	Analysis of theoretical boundaries of the study	Preliminary study with simple tools	Advanced study of the solution	Solution
	Choice of applicable tools for the design	Verification of the assumptions and the tools	Verification of the study with simple tools	
		Proposal of a solution	Redesign?	

Realistic workflow…

But more often you get this…

Problem → What does engineer feel, that should work → CFD / Plenty of pictures to support the first case → Solution → If it does not work, it is a problem…

Tools at your disposal

So what is in our toolbox?

- Simple „hand calculation” models that origin from experimental studies and relate to particular phenomena;
- Zone (or lumped) models that relate to a global view on the fire, but in a simplified geometry and discretization
- CFD and other numerical tools, that may give the most detailed answer but are time and resource consuming

Hand calc

Hand calculations/simple models

- steady state calculations unless the time is directly connected to the investigated phenomena (i.e. sprinkler activation, surface flame spread);
- finding realistic limits for a phenomena (i.e. maximum temperature that can occur);
- initial check, preliminary studies in which instant result is required;
- spatial domain directly connected to the size of phenomena investigated;
- level of details described by the method is directly connected to the size of the domain.

Zone models

Zone Fire Models

- transient simulations;
- situations in which the zone averaged output is enough and the detailed local conditions are not in the main scope of the analysis;
- quick computational time makes it a suitable tool for probabilistic studies;
- model made with modular geometry of compartments, with hard limitations in their size;
- flows between compartments may be analyzed;
- possible use of sub models (plume, ceiling jet), but have the same limitations as the hand calculations.

CFD

CFD

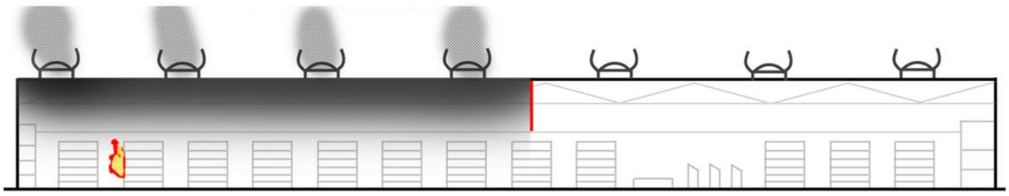
- transient or steady state simulations of complex flows of heat and mass in almost any geometry;
- location of features within the model influences the results – can be used in assessment of complex ventilation system and their optimization;
- the level of details that can be investigated is limited mostly by the time and space discretization;
- overall size and complexity of the model is limited only by the preparation time and computational power available;
- investigation of far field results without focusing on details of complex phenomena (i.e. to assess smoke movement we substitute pyrolysis and flamelet model into volumetric source of heat and smoke)

Break / 11:40 – 12:00

Agenda/ 12:00 – 13:30

- Natural draft smoke and heat ventilation systems, application and design examples:
  - Examples of solutions with protection strategy – rescue of people;
  - Examples of solutions with a protection strategy – support of the fire-fighting proces;
  - Examples of solutions with a protection satrategy – property rescue and/or process continuity.
- Q&A session

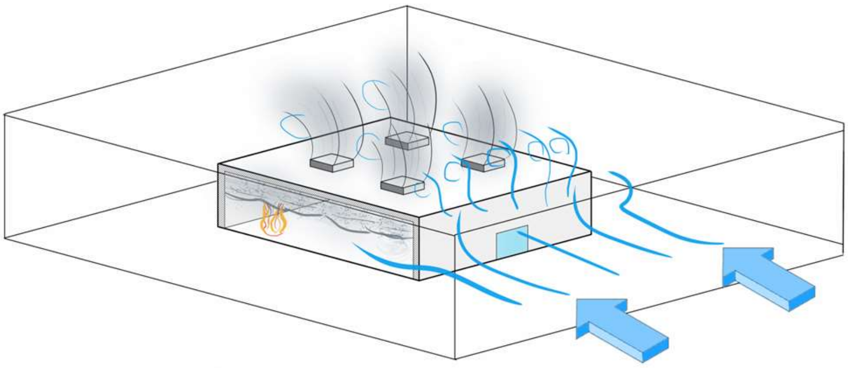
What is NSHEVs



Natural smoke and heat extraction systems:

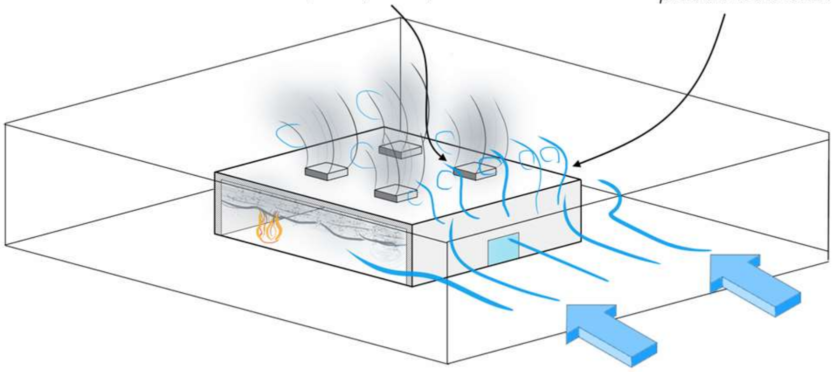
- Based on openings – outlets and inlets. INLETS ARE AS IMPORTANT AS OUTLETS!
- Works due to smoke buoyancy – no smoke buoyancy, no system operation.
- No matter what manufacturers tell you – there is no way to tell how a single vent will work on the roof. They work as a system, and are hostages of the wind.
- Are actually really good if you know what you are doing. Viable in shops, warehouses, atria, airports and railway stations.

Wind impact



W. Węgrzyński, T. Lipecki, Wind and Fire Coupled Modelling—Part I: Literature Review, Fire Technol. 54 (2018) 1405–1442. https://doi.org/10.1007/s10694-018-0748-5.

Wind impact



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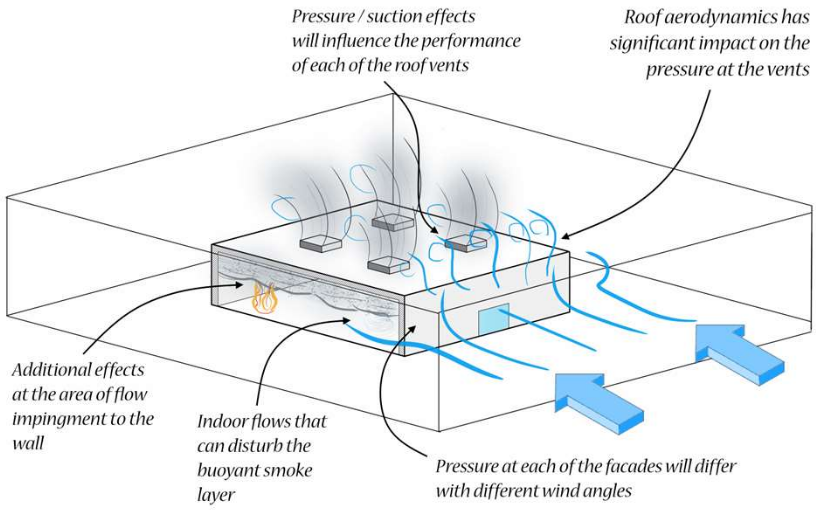
Wind impact



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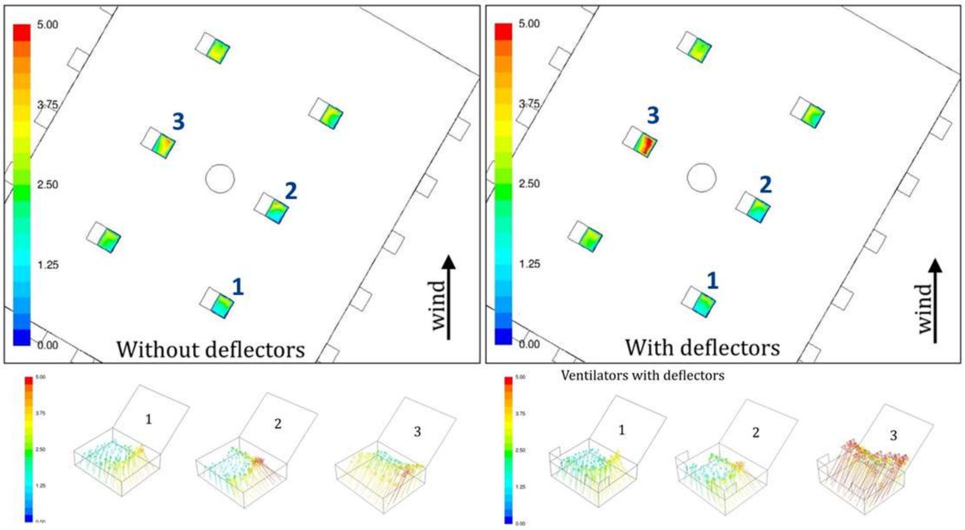
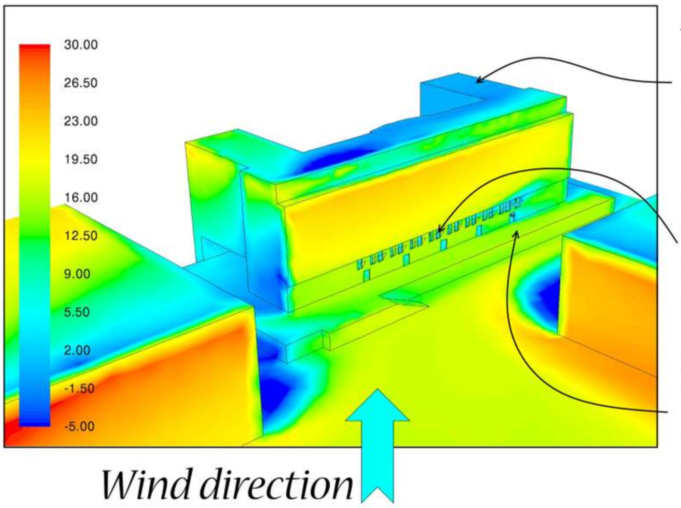
Individual vent performance

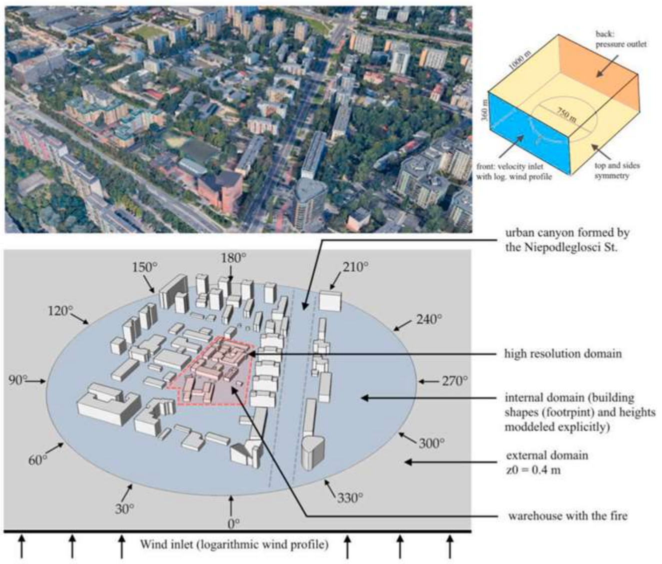


W. Węgrzyński, G. Krajewski, Influence of wind on natural smoke and heat exhaust system performance in fire conditions, J. Wind Eng. Ind. Aerodyn. 164 (2017) 44–53. doi:10.1016/j.jweia.2017.01.014.

Pressure distribtion



Complex wind engineering



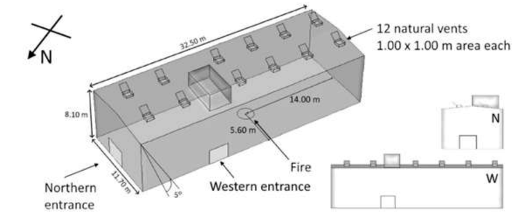
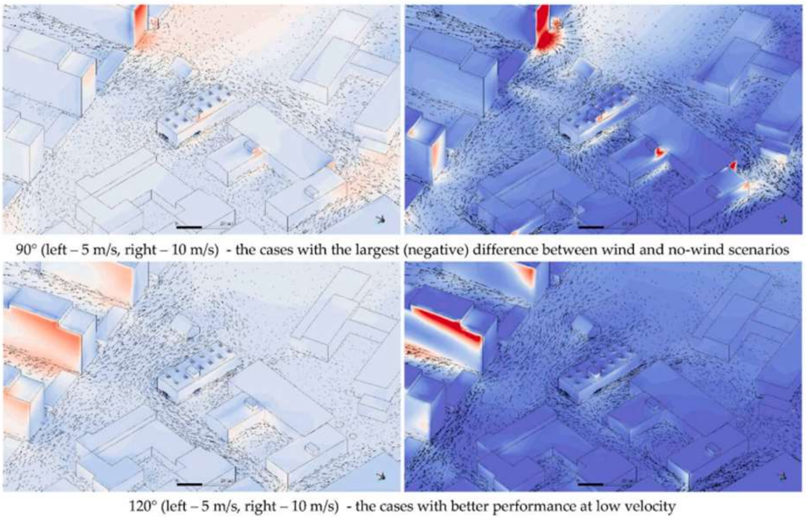


Fig. 1. The hypothetical warehouse building modelled over a shape of existing building in the same location.

W. Węgrzyński, G. Krajewski, G. Kimbar, T. Lipecki, Fire smoke dispersion inside and outside of a warehouse building in moderate and strong wind conditions, Fire Saf. J. (2023) 103760. https://doi.org/10.1016/j.firesaf.2023.103760.

Impact of wind in the city



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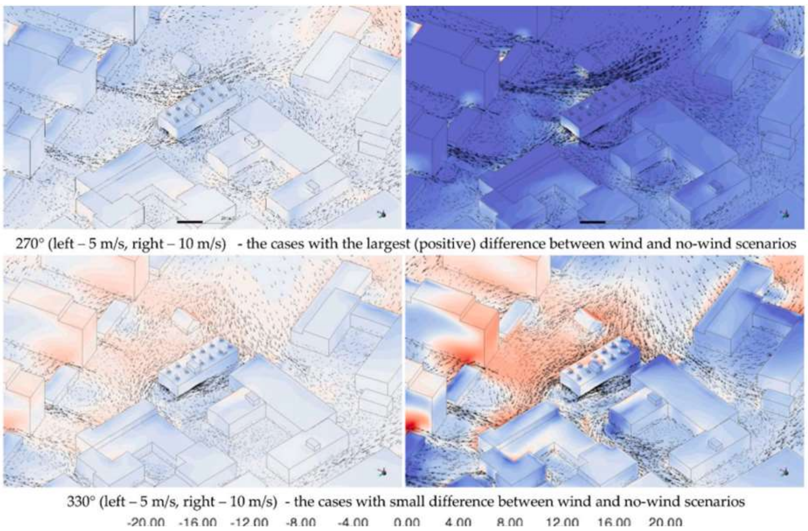
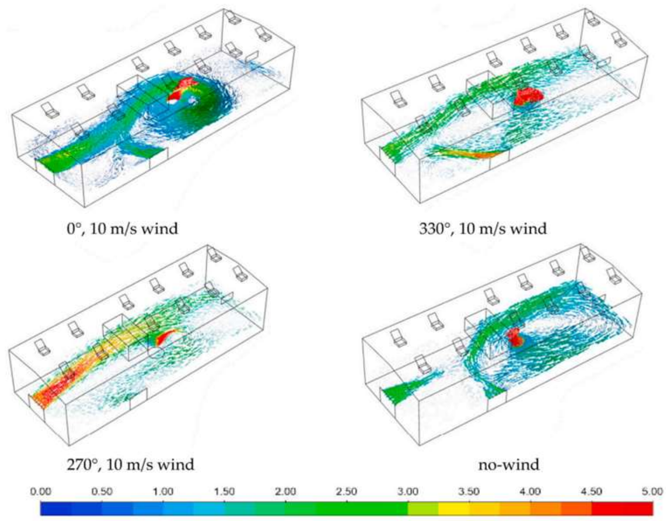


What happens inside?

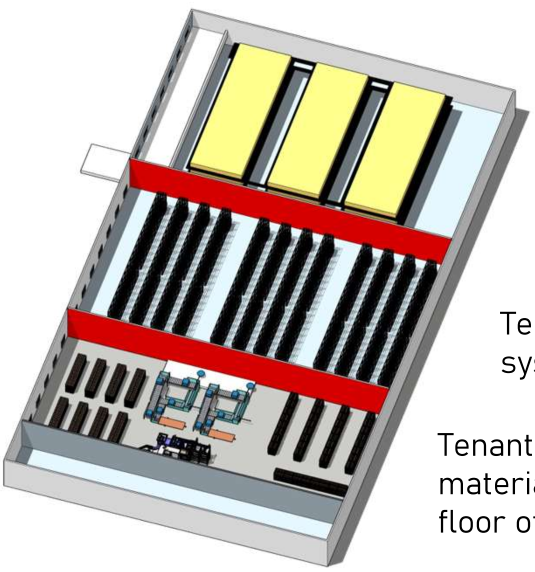


Different flows inside

Different external wind conditions lead to completely different flow path inside the building, and in consequence to different performance of smoke control.

W. Węgrzyński, G. Krajewski, G. Kimbar, T. Lipecki, Fire smoke dispersion inside and outside of a warehouse building in moderate and strong wind conditions, Fire Saf. J. (2023) 103760. https://doi.org/10.1016/j.firesaf.2023.103760.

Practical considerations



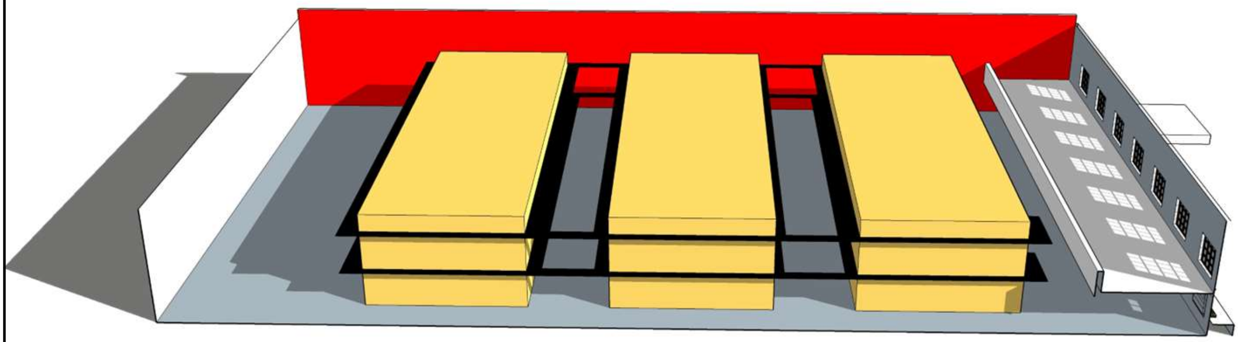
Tenant 1 – High bay storage with 2 levels of cat-walks at levels of 4 and 8 m (document archive), additional office mezzanine above loading bay

Tenant 2 – High bay storage with man-up system (car parts warehouse)

Tenant 3 – Production of furniture with raw material storage and ready products storage, 2 floor office building

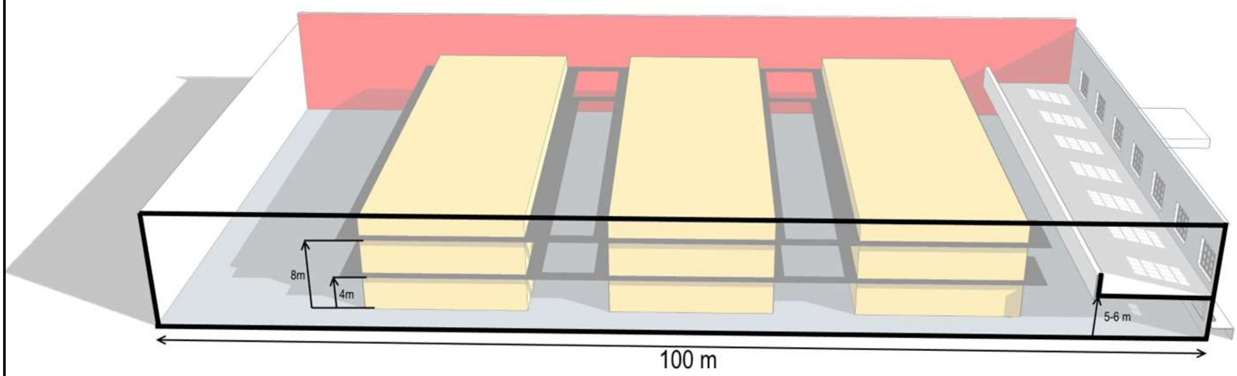
Designing a system

Design example – the design of NSHEV system of the tenant 1 zone. The goal is to allow safe evacuation, limit the spread of fire and the damage done to the archive, and allow rescue operations.



Designing a system

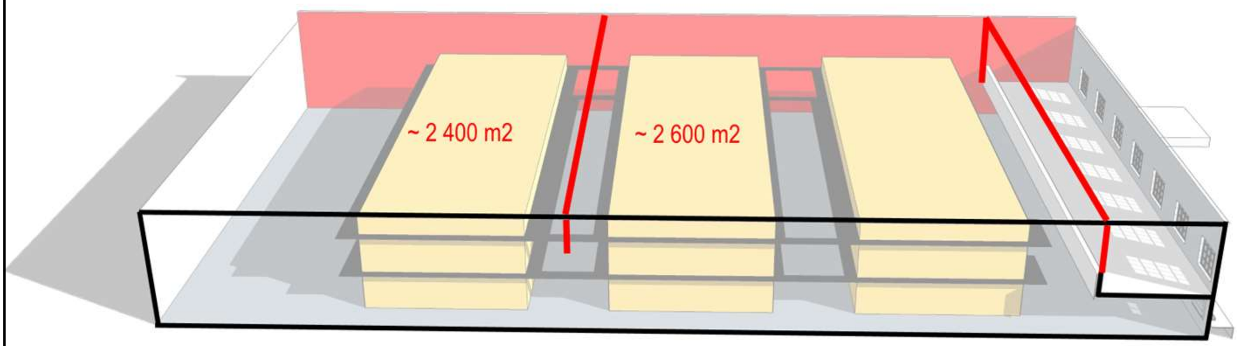
There are mezzanine levels in the zone, so the evacuation from top tier (+8,00 m) must be possible. The office must be separated from the smoke zone of archive, by at least a smoke curtain.



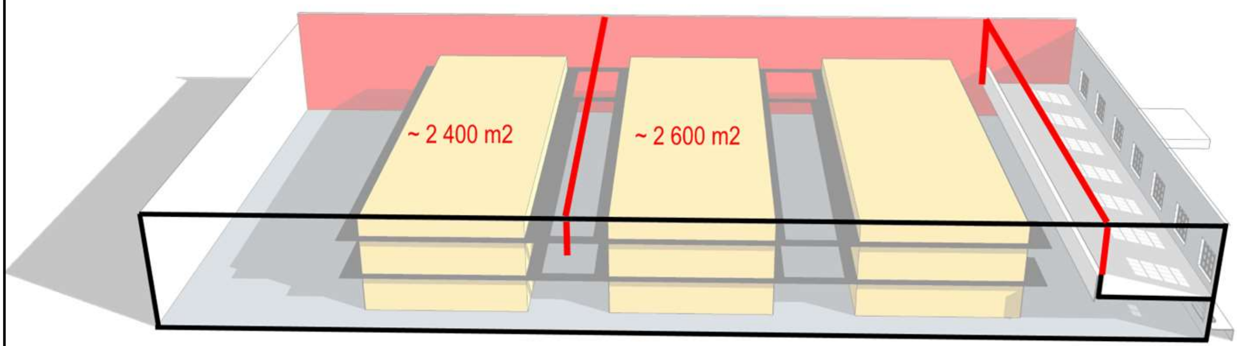
Designing a system

Standard approach – PN-B 02877. Max area of smoke zone – 2 600m²

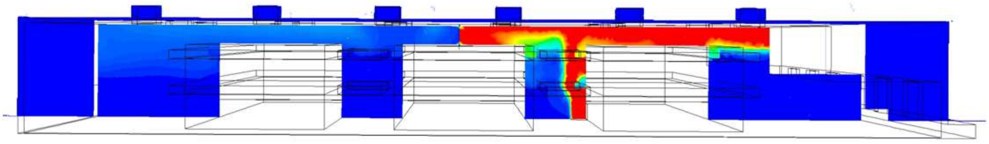
Min. Height of smoke curtain – 3,075 m, which makes smoke free height of ~ 9,00 m (does not guarantee safe evacuation!)



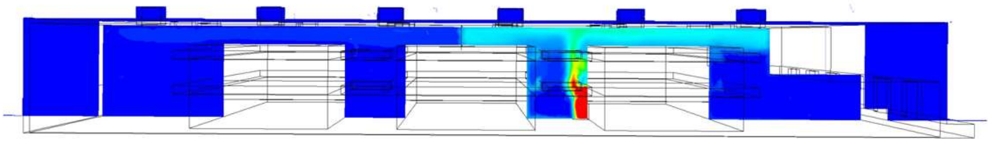
Aerodynamic area of smoke ventilators in each smoke zone – 1,50% of the zone area, which relates to 39 m²



How this system worked

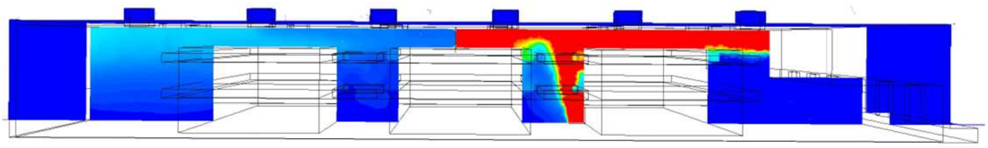


Mass density of smoke (0,00 – 0,20 g/m3) t = 10 min, 5 MW fire

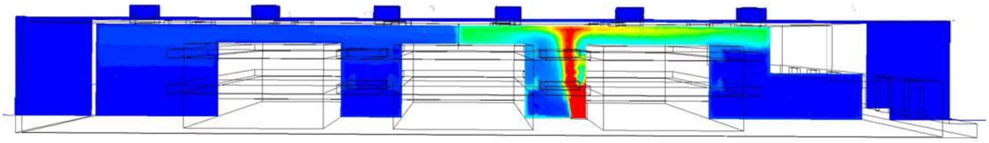


Temperature (293 – 473 K) t = 10 min, 5 MW fire

How this system worked

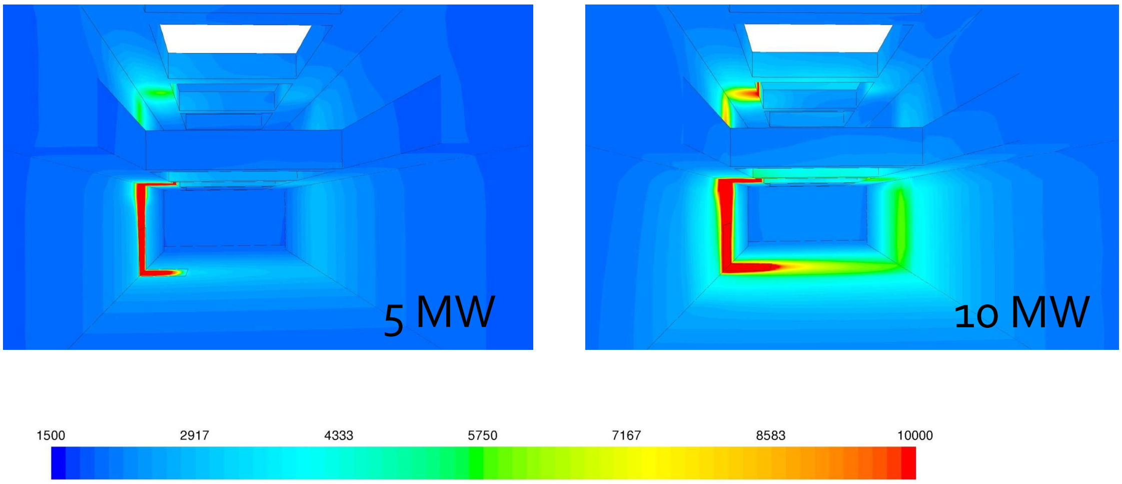


Mass density of smoke (0,00 – 0,20 g/m3) t = 10 min, 10 MW fire



Temperature (293 – 473 K) t = 10 min, 10 MW fire

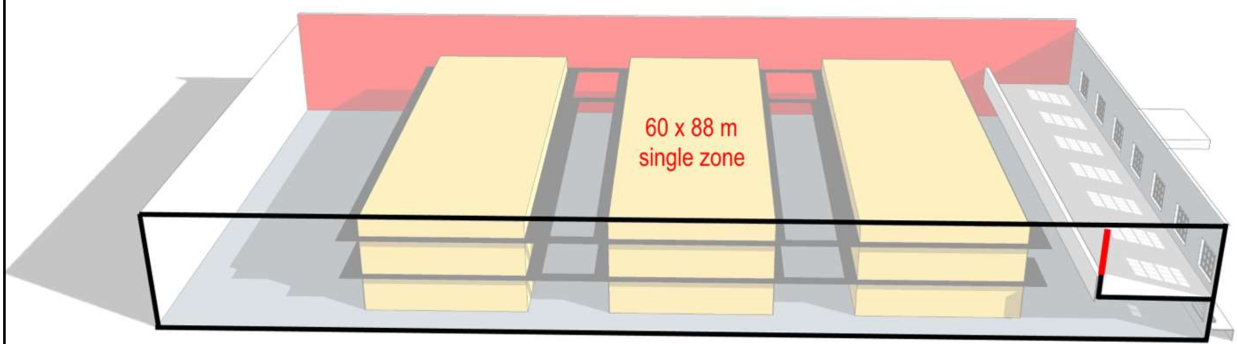
Radiation from fire



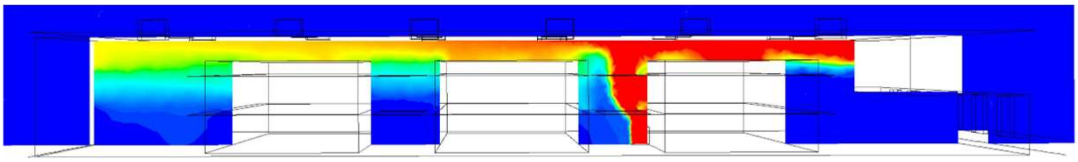
Optimizing...

Replacing PN-B approach with NFPA 204.

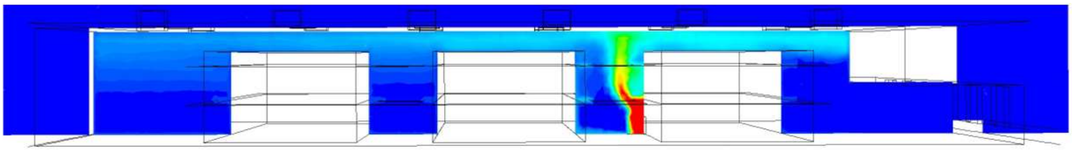
The fire for an archive may be considered as „*slow*". The calculated aerodynamic free area of the ventilators is 39,6 m²



Optimized solution

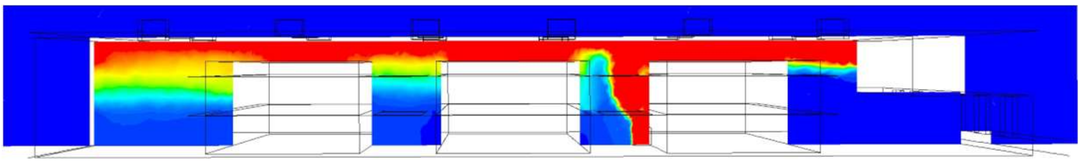


Mass density of smoke (0,00 – 0,20 g/m3) t = 10 min, 5 MW fire

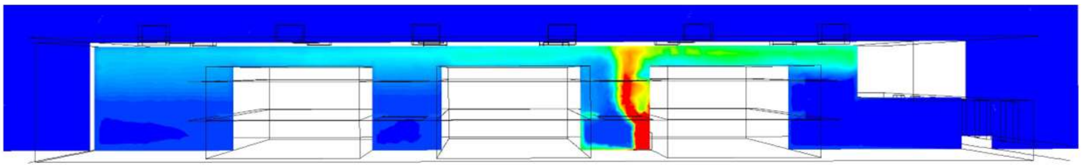


Temperature (293 – 473 K) t = 10 min, 5 MW fire

Optimized solution



Mass density of smoke (0,00 – 0,20 g/m3) t = 10 min, 10 MW fire



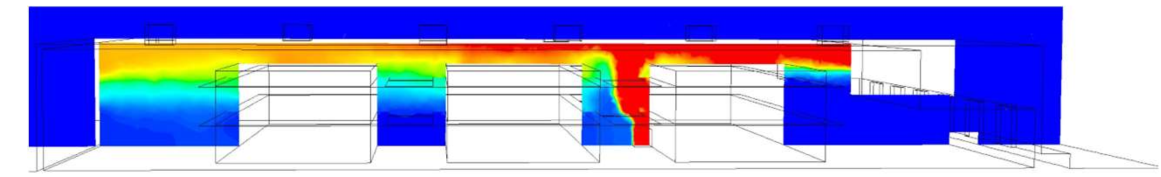
Temperature (293 – 473 K) t = 10 min, 10 MW fire

Can we go further?

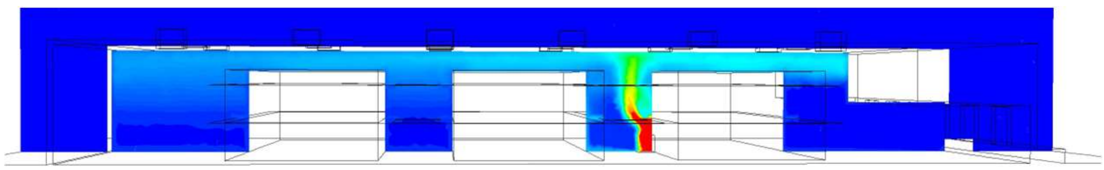
Can we further optimize the system with Computational Fluid Dynamics tools?

The search for the minimum area of ventilators

Even more optimized solution…

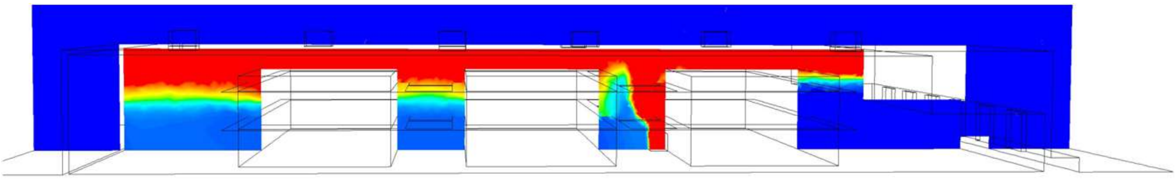


Mass density of smoke (0,00 – 0,20 g/m3) t = 10 min, 5 MW fire

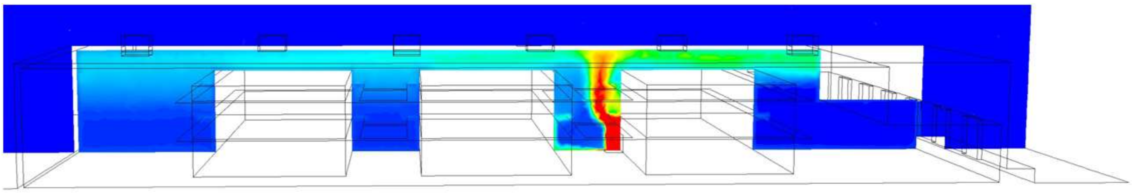


Temperature (293 – 473 K) t = 10 min, 5 MW fire

Even more optimized solution…



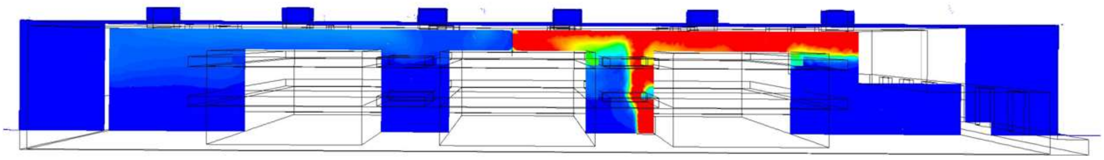
Mass density of smoke (0,00 – 0,20 g/m3) t = 10 min, 10 MW fire



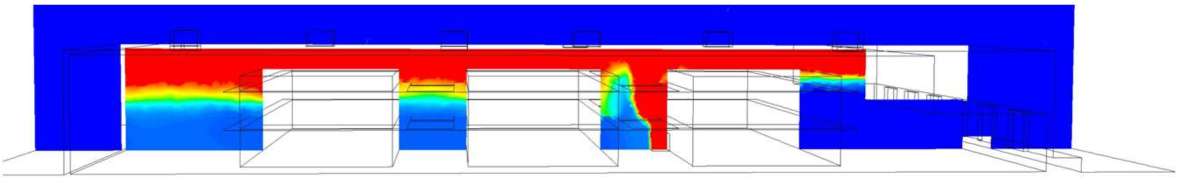
Temperature (293 – 473 K) t = 10 min, 10 MW fire

Compare the results

Mass density of smoke (0,00 – 0,20 g/m3) t = 10 min, 10 MW fire

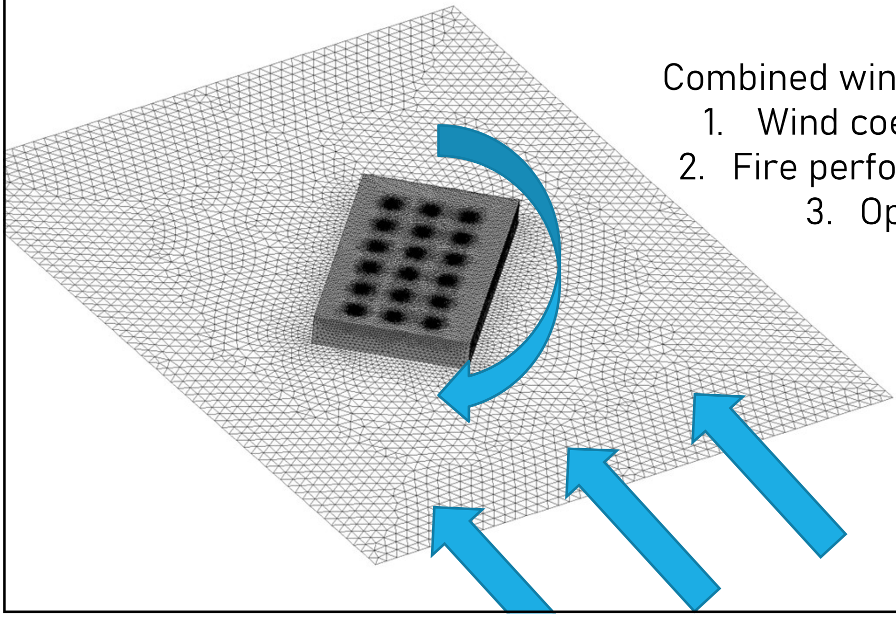


Initial effort based on the prescribed standard



Optimized to the maximum with CFD modelling

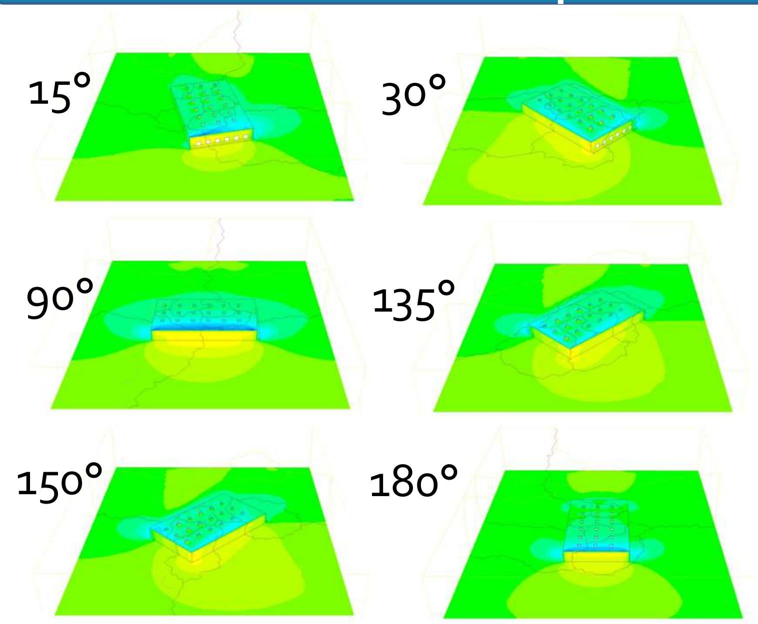
Wind



Combined wind and fire analysis:

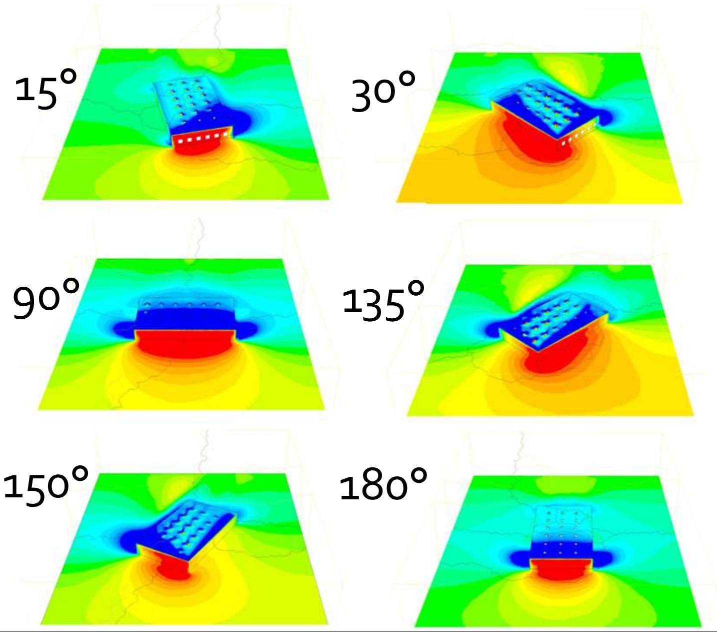
1. Wind coefficient analysis
2. Fire performance of NSHEV
3. Optimization

Wind pressure



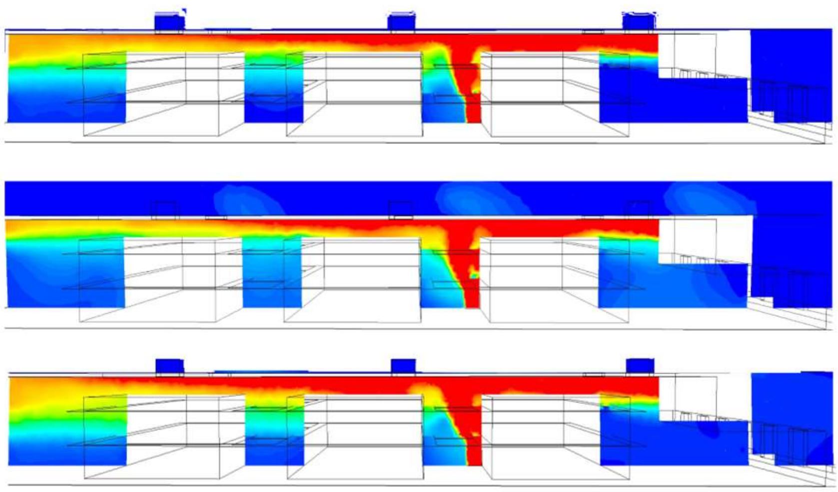
Wind pressure coefficient, for Uref = 4,67 m/s, at Zref = 10 m

Wind pressure



Wind pressure coefficient, for Uref = 10,00 m/s, at Zref = 10 m

How results change with wind

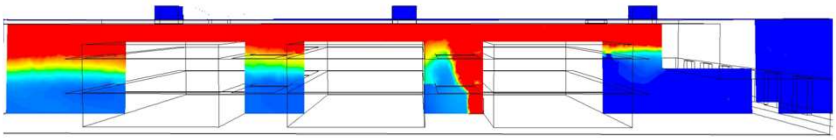


HRR = 5 MW,
α = 135°, A = 26 m²
for Uref = 1,0 m/s

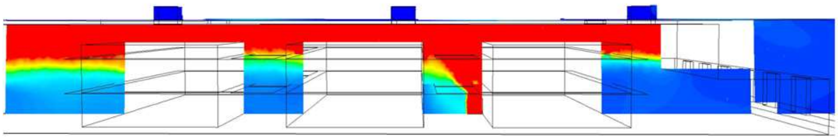
for Uref = 4,67 m/s

for Uref = 10,0 m/s

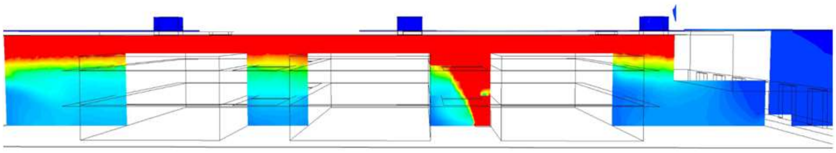
How results change with wind



HRR = 10 MW,
α = 135°, A = 26 m²
for Uref = 1,0 m/s



for Uref = 4,67 m/s



for Uref = 10,0 m/s

Vents vs sprinklers

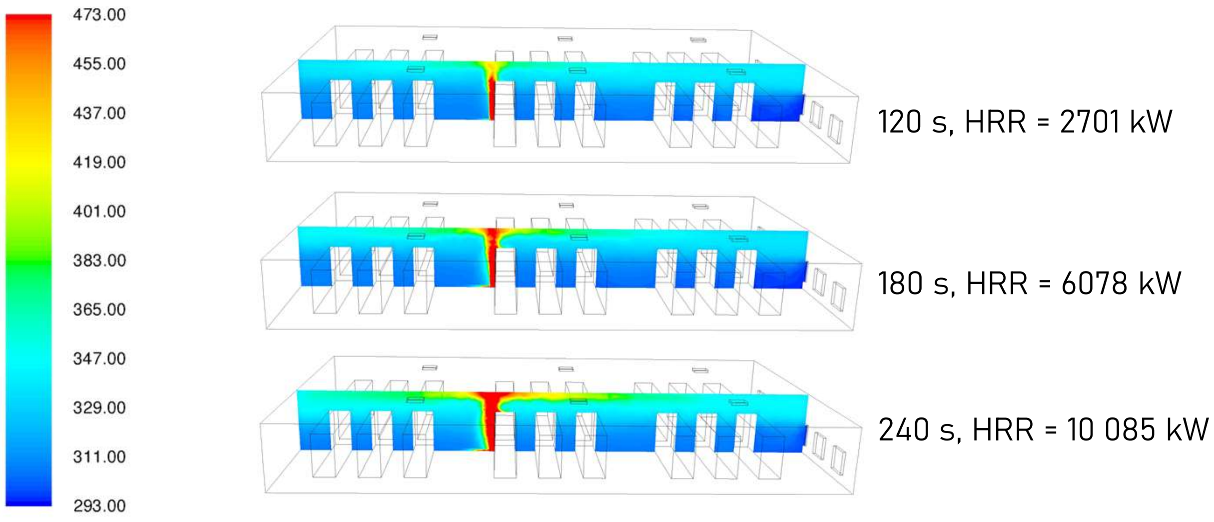
When your design goal is protection of property, you often may run into problems with ESFR sprinklers and SHEVS

Vents vs sprinklers

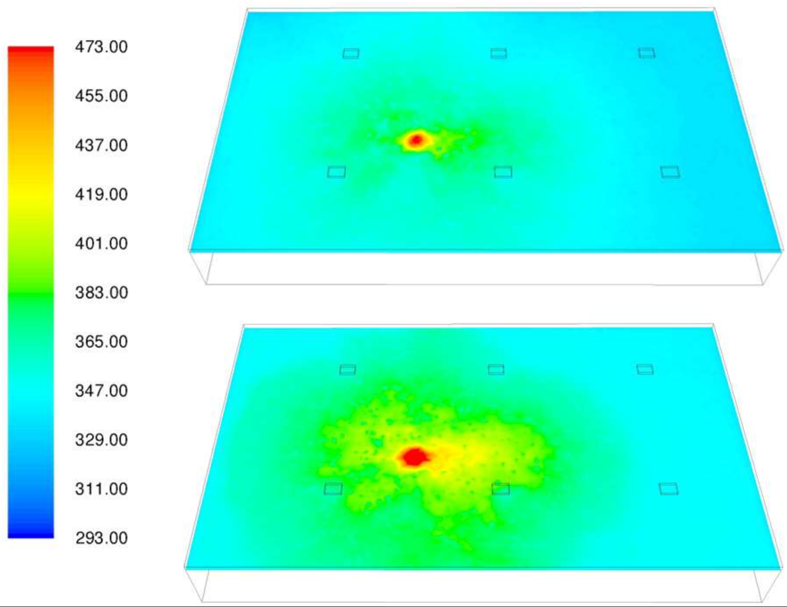
Issue with ESFR sprinklers and ventilation

- For the benefits shown in the beginning of the presentation, combination of SHEVS and sprinklers is required
- SHEVS system has to be automatic (by law), while most standards require SHEVS in manual control – ie. automatic solution is not allowed by VdS 2815 : 2013-09
- Solution is to provide high-temperature actuators (140°C, 182°C) for the ventilator, that allow sprinklers to operate long before the SHEVS, but at the same time, if for some case sprinklers do not actuate, the SHEVS system can

Vents vs sprinklers



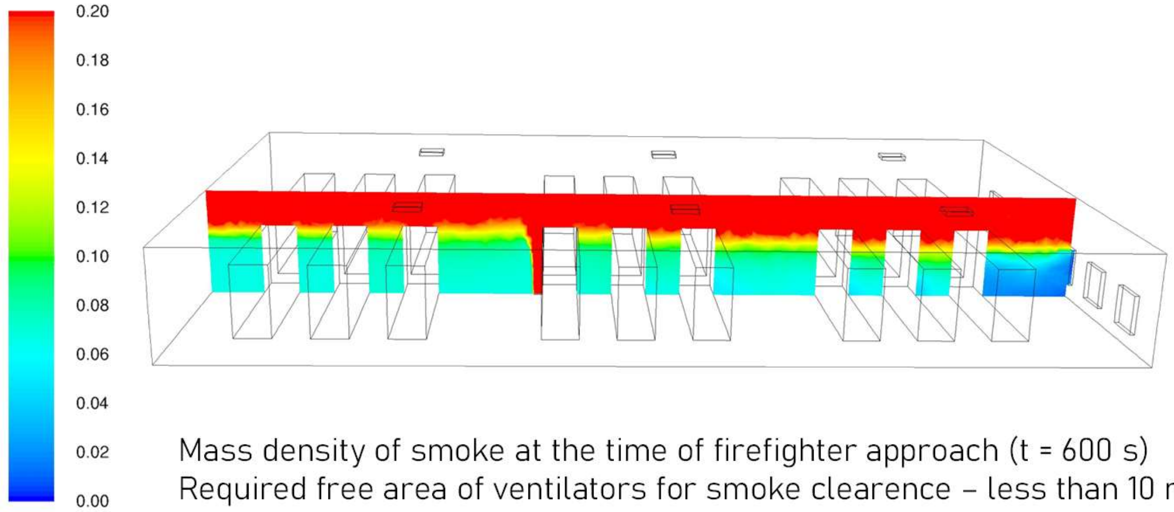
Vents vs sprinklers



Temperature (20 – 200°C)
H = 11,00 m
180 s, HRR = 6078 kW

240 s, HRR = 10 085 kW

Vents vs sprinklers



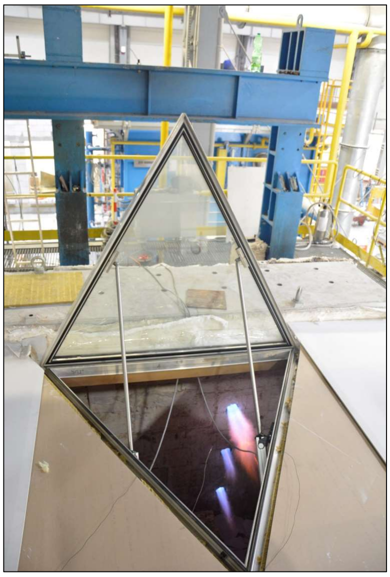
Mass density of smoke at the time of firefighter approach (t = 600 s)
Required free area of ventilators for smoke clearence – less than 10 m²

Break / 13:30 - 14:10

Agenda/ 14:10 – 16:00

- Characterisation and comparison of the technical performance of the system elements;
- Key design mistakes and stereotypes.
- Forced draught smoke and heat ventilation systems – description of system design methods and results according to the protection strategies defined above.
- Overpressure air systems – description of system design methods and best practices.
- Methodologyfor smoke volume prediction.
- Q&A session

EN 12101-2 – natural vents

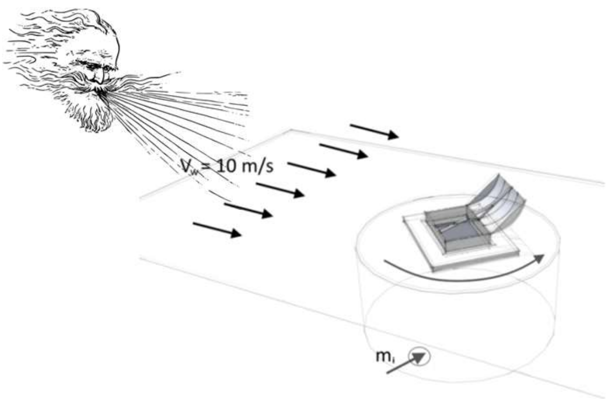


Testing and characteristics of natural smoke and heat ventilators

EN 12101-2

Re reliability
Sl snow load
Wl wind load
B fire resistance
F cold resistance
Av aerodynamic free area

EN 12101-2 – natural vents



Testing and characteristics of natural smoke and heat ventilators

EN 12101-2

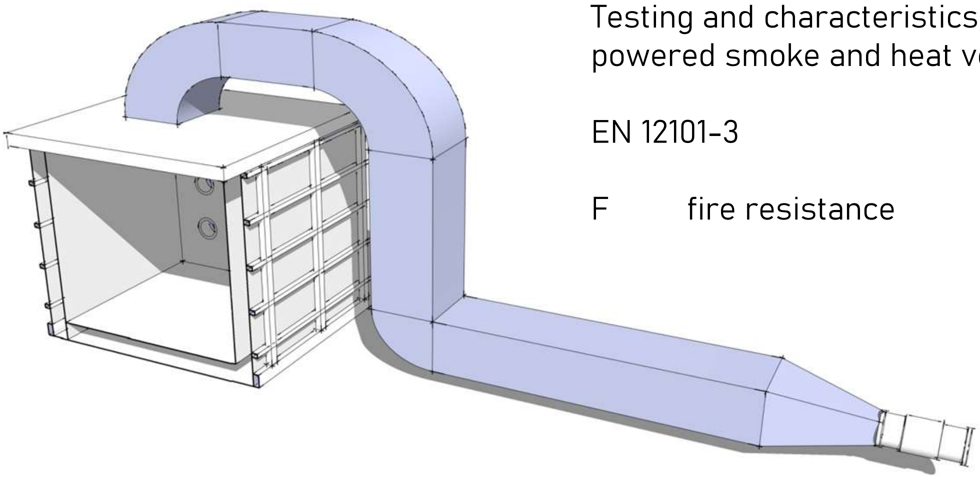
Re reliability
Sl snow load
Wl wind load
B fire resistance
F cold resistance
Av aerodynamic free area

$$C_V = \frac{\dot{m}_i}{A_{v,test}\sqrt{2\rho_{air}\Delta p_{\text{int}}}}$$

EN 12101-2 – natural vents

Atmospheric Boundary Layer Wind Tunnel, ITB

EN 12101-3 – powered vents



Testing and characteristics of powered smoke and heat ventilators

EN 12101-3

F fire resistance

EN 12101-3 – powered vents

Mechanical systems and their design

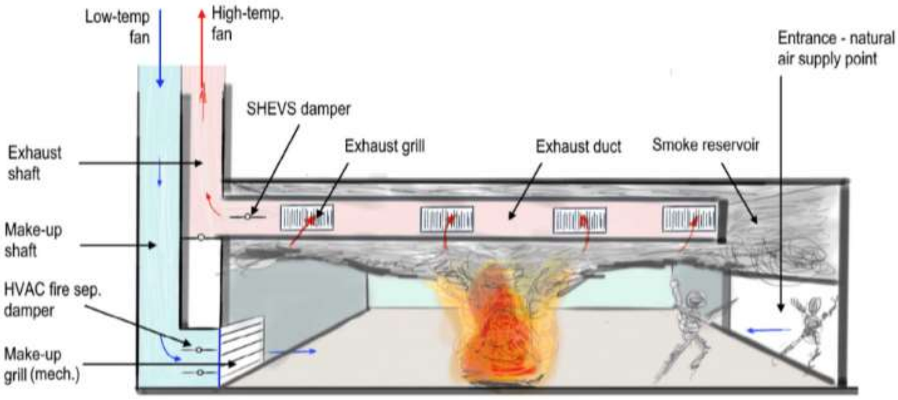


Fig. 1. Example of an SHEVS – smoke is removed from an upper layer of the compartment, and fresh air supplied close to the floor (own work).

EN 12101-3 – powered vents

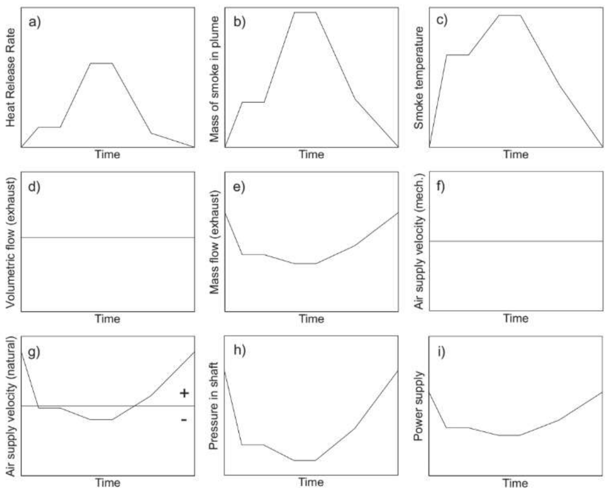


Fig. 2. Various parameters of fire, SHEVS, and flows in a transient fire, described in details in Section 2.1 (own work).

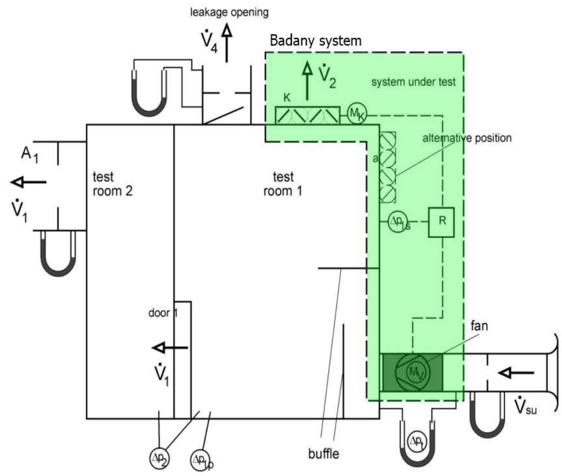
https://doi.org/10.1016/j.ijheatmasstransfer.2017.06.088

The fire itself may be described as a release of heat and mass into a system, that changes as the fire grows or decays (Fig. 2, chart(a)). The size of the fire (the rate of heat release, HRR) will deter-mine how much smoke is generated, and how much air entrains the convective plume – which essentially means that the amount of smoke that enters the reservoir will follow the growth and Decay of the fire (b). As the HRR increases, the temperature of the smoke generated within the compartment will increase as well (c), and that will lead to the drop of the density of smoke. This change of density is a key feature of the performance of smoke and heat exhaust system.

The mechanical exhaust will move the same volume of air with each rotation of the impeller – thus the volumetric exhaust rate should remain close to constant through the fire (d). As the density changes, the mass of the smoke exhausted changes as well (e). Due to the conservation of the mass in a system, this mass will be replenished through make-up air sources. Two different types of make-up solutions may be present. The mechanical (f) ones will always supply the same volume of air (and same mass, as the supply air operates at ambient conditions), while the natural ones will supply the difference between supply and exhaust (g).

If the mechanical supply/exhaust rate was designed as close to 1 at ambient temperature, in elevated temperature a reversed flow through natural opening can be observed. At the same time, the change of density of removed smoke will affect the pressure inside the ducts of the system (h). With the change of the mass moved by the impeller, but conserving the volume and rotational speed, the energy required to move the air will change, and that will lead to a change of electrical power supplied to the fan (i)

EN 12101-6 – pressurisation



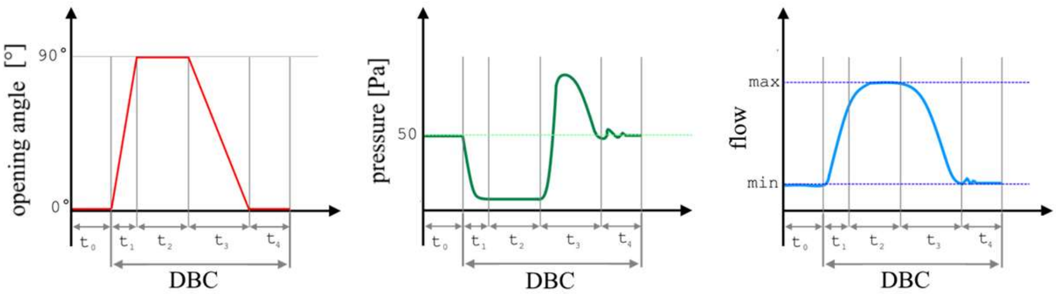
Testing and characteristics of pressurisation systems

EN 12101-6

Fu functionality
Re reliability
Du durability
Osc oscilative behaviour

EN 12101-6 – pressurisation

Testing and characteristics of pressurisation systems (EN 12101-6)



A single cycle of the test is the so-called Dynamic Behaviour Cycle (DBC). This cycle consists of:

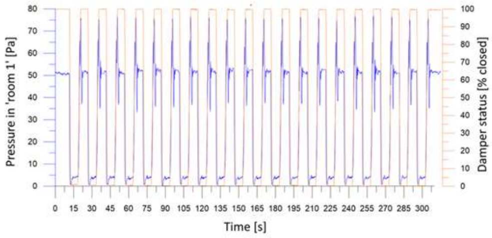
1. t_1 – the opening of the damper (doors), 1 s,
2. t_2 – delay to measure the response time of the PDS to rapid change in the pressure, 6 s,
3. t_3 – the closing of the damper (doors), 3 s,
4. t_4 – time for the pressure to stabilize in the 'room 1', 6 s.

The acceptance criteria are:

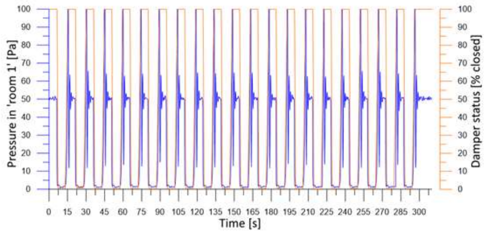
1. after t_1 the system must obtain 90% of nominal flow rate within 3 s;
2. after t_3 the system must stabilize the pressure in 80-120% of the nominal value.

EN 12101-6 – pressurisation

Testing and characteristics of pressurisation systems (EN 12101-6)



PASS



FAIL

Pressurisation (examples)

Protection of stairwells with constant flow systems

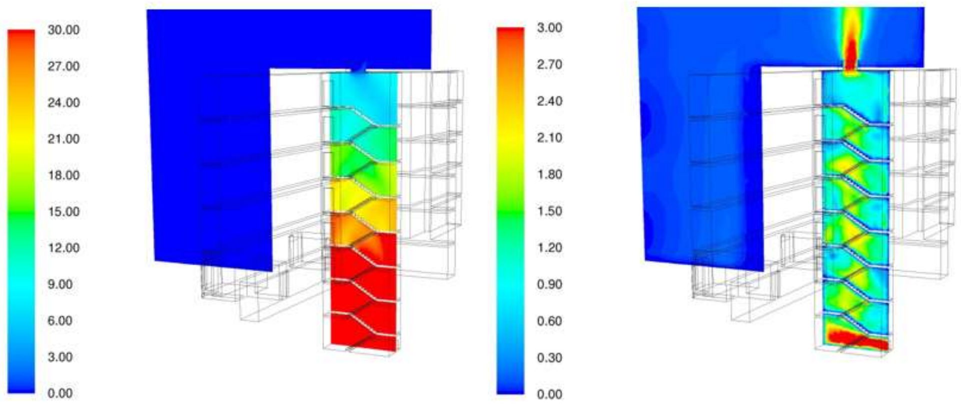
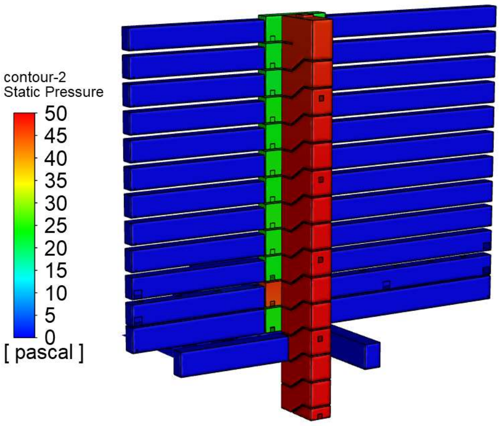
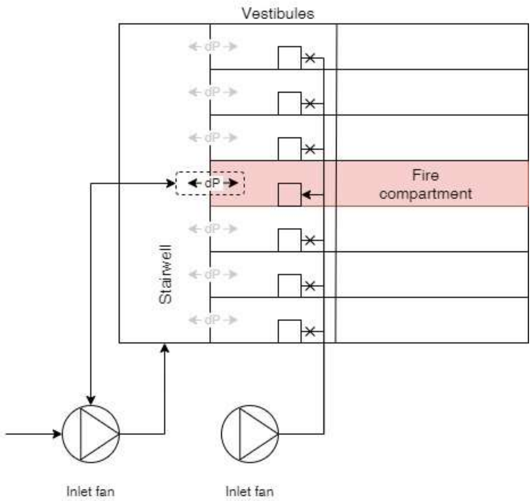


Fig. 2. Pressure (left) and flow velocity (right) in a stairwell of a building with a constant air supply at the bottom, and an opening on the top. ANSYS Fluent CFD simulations.

Pressurisation (examples)

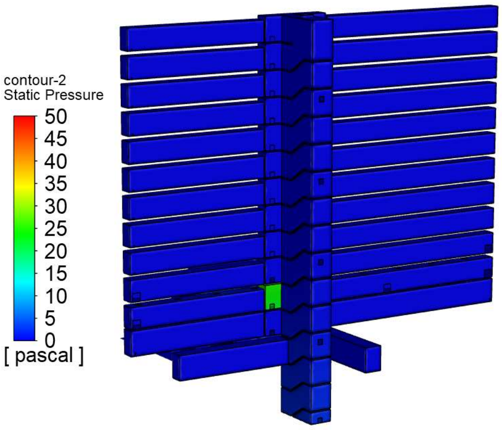
Protection of stairwells with pressurization system

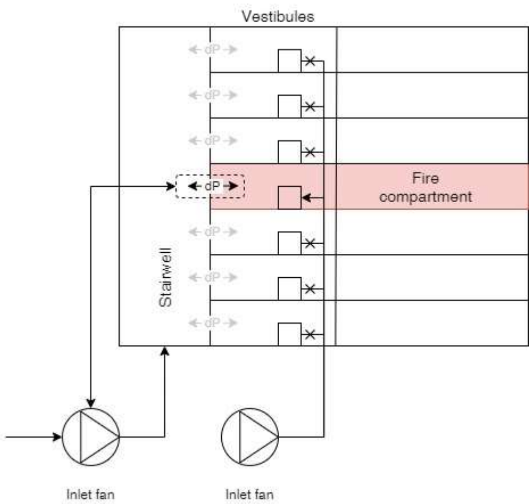




Pressurisation (examples)

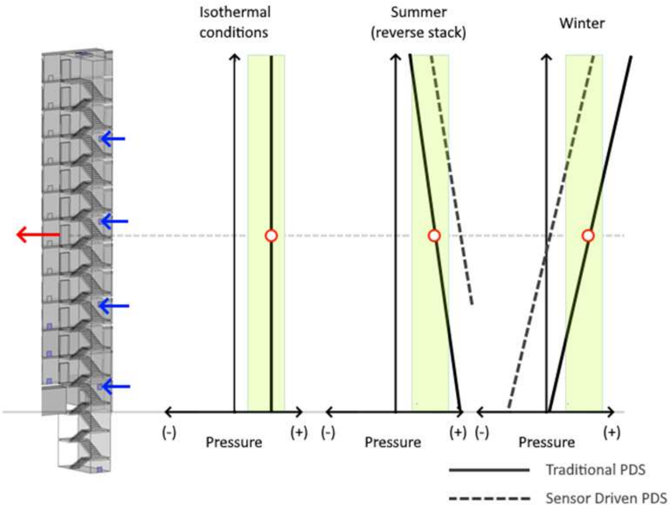
Protection of stairwells with pressurization system





Stack effect

Pressurization systems are vulnerable to stack effect



Calculating smoke volumes

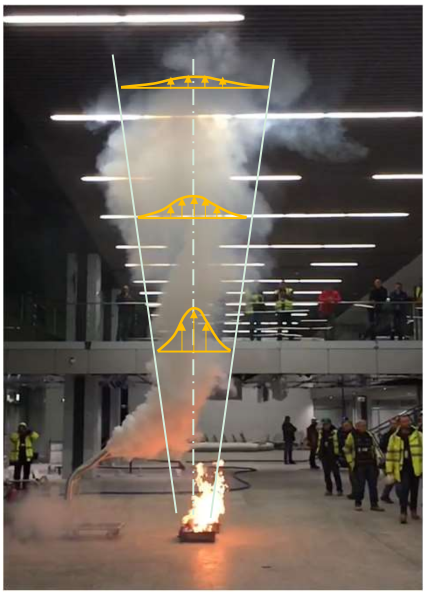


Table 1
Plume Models Used in Chosen Codes and Design Guidelines

Code or design guide	Type	Country of origin	Plume entrainment correlations (relevant section of the paper)
NFPA 92 [1]	National code	USA	Heskestad (2.5)
EN 12101-5 [22]	International code	EU	Thomas (2.2) and Heskestad (2.5)
TM19 [23]	Design guideline	UK	Heskestad (2.5) Thomas (2.2) as an alternative
NBS S21-208-1 [24]	National code	Belgium	Thomas (2.2)
BRE 368 [25]	Design guideline	Europe	Thomas (2.2) Zukoski (2.3)
BS 5588-7 [26]	Design guideline	UK	Redirect to BS EN 12101-5 [22]
BS 9999:2017 [27]	National code	UK	Redirect to BS EN 12101-5 [22]
AS 1668.3-2001 [28]	National code	Australia	Thomas (2.2)
Principles of Smoke Management [29]	Design guideline	USA	Heskestad (2.5)
Handbook of Smoke Control Eng. [30]	Design guideline	USA	Heskestad (2.5)

G. Vigne, C. Gutierrez-Montes, A. Cantizano, W. Węgrzyński, G. Rein, Review and Validation of the Current Smoke Plume Entrainment Models for Large-Volume Buildings, Fire Technol. 55 (2019) 789–816. https://doi.org/10.1007/s10694-018-0801-4.

Calculating smoke volumes

Estimating the smoke volumes in simple spaces (Thomas plume model)

$$M_f = C_e P Y^{\frac{3}{2}}$$

Coefficient (0.19 for free space, 0.38 for flow into adjacent space)

Fire perimeter

Entrainment height (from floor to edge of smoke layer)

$$T = T_a + \Theta_l \qquad \Theta_l = \frac{Q_c}{M_l * c_p}$$

To calculate smoke temperature you need the convective part of HRR (Qc) and the mass of smoke (previous equation). Cp is specific heat of air and is constant.

Calculating smoke volumes

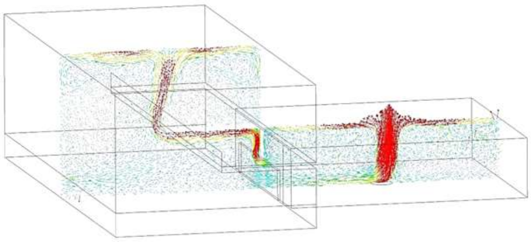
$$M_f = C_e P Y^{\frac{3}{2}}$$

$$T = T_a + \Theta_l \qquad \Theta_l = \frac{Q_c}{M_l * c_p}$$

Once you know the mass flow and the temperature, you are able to calculate the smoke volume assuming that smoke is incompressible ideal gas.

$$V_l = \frac{M_l T_l}{\rho_{amb} T_{amb}}$$

Small compartment adjacent to mall



Example

Convective part of HRR	Q_c= 2 500 kW
Area of fire	A = 5 m^2
Perimeter of fire	P = 9 m

Fire flows from one room to another (Ce = 0.38)
Design smoke layer height Y = 6,00 m

Small compartment adjacent to mall

$$M_f = C_e P Y^{\frac{3}{2}} \qquad M_f = 0{,}38 * 9 * 6^{\frac{3}{2}} = 50{,}26 \frac{kg}{s}$$

Step 1: calculate the mass of smoke

$$\Theta_l = \frac{Q_c}{M_l * c_p} \qquad \Theta_l = \frac{2500}{50{,}26 * 1{,}01} = 34{,}5\ K$$

Step 2: calculate the smoke temperature rise

$$T = T_a + \Theta_l \qquad T = 293 + 34{,}5 = 327\ K = 54{,}5\ °C$$

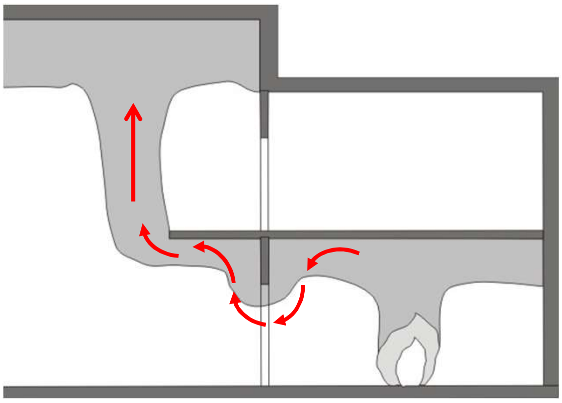
Step 3: calculate the smoke temperature

$$V_l = \frac{M_l T_l}{\rho_{amb} T_{amb}} \qquad V_l = \frac{50{,}26 * 327}{1{,}205 * 293} = 46{,}81 \frac{m^3}{s} = 168\ 000 \frac{m^3}{h}$$

Step 4: calculate the volume of smoke

Complex mall

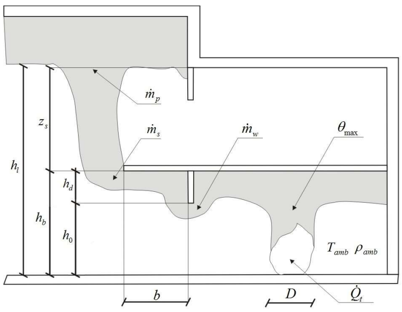
Estimating the smoke volumes in complex spaces (based on NFPA 92) – the properties

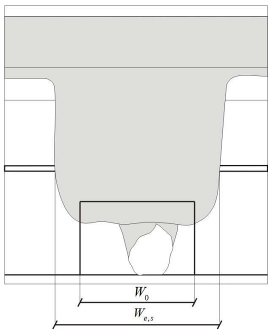


Complex mall

Estimating the smoke volumes in complex spaces (based on NFPA 92) – input

Convective HRR	Q_c= 2 500 kW
Area	A = 5 m^2
Perimeter	P = 9 m
Compartment height	Y = 4,60 m;
Opening height	h = 3,60 m;
Opening width	w = 8 m;
Height of balcony	h = 7,32 m;
Depth of balcony	L = 2 m;
Design layer height	h = 12,6 m;
From balcony to upper layer	Y= 5,28 m;





Complex mall

$W = w + b$

$W = 8 + 2 = 10\ m$

Step 1: find the width of the spill plume

$m = 0{,}36(QW^2)^{\frac{1}{3}}(z_b + 0{,}25H)$

$m = 0{,}36(2500 * 10^2)^{\frac{1}{3}}(5{,}28 + 0{,}25 * 7{,}32) = 181.96\ kg/s$

Step 2: calculate the mass flow in the spill plume

$$T_a = T_0 + \frac{K_c + Q_c}{m\ C_p}$$

$$T_a = 293 + \frac{1 * 2500}{181{,}96 * 1{,}01} = 306{,}74\ K = 33{,}74°C$$

Step 3: calculate the smoke temperature

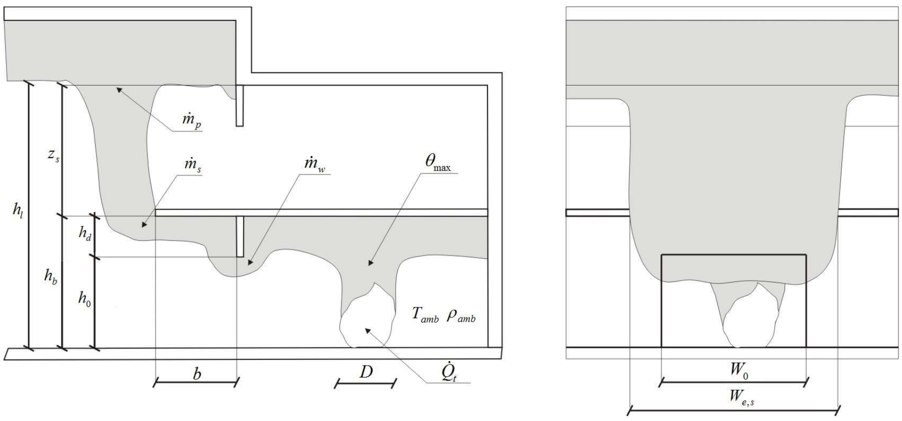
$$V = \frac{mRT_a}{P_a}$$

$$V = \frac{181.96 * 287 * 306{,}74}{101325} = 158{,}09\frac{m^3}{s} = \mathbf{569100}\frac{m^3}{h}$$

Step 4: calculate the volume of smoke

Complex mall

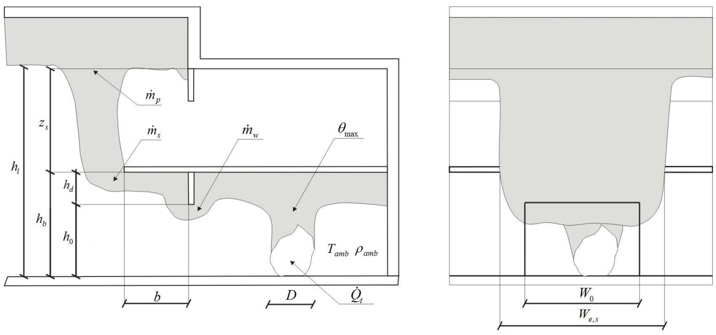
Estimating the smoke volumes in complex spaces – same case study but with BS approach



Complex mall

Estimating the smoke volumes in complex spaces – same case study but with BS approach

Convective HRR	Q_c= 2 500 kW
Area	A = 5 m²
Perimeter	P = 9 m
Compartment height	Y = 4,60 m;
Opening height	h = 3,60 m;
Opening width	w = 8 m;
Height of balcony	h = 7,32 m;
Depth of balcony	L = 2 m;
Design layer height	h = 12,6 m;
From balcony to upper layer	Y= 5,28 m;



Complex mall

$$M_w = \frac{C_e P W h^{\frac{3}{2}}}{\left[W^{\frac{3}{2}} + \frac{1}{C_d} * \left(\frac{C_e P}{2}\right)^{\frac{2}{3}}\right]^{\frac{3}{2}}}$$

Step 1: find the mass flow in the opening

$$M_w = \frac{0,337 * 9 * 8 * 3,60^{\frac{3}{2}}}{\left[8^{\frac{2}{3}} + \frac{1}{0,65} * \left(\frac{0,337 * 9}{2}\right)^{\frac{2}{3}}\right]^{\frac{3}{2}}} = 10,4\frac{kg}{s}$$

$$M_b = 2 * M_w = 20,8\frac{kg}{s}$$

Step 2: find the mass flow at the Edge of balcony (2 x mass flow at opening)

Complex mall

$$M_p = 0,16 * y * Q_c^{\frac{1}{3}} * L^{\frac{2}{3}} + 0,0014 * Q_c + 1,40 * M_b$$

$$M_p = 0,16 * 5,3 * 2500^{\frac{1}{3}} * 24^{\frac{2}{3}} + 0,0014 * 2500 + 1,40 * 20,8 = 127,1 \frac{kg}{s}$$

Step 3: find the mass flow in the plume

$$\Theta_l = \frac{Q_c}{M_l * c_p} \qquad \Theta_l = \frac{2500}{127,1 * 1,01} = 19,5\ K$$

$$T = T_a + \Theta_l$$

$$T = 293 + 19,5 = 312,5\ K = 39,5\ ^\circ C$$

Step 4: find the temperature of the smoke

$$V_l = \frac{M_l T_l}{\rho_{amb} T_{amb}}$$

$$V_l = \frac{127,1 * 312,5}{1,205 * 293} = 112,5 \frac{m^3}{s} = 405\,000 \frac{m^3}{h}$$

Step 5: find the volume of the smoke

Ekonomikas ministrija

CMB | INŽENIERU KOMPETENCES CENTRS

Thank you for attention!

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