Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes - Proposal for a simplified method for sizing smoke ventilation systems in atria.

Jean-Philippe Vériter
Preface

I would like to thank the following people for their contribution to the outcome of this thesis.

Bart Merci, my supervisor, who believed from the beginning in the usefulness of this study.

Pierre Spehl, who is the person who introduced me to the fire safety engineering and to the design of smoke ventilation systems. I would like to address him a special thanks for his role in my professional career.

My wife Marjolein, my children Allan and Emily, who supported me in this effort and have accepted the sacrifices on family life.

All who have encouraged me, especially Thilde, without which I still doubt that I could complete this project.
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August 8, 2012

Jean-Philippe Vériter
Modern architecture often includes the presence of an atrium inside the building. It creates a vertical space that, in the event of fire, allows the spread of hot smoke between different floors. To limit the risk of this effect, a smoke ventilation system (SHEVS) can be placed on top of the atrium.

This installation, which can be natural (vents) or mechanical (motorized), must be sized to meet design criteria such as the height of the smoke layer base or its temperature.

In both cases (natural or mechanical SHEVS), the mass flow rate of the smoke entering the smoke layer in the atrium needs to be calculated. To achieve this, the air entrainment within the smoke plume that occurs along the path of the smoke flow, from the fire room until the base of the smoke layer in the reservoir must be evaluated.

This evaluation can either be performed using a numerical modeling (CFD), or an empirical method of calculation.

The aim of this study is to compare existing empirical methods in terms of their range of validity, their numerical results and ease of use. Based on these criteria, a new empirical method is proposed.

The empirical method described in the BRE368 and in the TR12105-5 is a basis for this study being an excepted reference method in both Belgium and across Europe.

Keywords: smoke, spill plume, empirical method, atrium, SHEVS
Extended abstract

Context
Modern architecture often includes the presence of an atrium inside the building. It creates a vertical space that, in the event of fire, allows the spread of hot smoke between different floors. To limit the risk of this effect, a smoke ventilation system (SHEVS) can be placed on top of the atrium.

This installation, which can be natural (vents) or mechanical (motorized), must be sized to meet design criteria such as the height of the smoke layer base or its temperature.

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This evaluation can either be performed using a numerical modeling (CFD), or an empirical method of calculation. This study focuses on the second approach.

Literature review and comparison between existing empirical methods
The study began with a literature review which aimed to compare the existing empirical methods to quantify the air entrainment into smoke spill plumes. 10 empirical methods developed between the early 80's and 2011 were compared.

There is on the one hand a complex method (BRE-method developed by the Building Research Establishment) which involves a large amount of parameters and calculation steps, and on the other hand a series of 9 simplified methods which involves between 4 and 6 parameters and allows a 1- or 2-steps calculation process. All the reviewed methods assume that the smoke flow leaving the fire room doesn't contain unburned gases from the pyrolysis.

The comparison highlighted the following points:

- None of the existing simplified methods covers the full scope of the BRE-method. There are always restrictions with regard to the type of spill plume (free/adhered; entrainment/no entrainment into the ends of the spill plume).
- There is no satisfactory matching between the results of the BRE-method and those of the existing simplified methods. The results generally differ from 20 to 40%, considering in each case the best matching simplified method.

Consequently, none of the existing simplified methods could serve as an acceptable alternative to the BRE-method.

Analysis of the BRE-method
The analysis of the calculation flow of the BRE-method was conducted in order to identify its input parameters and some ‘useful’ intermediate parameters that are
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necessary for design issues (sizing of the channelling screens, thermal requirements for facade).

A global sensitivity analysis has been performed with respect to all the input parameters. It has shown that 9 of the 10 identified input parameters have a significant effect on the result of the calculation of the mass flow rate in the spill plume.

The performed analyzes led to the development of a simplified BRE-method which is based on a 2-steps calculation process:

STEP 1: the calculation of the mass flow rate under the balcony ($m_B$);

STEP 2: the calculation of the mass flow rate in the spill plume ($m_X$) which can be decomposed as follows:

- STEP 2.1: the calculation of the air entrainment along the width of the spill plume ($m_{X,\text{width}}$);
- STEP 2.2: the calculation of the air entrainment within the ends of the spill plume ($m_{X,\text{ends}}$).

**Search for a simplified BRE-method**

Formally, only STEP 2 is considered since the calculation process of STEP 1 included in the BRE-method is simple enough.

Basic analysis of the graphs of $m_X$ as a function of $X$ (height of rise in the atrium) clearly shows that:

- $m_{X,\text{width}}$ is a linear function of $X$ and can be expressed as: $m_{X,\text{width}} = K_1 X + K_2 + K_{mB} m_B$
- $m_{X,\text{ends}}$ is a quadratic function of $X$ that passes through the origin and can be expressed as: $m_{X,\text{ends}} = K_3 X^2 + K_4 X$

A detailed sensitivity analysis has given the value of $K_1, K_2, K_{mB}, K_3$ and $K_4$ as a function of the parameters $m_B, Q_C$ and $W_B$.

Finally the value of $m_{X,\text{width}}$ and $m_{X,\text{ends}}$ can be expressed by the following.

- For free plumes:
  
  $$m_{X,\text{width}} = 0,205 Q_C \frac{1}{3} W_B^{2/3} X + 1,65 m_B + 0,0033 Q_C$$
  
  $$m_{X,\text{ends}} = 0,03 \left( \frac{Q_C}{W_B} \right)^{1/3} X^2 + \frac{0,4 m_B Q_C^{2/15}}{W_B} X$$

- For adhered plums:
  
  $$m_{X,\text{width}} = 0,078 Q_C \frac{1}{3} W_B^{2/3} X + 1,50 m_B + 0,0033 Q_C$$
  
  $$m_{X,\text{ends}} = 0,006 \left( \frac{Q_C}{W_B} \right)^{1/3} X^2 + \frac{0,19 m_B Q_C^{2/15}}{W_B} X$$
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where:

\( m_{X,\text{ends}} \) = air entrainment that occurs into the ends of the spill plume, between the spill edge and the height \( X \) in the atrium [kg/s]

\( m_{X,\text{width}} \) = mass flow rate at a height \( X \) in the atrium, where no air entrainment occurs into the ends of the spill plume [kg/s]

\( Q_C \) = convective part of the heat release rate [kW]

\( W_B \) = width of the smoke flow at the spill edge [m]

\( X \) = current height where the mass flow rate \( m_X \) is considered [m]

\( m_B \) = mass flow rate of smoke under the balcony [kg/s]

The proposed equations give a good agreement with the original BRE-method:

- the largest observed relative difference is less than 8%;
- the average relative difference for free plumes is less than 1%;
- the average relative difference for adhered plumes is less than 2%.

Conclusions

Wherever the BRE-method is considered as an acceptable design standard, the proposal for a simplified BRE-method developed in this study is a satisfactory alternative.

This simplification has two main advantages: it reduces the risk of miscalculation and allows quick check by the authorities.
Uitgebreide samenvatting

Context
Moderne architectuur voorziet vaak de aanwezigheid van een atrium in het gebouw. Het creëert een verticale ruimte die, in geval van brand, de verspreiding van warme rook tussen verschillende bouwlagen mogelijk maakt. Om het risico van dit effect te beperken, kan een rook- en warmteafvoerinstallatie (RWA) bovenop het atrium voorzien worden.

Deze natuurlijke of mechanische installatie wordt gedimensioneerd om aan bepaalde ontwerpcriteria te voldoen zoals de hoogte van de rooklaag of haar temperatuur.

In beide gevallen (natuurlijke of mechanische RWA) dient het massadebiet van de rook die de rooklaag in het atrium bereikt, berekend te worden. Daarvoor moet de luchtinmenging die plaatsvindt langs het traject van de rookpluim geëvalueerd worden, vanuit de brandhaard tot aan de rooklaag in het atrium.

Dit kan hetzij door middel van numerieke modelering, hetzij door het toepassen van een empirische berekeningsmethode. Deze studie richt zich op de tweede benadering.

Literatuuronderzoek en vergelijking tussen de bestaande empirische methoden
De studie begon met een literatuuronderzoek met als doel om de bestaande empirische berekeningsmethoden voor de luchtinmenging in lijnpluimen te vergelijken. 10 empirische methoden, ontwikkeld tussen de vroege jaren tachtig en 2011, werden met elkaar vergeleken.

Er is enerzijds een complexe methode (BRE-methode ontwikkeld door de Building Research Establishment) met een groot aantal parameters en berekeningsstappen en anderzijds een reeks van 9 vereenvoudigde methoden met 4 tot 6 parameters en één- of tweestappen rekenproces. Alle beoordeelde methoden gaan ervan uit dat de rookgassen die uit de getroffen ruimte stromen geen onverbrande gassen uit pyrolyse bevatten.

De vergelijking heeft gewezen op de volgende punten:

- Geen van de bestaande vereenvoudigde methoden beslaat het volledige toepassingsgebied van de BRE-methode. Er zijn altijd beperkingen met betrekking tot het soort lijnpluim (dubbelzijdig/enkelzijdig, met al dan niet luchtinmenging op de uiteinden van de lijnpluim).
- Er is geen bevredigende overeenkomst tussen de BRE-methode en de bestaande vereenvoudigde methoden. De resultaten verschillen over het algemeen van 20 tot 40% in elk specifiek geval, rekening houdend met de best passende vereenvoudigde methode.

Bijgevolg kan geen van de bestaande vereenvoudigde methoden dienen als een aanvaardbaar alternatief voor de BRE-methode.
Analyse van de BRE-methode

De analyse van het rekenproces van de BRE-methode werd uitgevoerd om de invoerparameters en een aantal 'nuttige' tussenresultaten te identificeren. Deze laatste zijn gegevens die betekenisvol zijn voor de ontwerper (bepaling van de hoogte van de 'channeling screens', thermische eisen voor de gevel).

Een globale gevoeligheidsanalyse werd uitgevoerd ten opzichte van alle invoerparameters. Het is gebleken dat 9 van de 10 geïdentificeerde invoerparameters een betekenisvol effect hebben op het resultaat van de berekening van de massastroom in de lijnpluim.

De uitgevoerde analyse leidde tot de ontwikkeling van een vereenvoudigde BRE-methode die gebaseerd is op een tweestaps rekenproces:

- **STAP 1**: de berekening van de massastroom onder het balkon \((m_B)\);
- **STAP 2**: de berekening van de massastroom in de lijnpluim \((m_X)\) die als volgt kan worden uitgesplitst:
  - **STAP 2.1**: de berekening van de luchtinmenging langs de breedte van de lijnpluim \((m_{X,\text{width}})\);
  - **STAP 2.2**: de berekening van de luchtinmenging op de uiteinden van de lijnpluim \((m_{X,\text{ends}})\).

Op zoek naar een vereenvoudigde BRE-methode

Formeel, zal enkel STAP 2 beschouwd worden omdat het rekenproces van STAP 1 in de BRE-methode simpel genoeg is.

De analyse van de grafieken van \(m_X\) in functie van \(X\) (hoogte van de stijging van de lijnpluim in het atrium) heeft duidelijk aangetoond dat:

- \(m_{X,\text{width}}\) een lineaire functie is van \(X\), die als volgt uitgedrukt kan worden:
  \[
  m_{X,\text{width}} = K_1 X + K_2 + K_{mB} m_B
  \]
- \(m_{X,\text{ends}}\) een kwadratische functie is van \(X\), die als volgt uitgedrukt kan worden:
  \[
  m_{X,\text{ends}} = K_3 X^2 + K_4 X
  \]

Een gedetailleerde gevoeligheidsanalyse heeft aanleiding gegeven tot de uitdrukkingen van \(K_1, K_2, K_{mB}, K_3\) en \(K_4\) als functies van de parameters \(m_B, Q_C, W_B\).

We hebben uiteindelijk de volgende uitdrukkingen van \(m_{X,\text{width}}\) en \(m_{X,\text{ends}}\) gevonden.

- Voor dubbelzijdige lijnpluimen:

  \[
  m_{X,\text{width}} = 0.205 Q_C^{1/3} W_B^{2/3} X + 1.65 m_B + 0.0033 Q_C
  \]

  \[
  m_{X,\text{ends}} = 0.03 \left(\frac{Q_C}{W_B}\right)^{1/3} X^2 + \frac{0.4 m_B Q_C^{2/15}}{W_B} X
  \]
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- Voor enkelzijdige lijnpluimen:

\[ m_{X,\text{width}} = 0.078 Q_C^{1/3} W_B^{2/3} X + 1.50 m_B + 0.0033 Q_C \]

\[ m_{X,\text{ends}} = 0.006 \left( \frac{Q_C}{W_B} \right)^{1/3} X^2 + \frac{0.19 m_B Q_C^{2/15}}{W_B} X \]

waar:

- \( m_{X,\text{ends}} \) = luchtmenging die plaatsvindt op de uiteinden van de lijnpluim, tussen het rotatiepunt en een hoogte \( X \) in het atrium [kg/s]
- \( m_{X,\text{width}} \) = massadebiet op een hoogte \( X \) in the atrium, wanneer geen luchtmenging plaatsvindt op de uiteinden van de lijnpluim [kg/s]
- \( Q_C \) = convectieve deel van het vermogen van de brandhaard [kW]
- \( W_B \) = breedte van de rookstroom ter plaatse van het rotatiepunt [m]
- \( X \) = hoogte waar het massadebiet \( m_X \) beschouwd wordt [m]
- \( m_B \) = massadebiet van de rookstroom onder het balkon [kg/s]

De voorgestelde formules geven een goede overeenkomst met de originele BRE-methode:

- het grootste waargenomen relatieve verschil is minder dan 8%;
- het gemiddelde relatieve verschil voor dubbelzijdige lijnpluimen is minder dan 1%;
- het gemiddelde relatieve verschil voor enkelzijdige lijnpluimen is minder dan 2%.

Conclusies

Daar waar de BRE-methode beschouwd wordt als een aanvaardbare berekeningsmethode, kan de vereenvoudigde BRE-methode die ontwikkeld werd in deze studie toegepast worden als een waardevol alternatief.

De vereenvoudiging van de berekeningsmethode heeft twee belangrijke voordelen: het vermindert het risico op foutieve berekening en laat een snelle controle door de overheden toe.
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Abbreviations

BRE Building Research Establishment
CFD Computational fluid dynamics
CIBSE Chartered Institute of Building Services Engineers
HRR Heat release rate
SHEVS Smoke and heat exhaust ventilation system
### Nomenclature

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<td>$g$</td>
<td>= acceleration due to the gravity = 9.81 [m/s$^2$]</td>
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<td>$m_B$</td>
<td>= mass flow rate of smoke under the balcony [kg/s]</td>
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<tr>
<td>$m_i$</td>
<td>= mass flow rate of the smoke flow at the section $i$ [kg/s]</td>
</tr>
<tr>
<td>$m_L$</td>
<td>= mass flow rate entering the smoke layer in the atrium [kg/s]</td>
</tr>
<tr>
<td>$m_R$</td>
<td>= mass flow rate after rotation [kg/s]</td>
</tr>
<tr>
<td>$m_W$</td>
<td>= mass flow rate at the opening of the fire room [kg/s]</td>
</tr>
<tr>
<td>$m_X$</td>
<td>= mass flow rate at a height $X$ above the spill edge [kg/s]</td>
</tr>
<tr>
<td>$m_{X,ends}$</td>
<td>= air entrainment that occurs into the ends of the spill plume, between the spill edge and the height $X$ in the atrium [kg/s]</td>
</tr>
<tr>
<td>$m_{X,width}$</td>
<td>= mass flow rate at a height $X$ in the atrium, where no air entrainment occurs into the ends of the spill plume [kg/s]</td>
</tr>
<tr>
<td>$t_i$</td>
<td>= temperature of the smoke at the section $i$ [°C]</td>
</tr>
<tr>
<td>$t_R$</td>
<td>= temperature of the smoke layer after rotation (spill edge) [°C]</td>
</tr>
<tr>
<td>$t_X$</td>
<td>= temperature of the smoke layer at a current height = $X$ [°C]</td>
</tr>
<tr>
<td>$A_I$</td>
<td>= area of the inlets [m$^2$]</td>
</tr>
<tr>
<td>$A_L$</td>
<td>= horizontal area of the smoke layer in the atrium [m$^2$]</td>
</tr>
<tr>
<td>$A_V$</td>
<td>= throat area of the vents in the roof of the atrium [m$^2$]</td>
</tr>
<tr>
<td>$B$</td>
<td>= length of the balcony, measured between the opening of the fire room and the spill edge [m]$^1$</td>
</tr>
<tr>
<td>$C$</td>
<td>= specific heat of air at constant pressure $\approx$ 1 [kJ/kg.K]</td>
</tr>
</tbody>
</table>
| $C_e$  | = coefficient of entrainment in the fire room  
= 0.19 for large rooms  
= 0.337 for small rooms |
| $C_d$  | = coefficient of discharge of the opening  
= 0.65 ...1 |
| $C_I$  | = coefficient of discharge of the inlets |

---

$^1$ $B$ and $W_w$ are represented in Figure 2-4 (page 12).
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes -
Proposal for a simplified method for sizing smoke ventilation systems in atria

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{LR} )</td>
<td>= 2 for small rooms  = 3 for large rooms</td>
</tr>
<tr>
<td>( C_m )</td>
<td>= dimensionless entrainment coefficient, found experimentally to be 0.44 for a free plume and 0.21 for an adhered plume</td>
</tr>
<tr>
<td>( C_{RAW} )</td>
<td>= 1 when the underside of balcony is flat with the opening of the fire room  = 2 when the underside of the balcony is higher than the opening of the fire room (the smoke rises after the opening)</td>
</tr>
<tr>
<td>( C_V )</td>
<td>= coefficient of discharge of the vents</td>
</tr>
<tr>
<td>( D_B )</td>
<td>= depth of the smoke layer under the balcony [m]</td>
</tr>
<tr>
<td>( D_D )</td>
<td>= depth of the downstand at opening of the fire room [m]</td>
</tr>
<tr>
<td>( D_i )</td>
<td>= depth of the horizontal smoke flow at the section i [m]</td>
</tr>
<tr>
<td>( D_L )</td>
<td>= visible depth of the smoke layer in the atrium [m]</td>
</tr>
<tr>
<td>( D_{L, eff} )</td>
<td>= effective depth of the smoke layer in the atrium [m]</td>
</tr>
<tr>
<td>( H_B )</td>
<td>= height of the spill edge above the fuel [m]</td>
</tr>
<tr>
<td>( H_W )</td>
<td>= height of the opening of the fire room above the fuel [m]</td>
</tr>
<tr>
<td>( Q_C )</td>
<td>= convective part of the heat release rate [kW]</td>
</tr>
<tr>
<td>( P )</td>
<td>= perimeter of the fire [m]</td>
</tr>
<tr>
<td>( T_0 )</td>
<td>= absolute ambient temperature = 288 [K]</td>
</tr>
<tr>
<td>( T_B )</td>
<td>= temperature of the smoke flow under the balcony [K]</td>
</tr>
<tr>
<td>( T_L )</td>
<td>= absolute temperature of the smoke layer [K]</td>
</tr>
<tr>
<td>( T_i )</td>
<td>= absolute temperature of the smoke at the section i [K]</td>
</tr>
<tr>
<td>( V_r )</td>
<td>= required ventilation rate = fan capacity [m³/s]</td>
</tr>
<tr>
<td>( W_B )</td>
<td>= width of the smoke flow at the spill edge [m]</td>
</tr>
<tr>
<td>( W_W )</td>
<td>= width of the opening of the fire room [m]</td>
</tr>
<tr>
<td>( X )</td>
<td>= current height where the mass flow rate ( m_X ) is considered [m]</td>
</tr>
<tr>
<td>( \Delta )</td>
<td>= empirical height of virtual source below void edge [m]</td>
</tr>
<tr>
<td>( \rho_0 )</td>
<td>= density of ambient air ( \approx 1.293 ) [kg/m³]</td>
</tr>
<tr>
<td>( \rho_L )</td>
<td>= density of the smoke layer [kg/m³]</td>
</tr>
<tr>
<td>( \rho_X )</td>
<td>= density of the smoke at a height ( X ) above the spill edge [kg/m³]</td>
</tr>
<tr>
<td>( \theta_i )</td>
<td>= temperature elevation of the smoke at the section i [K]</td>
</tr>
<tr>
<td>( \theta_B )</td>
<td>= temperature elevation of the smoke under the balcony [K]</td>
</tr>
<tr>
<td>( \theta_L )</td>
<td>= temperature of the smoke layer above the ambient [K]</td>
</tr>
</tbody>
</table>
1 Introduction

This study aims to propose a simplified design method of SHEVS in building atria, considering the particular case of the plume that originates from an adjacent space and flows into the smoke layer situated in the atrium.

This case of smoke development can be analysed considering the following successive stages (see Figure 1-1):

- Stage 1: smoke rising vertically in the fire room;
- Stage 2: smoke flowing horizontally towards the spill edge;
- Stage 3: smoke rising from the spill edge till the smoke layer situated in the atrium.

The hot smoke is mixed with the cooler surrounding ambient air along its entire trajectory, from the fire room until the smoke layer in the atrium. This air entrainment results in a gradual cooling of the smoke. Once the smoke reaches the base of the smoke layer, it can be assumed that the mixing between the smoke and the surrounding air stops. Consequently, the physical characteristics of the smoke entering in the smoke layer are identical to those of the smoke extracted from the building.

![Figure 1-1 Smoke development in an atrium](image.png)
In order to propose a method that is practically usable for SHEVS designers, the approach will not only focus on air entrainment in the spill plume (which correspond to the third stage), but will also take into account the air entrainment that occurs in the two first stages.

In an intuitive way, it can be recognized that the height the smoke rises in the atrium is important, the majority of air entrainment into the smoke occurs in the atrium itself. It is also important to analyze the influence of different flow characteristics of the smoke at the spill edge on the total flow entering the smoke layer in the atrium. This will be achieved in the form of a sensitivity analysis.

1.1 Definitions
The definitions given in this section are those contained in the TR12101-5 [1].

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spill plume</td>
<td>Vertically rising plume resulting from the rotation of an initially horizontally-flowing smoke layer around a spill edge. (=Line plume)</td>
</tr>
<tr>
<td>Free plume</td>
<td>Spill plume into which air can freely entrained into both long sides of the plume (see Figure 1-2) (=Double-sided plume)</td>
</tr>
<tr>
<td>Adhered plume</td>
<td>Spill plume rising against a vertical surface and into which air entrains on one long side (see Figure 1-3). (=Single-sided plume)</td>
</tr>
<tr>
<td>Atrium</td>
<td>Enclosed space passing through two or more storeys in a building.</td>
</tr>
<tr>
<td>Channelling screen</td>
<td>Smoke barrier installed beneath a balcony to direct the flow of smoke from a room opening to the spill edge.</td>
</tr>
<tr>
<td>Convective heat flux</td>
<td>Total heat energy carried by the gases (= the smoke flow) crossing a specified boundary per unit time.</td>
</tr>
<tr>
<td>Design fire</td>
<td>Hypothetical fire having characteristics that are sufficiently severe for it to serve as the basis of the design of smoke and heat exhaust ventilation system.</td>
</tr>
</tbody>
</table>
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
Proposal for a simplified method for sizing smoke ventilation systems in atria
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

Flashover: Rapid transition from a fuel-bed controlled fire to a state of total surface involvement of combustible materials in a fire within an enclosure.

Fuel-bed controlled fire: Fire in which the rate of combustion and the heat output are primarily dependent on the fuel being burned.

Fully-involved fire: Fire in which all surfaces of the combustible.

(=Fully-developed fire)

Heat release rate (HRR): Caloric energy released by a fire per unit time.

Smoke and heat exhaust ventilation system (SHEVS): System in which components are jointly selected to exhaust smoke and heat in order to establish a buoyant layer of warm gases above cooler, cleaner air.

Smoke barrier: Device used to channel, contain and/or prevent the migration of smoke.

Smoke reservoir: Region within a building limited or bordered by smoke barriers or structural elements in order to retain a thermally buoyant smoke layer in the event of a fire.

Spill edge: Edge of a soffit beneath which a smoke layer is flowing, and adjacent to a void

(= Rotation point)

1.2 Fundamental assumptions

1.2.1 Ambient temperature

In this study, it is considered that the temperature of the atmosphere (=ambient temperature) is uniform inside the building and is equal to 15°C, except for the smoke flow and the smoke layer in the atrium.

1.2.2 Temperature of the smoke flow

In this study, it is considered that the temperature of smoke flow at any section is uniform.
1.2.3 Adiabatic building

To simulate the thermal energy absorbed by the building itself and its content, it is considered that the convective part of the HRR is equal to 70% of the total HRR. The remaining 30% are absorbed by the building itself and its content.

In this way, models and methods used in this study are assuming an adiabatic building, considering only the convective part of the HRR.

1.2.4 Temperature of the smoke above the ambient

In light of the foregoing, the temperature above the ambient at a given location in a smoke flow can be calculated as follows:

$$\theta_i = \frac{Q_c}{m_i \cdot C}$$

Equation 1-1

where

- $\theta_i$ = temperature elevation of the smoke at the section i [°C]
- $Q_c$ = convective part of the heat release rate [kW]
- $m_i$ = mass flow rate of the smoke flow at the section i [kg/s]
- $C$ = specific heat of air at constant pressure $\approx 1$ [kJ/kg.K]

Thus:

$$t_i = 15 + \frac{Q_c}{m_i}$$

Equation 1-2

where

- $t_i$ = temperature of the smoke at the section i [°C]

1.2.5 Steady state approach

If we consider that the smoke reservoir is adiabatic and that the smoke layer base is stationary (steady state situation), the value of mass flow rate entering the smoke layer determines:

- the temperature of the smoke layer and its density;
- the volume extraction rate [m³/s] (in case of mechanical SHEVS).

If in addition we know the depth of the smoke layer in the atrium, we can determine the size of the required openings [m²] (in case of natural SHEVS).
1.2.6 Design fire size

The design fires used in most standards including CEN/TR 12101-5 are steady-state fires. Those are fires with a constant size (i.e. a constant area and a constant perimeter) and a constant heat release rate.

These design fires are based on statistical data from fire of a particular type (office building, shops, ...) and on experimental results. It is neither based on a average maximum fire size (percentile 50%), nor on the largest possible fire (percentile 100%), but rather on a fire size which is a 'subjectively acceptable'(percentile 90-95%).

The choice of using a steady-state fire offers the following advantages:

- The calculation process is simpler: the characteristics of the fire (its size and HRR) and of the smoke layer (its thickness and temperature) are constant.
- No assumption must be made regarding the fire growth rate
- No comparison must be made between the evolution of the smoke layer and the egress time (resp. the attendance time of the fire-fighting services)

This study will use the design fires given in the TR 12101-5 [1]. The validity of these fires will not be discussed further. Specific information about this topic can be found in the BR368 [2].

<table>
<thead>
<tr>
<th>Type of occupancy</th>
<th>Fire perimeter P [m]</th>
<th>Convective heat release rate Qc [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hotel bedroom with standard sprinklers</td>
<td>6</td>
<td>300</td>
</tr>
<tr>
<td>Hotel bedroom without sprinklers</td>
<td>??</td>
<td>1000</td>
</tr>
<tr>
<td>Office with standard response sprinklers</td>
<td>14</td>
<td>1000</td>
</tr>
<tr>
<td>Shop with fast response sprinkler</td>
<td>9</td>
<td>2500</td>
</tr>
<tr>
<td>Shop with standard response sprinkler</td>
<td>12</td>
<td>5000</td>
</tr>
<tr>
<td>Office without sprinkler</td>
<td>24</td>
<td>6000</td>
</tr>
</tbody>
</table>

1.3 Legislative situation in Belgium

In Belgium, the fire safety in buildings is regulated by many laws, royal decrees, ministerial decrees and local regulations. This complexity is partly due to the complexity of the Belgian Federal system.

The only Belgian mandatory document that covers the topic of SHEVS in atria is the Royal Decree of 7 July 1994 [3], which has been amended several times since 1994.

The requirement can be found in the paragraph 2.1 of the appendixes 2, 3 and 4 of the royal decree. The following rule is valid for every new building or extension of an existing building.
2.1. The building is divided into compartments with an area smaller than 2500 m². (...) The area of a compartment may exceed 2500 m², if it is equipped with a sprinkler system and a smoke and heat exhaust ventilation system, which meet the standards or rules of the art, approved by the Minister of Interior, according to the procedure and conditions it determines. The height of a compartment is the height of a level. The following exceptions are allowed:

(…)
- The height of a compartment can be extended to two levels with internal communication through stairs (duplex), provided that the sum of their total area does not exceed 2500 m²;
(…)
- The height of a compartment can be extended to several levels (atrium) provided that compartment is equipped with a sprinkler system and a smoke and heat exhaust ventilation system, which meet the standards or rules of the art, approved by the Minister of Interior, according to the procedure and conditions it determines.

Sprinkler installation and SHEVS are thus mandatory in the following situations:

- Compartments of 1 or 2 levels with a total area bigger than 2500 m²;
- Every compartment with more than 2 levels.

It may be noted that the requirement for SHEVS is always linked to the requirement to have a sprinkler installation.

1.4 Standards

The BRE-method has partially been integrated in current British and European reference document for smoke control design in atrium buildings: BS 7346-4:2003 [4] and TR 12105-5:2005 [1]. These European and British standards are not 'self supporting' as they do not contain the necessary information to perform the calculation for air entrainment in spill plume and refer therefore to the BRE 368 [2].

1.4.1 Standards in Europe

At the European level, the state of current debate focuses around the reference document TR 12101-5. This results from a former pre-standard document named prEN12101-5 but has never reached a consensus to become a standard. The main reason for the lack of consensus of the proposed method is considered to be the high degree of complexity considered unnecessary by some nations.

1.4.2 Standards in Belgium

In Belgium, there are currently three Belgian standards relating to the design of SHEVS:
- NBN S21-208-1 concerns the design of SHEVS for large spaces, considering only axisymmetric plumes;
- NBN S21-208-2 concerns the design of SHEVS for car parks;
- NBN S21-208-3 concerns natural SHEVS for staircases.

None of these Belgian standards deal with spill plumes.
2 Literature review

This literature review focuses on the existing empirical calculation methods of air entrainment in smoke line plumes (spill plumes) as well as their validation either by (small-size or full-size) scale testing or CFD calculation.

This review is sorted by date of publication as many of the sources refer to preview publications.

2.1 Nomenclature

This study includes a comparison of different calculation methods where each has its own naming convention. The list below provides a nomenclature, based primarily on that of the BR 368. Given the complexity of this nomenclature, the Figure 1-1 and the Figure 1-2 illustrate the meaning of most of the geometric parameters used.

2.1.1 Nomenclature for the physical parameters of the smoke flow

The entire set of parameters is indexed according the plane perpendicular to the smoke flow (see Figure 2-1):

- Index 'W' refers to the vertical plane of the window (or the door opening) of the fire room;
- Index ‘B’ refers to the vertical plane at the spill edge (also called balcony edge);
- Index ‘R’ refers to the horizontal plane at the spill edge, situated in the flow after the its 90° rotation;
- Index ‘X’ refers to the horizontal plane situated at a height X above the spill edge;
- Index ‘L’ refers to the horizontal plane where the spill plume reaches the smoke layer in the atrium.

At each of these sections, a series of physical parameters can be determined. The following list gives the nomenclature of the parameters used in this study, considering the section i:

\[ m_i \] = mass flow rate of the smoke flow at the section i [kg/s]
\[ T_i \] = absolute temperature of the smoke at the section i [K]
\[ t_i \] = temperature of the smoke at the section i [°C]
\[ \theta_i \] = temperature elevation of the smoke at the section i [K]
\[ D_i \] = depth of the horizontal smoke flow at the section i [m]

By combining the above, here are some examples of physical parameters used in this document:

- \( m_B \) = mass flow rate at the spill edge (before rotation) [kg/s];
- \( t_X \) = temperature of the smoke at height X above the spill edge [°C];
- \( D_B \) = depth of the horizontal smoke at the spill edge (before rotation) [m].
2.1.2 Nomenclature of the geometric parameters of the building

The following list gives the nomenclature of the geometric parameters used in this document:

- \( H_W \) = height of the opening of the fire room above the fuel [m]
- \( h_W \) = height of the opening of the fire room, measured from the bottom of the window [m]
- \( D_D \) = depth of the downstand at opening of the fire room [m]
- \( B \) = length of the balcony, measured between the opening of the fire room and the spill edge [m]²
- \( H_B \) = height of the spill edge above the fuel [m]
- \( W_W \) = width of the opening of the fire room [m]

---

\(^2\) \( B \) and \( W_W \) are represented in Figure 2-4 (page 12).
2.1.3 Difference between $m_X$ and $m_L$

The output data $m_X$ and $m_L$ are defined as follows:

$m_X$ = mass flow rate at a height X above the spill edge [kg/s]

$m_L$ = mass flow rate entering the smoke layer in the atrium [kg/s]

In most calculation methods, the value of $m_L$ is equal to the value of $m_X$, where the parameter X is equal to geometric height of rise of the spill plume (i.e. the height from the spill edge to the visible base of the smoke layer).

However, the BRE-method brings a new concept: the effective height of rise of the spill plume, which is smaller than the geometric height of rise in some cases (see Figure 2-3).

This point is discussed more in detail in the section 2.2.4.

The remainder of the study will systematically consider the calculation of $m_X$ (instead of $m_L$) in order to discuss the issue of the effective height of rise separately.

2.2 BR 368 (1999) [2]

The BR 368 - further called the 'BRE-method' - give a complete approach to evaluate the air entrainment in smoke which flows from an adjacent room, rotate at the spill edge and rise in the atrium until it reaches the smoke layer.

2.2.1 The BRE-method

The BRE-method originates from former publications of Morgan, Hansell and Marshall [5] [6] [7] [8]. It derives from experimental data collected prior to 1979 and has been adapted since then to lead to the current method described in the BRE 368.

This method is semi-empirical as it contains on the one hand equations and parameters which are based on physical principles (conservation of continuity, momentum and buoyancy), and on the other hand correction factors and empirical terms which have been determined in order to fit the experimental results.

The BRE-method is complex: it involves a very large amount of parameters (>60) and calculation steps. It also contains many alternative equations whose selection is based on numerical or logical criteria.
Since no commercial calculation tool is currently available, the use of the BRE-method implies the use of a customized spreadsheet, with a high risk of encoding error.

2.2.2 Calculation process of the BRE-method

The calculation process contains a succession of steps corresponding to a position within the smoke flow. After each calculation step, the local physical properties of the smoke flow are determined in order to be used as inputs for the next calculation step.

This method includes 10 calculation steps (step 5 and step 10 only apply in the case of an adhered spill plume):

- Step 1: calculation of the mass flow rate under the balcony ($m_B$);
- Step 2: calculation of the average temperature and the thickness of the smoke flow reaching the spill edge;
- Step 3: calculation of the mass flow rate after rotation at the spill edge ($m_R$);
- Step 4: calculation of the equivalent Gaussian source term;
- Step 5 (only for adhered spill plumes): correction of the equivalent Gaussian source term;
- Step 6: calculation of the source Froude number;
- Step 7: calculation of the air entrainment into the width of the spill plume ($m_{X,\text{width}}$);
- Step 8: calculation of the air entrainment into the ends of the spill plume ($m_{X,\text{ends}}$);
- Step 9: calculation of the total air entrainment into the spill plume ($m_X$);
- Step 10 (only for adhered spill plumes): correction of the total air entrainment.

2.2.3 Validity of the BRE-method

The BRE-method was developed on the basis of $1/10^\text{th}$ scale model experiments. The method has shown good agreements with a series of full-scale experiments that were conducted in Belgium [9], [10]. It must be noted that all the full-scale hot smoke tests were conducted in the following conditions:

- Large area smoke reservoir;
- Adhered spill plume;
- Air entrainment into the free ends of the spill plume;

The BRE-method does not specify any limit of geometrical dimensions.

As a limitation however, this method is only valid if no immersed ceiling jet occurs.

2.2.4 Effective layer depth- effective height of rise of the spill plume

In the case of large atria, experimental studies [11] have demonstrated that the temperature below the visible smoke layer is significantly higher than the ambient temperature. This results in reduced air entrainment.

In order to fit the experimental results, the air entrainment will be calculated till the base of the effective layer (see Figure 2-3), which can be lower than the base of the visible layer.

- For large atria, when $A_L > (1,5 \cdot D_L)^2$:
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

\[ D_{\text{L, eff}} = 1.26 \, D_{\text{L}} \]  \hspace{1cm} \text{Equation 2-1}

- For small atria when \( A_L \leq (1.5 \, D_L)^2 \):

\[ D_{\text{L, eff}} = D_L \]  \hspace{1cm} \text{Equation 2-2}

where

- \( A_L \) = horizontal area of the smoke layer in the atrium \([\text{m}^2]\)
- \( D_{\text{L, eff}} \) = effective depth of the smoke layer in the atrium \([\text{m}]\)
- \( D_L \) = visible depth of the smoke layer in the atrium \([\text{m}]\)

No correction of the visible layer depth (see Equation 2-2) will be applied if the resulting effective height of rise in the atrium is smaller than 0.75m.

Figure 2-3 Difference between the geometric and the effective height of rise of the spill plume
2.3 Method by Law (1986) [12]

This simplified method developed by Law is based on the experimental data from Morgan and Marshall [6].

It proposes the following equation for air entrainment into free plumes:

\[
m_X = 0.34 \, Q_c^{1/3} \, W_B^{2/3} (X + 0.15 \, H_B)
\]

Equation 2-3

where:

\[
W_B = \text{width of the smoke flow at the spill edge} \, [\text{m}]
\]

\[
X = \text{current height where the mass flow rate} \, m_X \text{is considered} \, [\text{m}]
\]

2.4 Method by Thomas (1987) [13]

This method developed by Thomas is based on the experimental data from Morgan and Marshall [5] [6] and applies only to large smoke reservoirs (see definition in Section 2.2.4).

The calculation of the air entrainment into the ends of the spill plumes is explicitly calculated (see additional term in the Equation 2-5).

This method proposes the two following equations for air entrainment into free plumes.

- If no air entrainment occurs into the ends of the spill plumes:

\[
m_X = 0.58 \, \rho_X \left[ \frac{g \, Q_c \, W_B^2}{\rho_X \, C \, T_0} \right]^{1/3} (X + \Delta)
\]

Equation 2-4

- If air entrainment occurs into the ends of the spill plumes:

\[
m_X = 0.58 \, \rho_X \left[ \frac{g \, Q_c \, W_B^2}{\rho_X \, C \, T_0} \right]^{1/3} (X + \Delta) \left[ 1 + \frac{0.22 \, (X + 2 \, \Delta)}{W_B} \right]^{2/3}
\]

Equation 2-5

where

\[
\rho_X = \text{density of the smoke at a height} \, X \text{above the spill edge} \, [\text{kg/m}^3]
\]

\[
g = \text{acceleration due to the gravity} = 9.81 \, [\text{m/s}^2]
\]

\[
T_0 = \text{absolute ambient temperature} = 288 \, [\text{K}]
\]

\[
\Delta = \text{empirical height of virtual source below void edge} \, [\text{m}]
\]

\[
D_B = \text{depth of the smoke layer under the balcony} \, [\text{m}]
\]

\[
m_B = \text{mass flow rate of smoke under the balcony} \, [\text{kg/s}]
\]
This method is not easily usable in practice because it requires knowledge of the value of \( \rho_X \) prior to the calculation of \( m_X \) which is not possible since \( \rho_X \) is dependant of \( m_X \).

### 2.5 Method by Law (1995) [14]

Law has modified the method he had previously developed (see Section 2.3), based on new experimental data from Hansell et al [15].

It proposes the following equation for air entrainment into free plumes:

\[
m_X = 0.31 \ Q_c^{1/3} \ W_B^{2/3} (X + 0.25 \ H_B)
\]

Equation 2-6

The above expression includes the air entrainment into the ends of the spill plumes.

### 2.6 Method published by the CIBSE (1995) [16]

This method has been developed by Klote and Milke and published by the CIBSE. It is based on experimental data from Morgan and Marshall (1979) [6].

It is this method which is proposed in the reference handbooks published by the SFPE [17] and [18].

The CIBSE-method proposes the following equation for air entrainment into free plumes (including air entrainment into the ends of the plume):

\[
m_X = 0.36 \ Q_c^{1/3} \ W_B^{2/3} (X + 0.25 \ H_B)
\]

Equation 2-7

In addition, there is a rule that evaluates the horizontal expansion of the smoke flow from the opening of the fire room to the spill edge, in the absence of channelling screens:

\[
W_B = W_W + B
\]

Equation 2-8

This rule assumes that the lateral expansion of the horizontal flow occurs with an angle of 26,5° (see Figure 2-4).
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2.7 Method by Poreh et al (1998)

This method has been developed by Poreh, Morgan, Marshall en Harrison [11] and is based on experimental data reported by Marshall and Harrison in 1996 [19] and applies only to a large smoke reservoir (see definition in Section 2.2.4).

It proposes the following equation for air entrainment into (free and adhered) spill plumes, with no air entrainment into the ends of the plume:

$$m_X = 0,3 \ C_m \ \rho_0 \ W_B^{2/3} \ Q_C^{1/3} \left[ X + D_b + \frac{m_B}{0,3 \ C_m \ \rho_0 \ W_B^{2/3} \ Q_C^{1/3}} \right]$$

Equation 2-9

where:

- $C_m$ = dimensionless entrainment coefficient, found experimentally to be 0.44 for a free plume and 0.21 for an adhered plume
- $\rho_0$ = density of ambient air $\approx$ 1,293 [kg/m$^3$]

The Equation 2-9 can be used provided that the characteristics of the smoke flow under the balcony (i.e. $m_B$ and $D_b$) are known. It is thus the second step of a two-step calculation.

The authors give the following limitations of the scope of the Equation 2-9:

- The air entrainment which occurs into the ends of the plume is not taken into account. In the case of free plumes, this supplementary air entrainment can be calculated following the procedure derived by Thomas (see Section 2.4). In the case of adhered plumes, no solution is proposed.
- The calculation only applies for 'large-area reservoirs' (see Section 2.2.4).
Considering that the density of the ambient air is 1,226 [kg/m$^3$] (at 15°C), the previous expression can be simplified as follows:

$$m_X = m_B + \left[ 0.16 Q_c^{1/3} W_B^{2/3} (X + D_B) \right]$$  \hspace{1cm} \text{for free plumes} \hspace{1cm} \text{Equation 2-10}

$$m_X = m_B + \left[ 0.077 Q_c^{1/3} W_B^{2/3} (X + D_B) \right]$$  \hspace{1cm} \text{for an adhered spill plume} \hspace{1cm} \text{Equation 2-11}

This simplification allows the following observations:

- The total air entrainment can be divided into two parts:
  - The air entrainment from the fire room until the spill edge ($m_B$);
  - The air entrainment in the rising plume;
- The air entrainment in a free plume is approximately twice that of the adhered plume.

### 2.8 Method by Thomas et al (1998)

This method has been developed by Thomas and is based on experimental data reported by Marshall and Harrison [19], and by Poreh et al [11].

It proposes two alternative equations for air entrainment into free plumes with no air entrainment into the ends of the plume:

$$m_{X,\text{width}} = 0.16 X Q_c^{1/3} W_B^{2/3} + 0.0027 Q_c + 1.2 m_B$$  \hspace{1cm} \text{Equation 2-12}

or (alternative equation):

$$m_{X,\text{width}} = 0.16 X Q_c^{1/3} W_B^{2/3} + 0.0014 Q_c + 1.4 m_B$$  \hspace{1cm} \text{Equation 2-13}

where:

$$m_{X,\text{width}} = \text{mass flow rate at a height X in the atrium, where no air entrainment occurs into the ends of the spill plume [kg/s]}$$

The Equation 2-12 and Equation 2-13 can be used provided that the mass flow rate under the balcony ($m_B$) is known. These equations are thus the second step of a two-step calculation.

In order to facilitate further comparison with the other methods and to avoid redundancy, it is proposed to use instead an average of the two previous equations. This gives the following expression:
\[ m_{X,\text{width}} = 0,16 X Q_c^{1/3} W_B^{2/3} + 0,00205 Q_c + 1,3 m_B \]  
Equation 2-14

The air entrainment into the ends of the spill plume can be calculated separately, using the following equation:

\[ m_{X,\text{ends}} = 0,09 X \left( \frac{Q_c}{W_B} \right)^{1/3} \]  
Equation 2-15

where:
\[ m_{X,\text{ends}} = \text{air entrainment that occurs into the ends of the spill plume, between the spill edge and the height } X \text{ in the atrium} \ [\text{kg/s}] \]

The total air entrainment (with air entrainment into the free ends of the spill plume) can be calculated as follows:

\[ m_X = m_{X,\text{width}} + m_{X,\text{ends}} \]  
Equation 2-16

2.9 Method by Harrison (2004) [20]

Harrison made a comparison of most relevant empirical methods for calculation of the air entrainment into spill plumes and conducted small scale experiments and CFD calculation in order to verify the reliability of those empirical methods.

The most important conclusions of his investigations are:

- The BRE-method gives a reasonably good agreement with the experimental results, provided the concept of 'effective height of rise' is not applied (see Section 2.2.4). Thus the air entrainment must be calculated taking into account the visible layer base. The agreement worsens with increasing HRR.
- The simplified methods proposed by Law (1986 and 1995), Thomas (1987), CIBSE (1995) and NFPA (2005) under predict the mass flow rate at low heights of rise and over predict this mass flow rate at higher heights of rise \((X > 3m)\).

Harrison proposes two alternative equations for the calculation of the air entrainment into free plume which show better agreement with his experimental results than the previous simplified methods. This formula includes the air entrainment into the ends of the spill plume:

\[ m_X = 0,2 Q_c^{1/3} W_B^{2/3} (X + D_B) + m_B \]  
Equation 2-17
or (alternative equation):

\[ m_X = 0.2 Q_c^{1/3} W_B^{2/3} X + 0.0017 Q_c + 1.5 m_B \]

Equation 2-18

In order to facilitate comparison with the others methods and to avoid redundancy, it is further proposed by this study to only consider the Equation 2-18.

2.10 NFPA 92B (2009) [21]

In the latest version of the standard NFPA 92B, three different equations are proposed, depending on the value of the parameters \( X \) and \( W_B \). Those equations relate to free plumes and consider the air entrainment into the ends of the plume:

- If \( X < 15 \text{m} \):
  - When \( W_B < 10 \text{m} \)
    
    \[ m_X = 0.59 Q_c^{1/3} W_B^{1/5} (X + 0.17 W_B^{7/15} H_B + 10.35 W_B^{7/15} - 15) \]

    Equation 2-19
  
  - When \( W_B \geq 10 \text{m} \)
    
    \[ m_X = 0.36 Q_c^{1/3} W_B^{2/3} (X + 0.25 H_B) \]

    Equation 2-20

- If \( X \geq 15 \text{m} \) (only valid if \( 10 \text{m} \leq W_B \leq 14 \text{m} \)):

  \[ m_X = 0.2 Q_c^{1/3} W_B^{2/3} (X + 0.51 H_B + 15.75) \]

  Equation 2-21

2.11 Method by Tilley [22]

Tilley has studied adhered spill plumes using CFD simulation, but does not address entrainment into the ends of the plume.

She found that the air entrainment into the plume becomes dependant on other geometrical parameters of the atrium (the length of the atrium and the vertical distance between the spill edge and the top of the atrium), from the threshold value \( X = (2/3 H_S) \).
Therefore, she proposed a set of two equations to calculate the air entrainment into the adhered plume:

- In the cases where \( X < \left( \frac{2}{3} \frac{H_S}{L_A} \right) \) or \( \frac{H_S}{L_A} > 2.5 \)

\[
m_X = m_B + \left[ 0.08 \, Q_c^{1/3} \, W_B^{2/3} \left( X + D_B \right) \right]
\]

Equation 2-22

- In the cases where \( X > \left( \frac{2}{3} \frac{H_S}{L_A} \right) \) and \( \frac{H_S}{L_A} < 2.5 \)

\[
m_X = m_B + \left[ 0.08 \, Q_c^{1/3} \, W_B^{2/3} \left( 2.5^{5/3} \left( \frac{L_A}{H_S} \right)^{5/3} \left( X - \frac{2}{3} H_S \right) + \frac{2}{3} H_S + D_B \right) \right]
\]

Equation 2-23

where

- \( L_A \) = the length of the atrium [m]
- \( H_S \) = vertical distance between the spill edge and the top of the atrium [m].

### 2.12 Conclusions on the literature review

The literature review covers 10 empirical methods developed between the early 80's and 2011. There is on the one hand a complex method (BRE-method) which involves a large amount of parameters and calculation steps, and on the other hand a series of simplified methods which involves between 4 and 6 parameters and allows a 1-step or 2-steps calculation process.

It must be noted that all the reviewed methods assume that the smoke flow leaving the fire room doesn’t contain unburned gases from the pyrolysis.

Most of the reviewed methods are based on the same experimental data resulting from small-scale (1/10) testing. The data was extrapolated to full scale methods, using the appropriate scaling laws.

The validity of the BRE-method was verified through full-scale testing. in the 90's. This validation only covered a reduced scope of the method (adhered plumes, air entrainment into the ends of the plume and large reservoir). This leaves thus some uncertainty.

More recently, Harrison and Tilley used CFD-calculations to verify some aspects of the existing empirical methods.

Harrison focused his study on free plumes and found that the BRE-method gives a reasonably good agreement with his own small-scale testing and CFD calculation, excepted for large heat release rates. However, he recommends not to use the correction factor (1.26) suggested by the BRE-method for calculating the effective height of rise. He also found that the existing simplified methods are less reliable.
Tilley focused her study on adhered plumes and found that there is a height of rise from which the air entrainment becomes dependant of additional parameters (related to the geometry of the atrium). She proposes therefore her own calculation method.

This study concludes that the existing published methods as reviewed in this chapter can only apply when there is no fully involved fire in the room. This requirement is generally met when the room is equipped with a sprinkler system.
3 BRE-method: first analysis

This chapter aims to analyze the result of the BRE-method from a strictly numerical point of view. This 'global approach' is based on an overall analysis of the variation of the mass flow rate of smoke in the atrium, as a function of the input parameters of the BRE-method.

3.1 BRE-method: Identification of the output, inputs and ‘useful’ intermediate parameters

3.1.1 Output of the BRE-method
The final result of the calculation (the output) is the mass flow rate of the smoke entering the smoke layer in the atrium. This mass flow rate is the value of $m_X$, where $X$ is equal to the effective height of rise in the atrium.

3.1.2 Inputs of the BRE-method
To perform a sensitivity analysis of the BRE-method, it is necessary to identify all its input parameters. These are the independent parameters needed to evaluate the mass flow rate $m_X$.

Some of the input parameters are numerical values (for example: the height and the width of the opening in the fire room), others are of the 'yes/no' binary type (for example: The smoke plume in the atrium is an adhered plume? yes or no).

The 10 input parameters of the BRE-method are (see Figure 3-1):

\[ P = \text{perimeter of the fire [m]} \]
\[ Q_C = \text{convective portion of the heat release rate [kW]} \]
\[ H_W = \text{height of the opening of the fire room, measured from the floor of the fire room [m]} \]
\[ D_D = \text{depth of the downstand at opening of the fire room [m]} \]
\[ W_B = \text{width of the smoke flow at the spill edge [m]} \]
\[ X = \text{current height where the mass flow rate } m_X \text{ is considered [m]} \]
\[ L.R. = \text{Is the fire room a Large Room? Yes /No [-]} \]
\[ R.A.W. = \text{Is the smoke Rising After the Window opening? Yes /No [-]} \]
\[ A.P. = \text{Is the plume in the atrium an Adhered Plume? Yes /No [-]} \]

In order to simplify the analysis, we have considered that the width of the opening of the fire room ($W_W$) and the width of the plume at the spill edge ($W_B$) are equal.
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F.E. = Is there air entrainment into the Free Ends of the plume? Yes / No [-]

3.1.3 ‘Useful’ intermediate parameters

The intermediate parameters are physical characteristics of the smoke flow (depth, width, average temperature and mass flow rate) at an intermediate stage of the calculation. Some of these parameters have associated physical data that can be useful for design issues. For example: the depth of the smoke flow under the balcony must be known to determine the minimal height of the channelling screens.

Figure 3-1 Inputs and output data of the BRE-method

Figure 3-2 Calculation process of the BRE-method
The others intermediate parameters (the largest number) are considered by this study to be meaningless for the designer. Some are physical quantities that do not interest the designer, others are mathematical quantities intended to simplify the whole calculation process into a series of simpler calculation steps.

We can consider that only the following intermediate parameters are useful for design issues:

\[ D_B = \text{depth of the smoke layer under the balcony [m]} \]
\[ t_R = \text{temperature of the smoke layer after rotation (spill edge) [°C]} \]
\[ t_X = \text{temperature of the smoke layer at a current height = X [°C]} \]

Those intermediate parameters are represented in the Figure 3-3.

The depth of the smoke layer under the balcony allows the determination of the minimal height for the channelling screen (see Figure 3-4) that is necessary to prevent lateral spillage of the smoke. Reference texts usually require an additional height between the smoke layer and the bottom of the channelling screens (for example: 1 meter).
The temperature of the smoke layer along the façade (as from the spill edge until the smoke layer) determines the required performance of the glazing of the façade.

The temperature \( t_R \) after rotation at the spill edge is the maximum temperature of the spill plume along the façade. When it is lower than the breaking temperature of the glazing, no provision must be made with regard to the glazing.

The temperature \( t_X \) decreases progressively as the height \( X \) increases. Its change along the façade can be used to determine the height (from the spill edge) where fire resistant glazing must be provided.

### 3.2 BRE-method: global sensitivity analysis

The global sensitivity analysis refers to the variation of the mass flow rate \( m_X \) at a height \( X \) above the spill edge as a function of all identified input parameters of the BRE-method (see next figure).

#### Parameters:
- \( P \): perimeter of the fire
- \( Q_c \): convective part of the HRR
- \( H_W \): height of the opening of the fire room
- \( D_b \): height of the downstand at the opening of the fire room
- \( W_b \): width of the plume at the balcony edge
- \( X_{eff} \): effective height of rise in the atrium
- \( L.R. \): large room? (yes/no)
- \( R.A.W. \): smoke rises after the window opening? (yes/no)
- \( A.P. \): adherent plume? (yes/no)
- \( F.E. \): free ends of the plume. (yes/no)

#### Output:
- \( m_X \): mass flow rate at a height \( X \)

Figure 3-5 Parameters and output of the global sensitivity analysis
The purpose of this analysis is to identify:

- The type of change (ascending, descending) of the result when one input varies;
- The input parameters that the most affect the result value;
- The input parameters that can possibly be neglected in the calculation process.

### 3.2.1 Range and default value of the input parameters

The first step of this sensitivity analysis is to determine the range (minimum and maximum value) and the default value of the input parameters.

When performing the sensitivity analysis with respect to a specific parameter, the value of the other parameters are fixed to this default value.

The range of the parameters was determined according the following principles:

- The size \( P \) and the HRR \( Q_C \) are based on the design fires proposed in the BRE-method [2].
- The geometrical quantities \( H_W, D_D, W_B \) and \( X_{eff} \) cover most common cases in real buildings.

The selected default value is either the median value of the range (for numerical data) or the binary value that gives the largest value of the mass flow rate (for binary data).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of data</th>
<th>Default value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P ) [m]</td>
<td>(6 ; 24)</td>
<td>15</td>
</tr>
<tr>
<td>( Q_C ) [kW]</td>
<td>(300 ; 6000)</td>
<td>3000</td>
</tr>
<tr>
<td>( H_W ) [m]</td>
<td>(2,5 ; 5,5)</td>
<td>4</td>
</tr>
<tr>
<td>( D_D ) [m]</td>
<td>(0 ; 2)</td>
<td>1</td>
</tr>
<tr>
<td>( W_B ) [m]</td>
<td>(2 ; 30)</td>
<td>16</td>
</tr>
<tr>
<td>( X_{eff} ) [m]</td>
<td>(2 ; 22)</td>
<td>12</td>
</tr>
<tr>
<td>L.R. [-]</td>
<td>Yes / No</td>
<td>No</td>
</tr>
<tr>
<td>R.A.W. [-]</td>
<td>Yes / No</td>
<td>Yes</td>
</tr>
<tr>
<td>A.P. [-]</td>
<td>Yes / No</td>
<td>No</td>
</tr>
<tr>
<td>F.E. [-]</td>
<td>Yes / No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### 3.2.2 Minimizing and maximizing inputs

The next step is to identify the general trend of \( m_X \) (ascending or descending) when each input varies independently.
It is found that $m_X$ increases when:
- $P$, $Q_C$, $H_W$, $W_B$ or $X$ increase;
- $D_D$ decreases;
- the fire is situated in a small room ($L.R. = no$);
- the smoke rises after the window ($R.A.W. = yes$);
- the plume is a free plume ($A.P. = no$);
- the ends of the spill plume are free ($F.E. = yes$).

The minimizing (resp. maximizing) inputs are defined as the set of inputs which gives the minimum (maximum) value of $m_X$.

The minimizing and maximizing inputs are shown in Table 3-2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of data</th>
<th>Minimizing inputs</th>
<th>Maximizing inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$ [m]</td>
<td>(6 ; 24)</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>$Q_C$ [kW]</td>
<td>(300 ; 6000)</td>
<td>300</td>
<td>6000</td>
</tr>
<tr>
<td>$H_W$ [m]</td>
<td>(2,5 ; 5,5)</td>
<td>2,5</td>
<td>5,5</td>
</tr>
<tr>
<td>$D_D$ [m]</td>
<td>(0 ; 2)</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>$W_B$ [m]</td>
<td>(2 ; 30)</td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td>$X_{eff}$ [m]</td>
<td>(2 ; 22)</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>$L.R.$ [-]</td>
<td>Yes / No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$R.A.W.$ [-]</td>
<td>Yes / No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>$A.P.$ [-]</td>
<td>Yes / No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$F.E.$ [-]</td>
<td>Yes / No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

3.2.3 BRE-method: results of the global sensitivity analysis

The results of the global sensitivity analysis can be found in the Appendix A (page 80) and reveals the following:
- With the exception of parameter $D_D$, all the parameters have a significant effect on the value of $m_X$. Consequently, $D_D$ is the only parameter that could reasonably be ignored in the proposed simplified method.
- The variation of $m_X$ as a function of the parameters $P$, $H_W$, $W_B$ and $X$ can be approximated by a linear regression.

The summary of results of the global sensibility analysis is shown in Table 3-3 that gives the ranking of the relative sensibility with respect to all the input parameters.
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Table 3-3 Summary of results of the global sensitivity analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Maximum absolute variation [kg/s]</th>
<th>Maximum relative variation [%]</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$: perimeter of the fire [m]</td>
<td>229</td>
<td>50%</td>
<td>6</td>
</tr>
<tr>
<td>$Q_C$: convective part of the heat release rate [KW]</td>
<td>592</td>
<td>84%</td>
<td>2</td>
</tr>
<tr>
<td>$H_W$: height of the opening of the fire room [m]</td>
<td>229</td>
<td>67%</td>
<td>3</td>
</tr>
<tr>
<td>$D_D$: depth of the downstand at the opening of the fire room [m]</td>
<td>24</td>
<td>16%</td>
<td>10</td>
</tr>
<tr>
<td>$W_S$: width of the smoke flow at the spill edge [m]</td>
<td>360</td>
<td>61%</td>
<td>4</td>
</tr>
<tr>
<td>$X$: height of rise of the spill plume in the atrium [m]</td>
<td>884</td>
<td>86%</td>
<td>1</td>
</tr>
<tr>
<td>Large room? yes/no</td>
<td>49</td>
<td>22%</td>
<td>8</td>
</tr>
<tr>
<td>Rise after window? yes/no</td>
<td>68</td>
<td>33%</td>
<td>7</td>
</tr>
<tr>
<td>Adherent plume? yes/no</td>
<td>360</td>
<td>56%</td>
<td>5</td>
</tr>
<tr>
<td>Free ends? yes/no</td>
<td>140</td>
<td>22%</td>
<td>9</td>
</tr>
</tbody>
</table>

The most significant parameter is the height of rise of the spill plume in the atrium ($X$).

Given the number of significant parameters (9) and the existence of ‘useful’ intermediate parameters, the study found it appropriate to conduct an analysis of the calculation flow for the BRE-method in order to decompose the whole method into simpler steps. This decomposition was conducted taking into account the following objectives:

- The number of calculation steps was to be as small as possible. Each step was to be used either to evaluate a ‘useful’ intermediate parameter or to differentiate the different geometric configurations (free/adhered plume, air entrainment into the free ends of the plume).
- The number of input parameters for each step was to be the smallest possible. Any redundancy was to be avoided.
- The use of empirical parameters without physical significance was to be avoided.

3.3 Conclusions on the first analysis of the BRE-method

This first analysis has identified 10 input parameters of the BRE-method and selected 3 'useful' intermediate parameters that are necessary for design issues (sizing of the channelling screens, thermal requirements for facade).

The identified input parameters and their ranges are the basis of the sensitivity analysis that has been performed. The set of ‘useful’ parameters will further guide the simplification strategy (see Chapter 5).

The global sensitivity has shown that 9 of the 10 identified input parameters have a significant effect on the result of the calculation of the mass flow rate in the spill plume. Consequently, any proposal for a simplified BRE-method will have to consider those 9 significant parameters.
4 Comparison between the BRE-method and the existing simplified methods

In this chapter, the study considers the five following simplified methods:

- Method by Law (1995);
- Method by CIBSE (1995);
- Method by Poreh et al (1998);
- Method by Thomas (1998);
- Method by Harrison (2004);
- NFPA 92B (2009);

The former methods of Law (1986) and Thomas (1987) were not considered since they were modified and improved later by their own authors, based on more recent data.

The literature review has shown that the existing simplified methods are mostly based on the same experimental data than those which allowed the development of the BRE-method. These simplified methods have in fact been established to facilitate the calculation and avoid applying the BRE-method which is considered as too complex.

4.1 Analytical comparison between the BRE-method and the simplified methods

The field of application of the BRE-methods and the simplified methods is summarized in the following table.

<table>
<thead>
<tr>
<th>Method</th>
<th>Type of spill plume</th>
<th>Air entrainment into the ends of the spill plume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Free</td>
<td>Adhered</td>
</tr>
<tr>
<td>BRE</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>LAW-95</td>
<td>OK</td>
<td>Not applicable</td>
</tr>
<tr>
<td>CIBSE</td>
<td>OK</td>
<td>Not applicable</td>
</tr>
<tr>
<td>POREH</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>THOMAS-98</td>
<td>OK</td>
<td>Not applicable</td>
</tr>
<tr>
<td>HARRISON</td>
<td>OK</td>
<td>Not applicable</td>
</tr>
<tr>
<td>NFPA-09</td>
<td>OK</td>
<td>Not applicable</td>
</tr>
<tr>
<td>TILLEY</td>
<td>Not applicable</td>
<td>OK</td>
</tr>
</tbody>
</table>
The study highlights the following points:

- Only the BRE-method allows the consideration of all the cases (adhered/free plume, with/without air entrainment into the ends of the plume);
- Two simplified methods consider adhered plumes: Poreh and Tilley;
- Three simplified methods allow the calculation of the mass flow rate where no air entrainment occurs into the ends of the spill plume: Poreh, Thomas (1998) and Tilley.

All simplified methods use the same basic set of input parameters:

\[ Q_C = \text{convective portion of heat release rate [kW]} \]
\[ W_B = \text{width of the smoke flow at the spill edge [m]} \]
\[ X = \text{current height where the mass flow rate } m_X \text{ is considered [m]} \]
\[ H_B = \text{height of the spill edge above the fuel [m]} \]

The methods developed by Poreh, Thomas (1998), Harrison and Tilley require prior calculation of one of the physical properties \( D_B \) or \( m_B \) of the smoke flow reaching the spill edge. Those three methods must be considered as the second step of a two-step calculation process. In the following numerical comparison, the parameters \( D_B \) or \( m_B \) will be evaluated in accordance with the BRE-method.
<table>
<thead>
<tr>
<th>Method</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRE</td>
<td>Very large set of equations with numerous parameters</td>
</tr>
<tr>
<td>LAW-95</td>
<td>For free plume: ( m_X = 0.31 , Q_C^{1/3} , W_B^{2/3} (X + 0.25 , H_B) )</td>
</tr>
<tr>
<td>CIBSE</td>
<td>For free plume: ( m_X = 0.36 , Q_C^{1/3} , W_B^{2/3} (X + 0.25 , H_B) )</td>
</tr>
<tr>
<td>POREH</td>
<td>For free plume: ( m_X = m_B + \left[0.16 , Q_C^{1/3} , W_B^{2/3} (X + D_B)\right] )</td>
</tr>
<tr>
<td></td>
<td>For adhered plume: ( m_X = m_B + \left[0.077 , Q_C^{1/3} , W_B^{2/3} (X + D_B)\right] )</td>
</tr>
<tr>
<td>THOMAS-98</td>
<td>For free plume, with no air entrainment into the ends of the plume: ( m_{X,\text{width}} = 0.16 , X , Q_C^{1/3} , W_B^{2/3} + 0.00205 , Q_C + 1.3 , m_B )</td>
</tr>
<tr>
<td></td>
<td>Air entrainment into the ends of the free plume: ( m_{X,\text{ends}} = 0.09 , X \left(\frac{Q_C}{W_B}\right)^{1/3} )</td>
</tr>
<tr>
<td></td>
<td>Total air entrainment (with air entrainment into the ends of the free plume) ( m_X = m_{X,\text{width}} + m_{\text{ends}} )</td>
</tr>
<tr>
<td>HARRISON</td>
<td>For free plume: ( m_X = 0.2 , Q_C^{1/3} , W_B^{2/3} , X + 0.0017 , Q_C + 1.5 , m_B )</td>
</tr>
<tr>
<td>NFPA-09</td>
<td>For free plume (with ( X &lt; 15m ) and ( W_B &lt; 10m )) ( m_X = 0.59 , Q_C^{1/3} , W_B^{1/5} , (X + 0.17 , W_B^{7/15} , H_B + 10.35 , W_B^{7/15} - 15) )</td>
</tr>
<tr>
<td></td>
<td>For free plume (with ( X &lt; 15m ) and ( W_B \geq 10m )) ( m_X = 0.36 , Q_C^{1/3} , W_B^{2/3} , (X + 0.25 , H_B) )</td>
</tr>
<tr>
<td></td>
<td>For free plume (with ( X \geq 15m ) and ( 10m \leq W_B &lt; 14m )) ( m_X = 0.2 , Q_C^{1/3} , W_B^{2/3} , (X + 0.51 , H_B + 15.75) )</td>
</tr>
<tr>
<td>TILLEY</td>
<td>For adhered plume, with no air entrainment into the ends of the plume:</td>
</tr>
<tr>
<td></td>
<td>• In the cases where ( X &lt; \frac{2}{3} , H_S ) or ( H_S/L_A &gt; 2.5 ) ( m_X = m_B + \left[0.08 , Q_C^{1/3} , W_B^{2/3} , (X + D_B)\right] )</td>
</tr>
<tr>
<td></td>
<td>• In the cases where ( X &gt; \frac{2}{3} , H_S ) and ( H_S/L_A &lt; 2.5 ) ( m_X = m_B + \left[0.08 , Q_C^{1/3} , W_B^{2/3} , (2.5^{5/3} \left(\frac{L_A}{H_S}\right)^{5/3} , X - \frac{2}{3} , H_S) + \frac{2}{3} , H_S + D_B\right] )</td>
</tr>
</tbody>
</table>
4.2 Numerical comparison between the BRE-method and the existing simplified methods

Given their restricted field of application (see Table 4-1), the study will only be able to achieve the comparisons between the BRE-method and the following simplified methods:

- For free plumes:
  A. With air entrainment into the ends of the spill plume:
     1. LAW-95
     2. CIBSE
     3. THOMAS-98
     4. HARRISON
     5. NFPA-09
  B. Without air entrainment into the ends of the spill plume:
     1. POREH
     2. THOMAS-98

- For adhered plumes:
  C. With no air entrainment into the ends of the spill plume:
     2. POREH
     3. TILLEY
  D. With air entrainment into the ends of the spill plume: no possible comparison (only the BRE-method is available for this case)

The numerical comparisons were conducted with respect to the 4 design fires and corresponding geometry described in the Table 4-3.

<table>
<thead>
<tr>
<th>Case n°</th>
<th>Type of occupancy</th>
<th>Fire perimeter P [m]</th>
<th>Convective heat release rate Qc [kW]</th>
<th>Height under the balcony [m]</th>
<th>Width of the opening [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hotel bedroom with standard sprinklers</td>
<td>6</td>
<td>300</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Office with standard response sprinklers</td>
<td>14</td>
<td>1000</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Shop with fast response sprinkler</td>
<td>9</td>
<td>2500</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>Shop with standard response sprinkler</td>
<td>12</td>
<td>5000</td>
<td>5</td>
<td>12</td>
</tr>
</tbody>
</table>

In all cases, it is considered that there is no downstand at the opening of the fire room and that the balcony is flat with this opening.
Furthermore, the cases 1 and 2 are treated like 'small rooms' (entrainment coefficient of the BRE-method = 0.337) whereas the cases 3 and 4 are treated like 'large rooms' (entrainment coefficient of the BRE-method = 0.19).

Regarding the method developed by Tilley, the additional parameters were set to the following values:

- \( H_S = 15m / 25m / 30m; \)
- \( L_A = 20m. \)

The results of this numerical comparison can be found in the Appendix B (page 92) and are summarized in the Table 4-1. This table gives the relative difference [%] between the result of the calculation with the BRE-method and those with the best matching existing simplified methods.

The study concludes that even the best matching simplified methods don’t show a good agreement with the BRE-method: the relative difference between the results is generally greater than 20% and can reach 100% in some cases.

Furthermore, it can be observed that:

- with the exception of NFPA-method, the existing simplified methods give results lower than those of the BRE-method;
- the choice of the best matching method depends on the type of spill plume and/or the design fire.

<table>
<thead>
<tr>
<th>Air entrainment into the ends of the spill plume?</th>
<th>Free plumes</th>
<th>Adhered plumes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hotel bedroom with standard sprinklers</td>
<td>No 24% (POREH)</td>
<td>Yes 24% (CIBSE)</td>
</tr>
<tr>
<td>Office with standard response sprinklers</td>
<td>No 24% (THOMAS)</td>
<td>Yes 29% (CIBSE)</td>
</tr>
<tr>
<td>Shop with fast response sprinkler</td>
<td>No 24% (THOMAS)</td>
<td>Yes 18% (LAW)</td>
</tr>
<tr>
<td>Shop with standard response sprinkler</td>
<td>No 25% (THOMAS)</td>
<td>Yes 12% (LAW)</td>
</tr>
</tbody>
</table>

Table 4-1 Summary of the results of the numerical comparison between the BRE-method and the existing simplified methods
4.3 Conclusions on the comparison between the BRE-method and the existing simplified methods

The comparison consists of two parts: an analytical part and a numerical part.

The analytical comparison highlighted the following points:

- None of the existing simplified methods covers the full scope of the BRE-method. There are always restrictions with regard to the type of spill plume (free/adhered; entrainment/no entrainment into the ends of the spill plume).
- The methods developed by Poreh, Thomas (1998), Harrison and Tilley are 2-steps methods which require prior calculation of the smoke flow reaching the spill edge.

The numerical comparison in this study considered the 4 recommended design fires for sprinklered spaces given in the BRE368 and shows that there is no satisfactory matching between the BRE-method and the existing simplified methods. The results generally differ from 20 to 40%, considering in each case the best matching simplified method.
5 BRE-method: strategies of simplification

5.1 Air entrainment in each region: \(m_1, m_2\) and \(m_3\)

The BRE-method allows evaluating the mass flow rate at different stages of the smoke flow. At every stage, the value of this mass flow rate corresponds to the cumulative air entrainment from the fire to this specific stage.

Considering the reference sections as shown in the Figure 2-1, the mass flow rate at the different stages can be written as follows:

- \(m_W\): mass flow rate of the smoke at the opening of the fire room;
- \(m_B\): mass flow rate of the smoke at the spill edge (before rotation);
- \(m_R\): mass flow rate of the smoke at the spill edge (after rotation);
- \(m_X\): mass flow rate of the smoke at the height X above the spill edge.

These different mass flow rates are represented in the Figure 5-1.

![Figure 5-1 Air entrainment until the different reference sections](image)

Since no ‘useful’ intermediate parameters were identified at the reference section \(W\) (see Section 3.1.2), the study subsequently only considered the sections \(B, R\) and \(X\).

Furthermore, the BRE-method allows consideration of different configurations:

- Free plumes and adhered plumes;
- Spill plumes with or without air entrainment into the free ends of the plume.

Consequently, the following expressions result.

For spill plumes without air entrainment into the ends of the plume:

\[
\frac{m_X}{m_{X, width}}
\]

Equation 5-1
- For spill plumes with air entrainment at both ends of the plume:
  \[ m_X = m_{X,\text{width}} + m_{X,\text{ends}} \]
  
  Equation 5-2

Given the above, the Figure 5-1 can be replaced by the following (Figure 5-2).

An alternative is to consider separately the air entrainment that occurs in each region of the smoke flow (see Figure 5-3):

- Region 1: air entrainment in the fire room and under the balcony (from the fire until section B);
- Region 2: air entrainment during the rotation at the spill edge (from section B until section R);
- Region 3: air entrainment during the rise of the smoke in the atrium (from section R until section X).
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

Figure 5-3 Identification of three separate regions

These ‘non cumulative’ air entrainments are shown in the Figure 5-4.

The value of those air entrainments can be calculated as follows:

\[ m_1 = m_B \]  
\[ m_2 = m_R - m_B \]

Equation 5-3  
Equation 5-4
\[ m_3 = m_X - m_R \]  

Equation 5-5

Furthermore, with regard to the region 3, it may be useful to distinguish:

- \( m_{3,\text{width}} \): the air entrainment that occurs along the width of the spill plume;
- \( m_{3,\text{ends}} \): the air entrainment into the free ends of the spill plume.

Consequently, the following expressions result:

- For spill plumes \textbf{without} entrainment into the ends of the plume:
  \[ m_X = m_1 + m_2 + m_{3,\text{width}} \]  
  
Equation 5-6

- For spill plumes \textbf{with} entrainment into the free ends:
  \[ m_X = m_1 + m_2 + m_{3,\text{width}} + m_{3,\text{ends}} \]  
  
Equation 5-7

5.2 Decomposition of the global calculation flow

The global calculation process can be represented as follows:

![Figure 5-5 Global calculation flow](image)

The set of input parameters of the global calculation process can then be divided into two sets of input parameters (see Figure 5-6):

- The minimal set of input parameters needed to evaluate \( m_B \);
- The complementary set of input parameters needed to evaluate \( m_X \).
Figure 5-6 Global calculation flow – first simplification

The calculation flow of $m_B$ can be summarized as follows:

The calculation flow of $m_R$ and $t_R$ can be summarized as follows:

The calculation flow of $m_{X, \text{width}}$, $m_{X, \text{ends}}$ and $m_X$ can be summarized as follows:

By considering $m_{X, \text{width}}$ and $m_{X, \text{ends}}$ separately the calculation flow becomes (see Figure 5-10 and Figure 5-11):
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

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Figure 5-10 Calculation flow of $m_{x,\text{width}}$

Figure 5-11 Calculation flow of $m_{x,\text{ends}}$
6 BRE-method : advanced numerical analysis

6.1 Calculation of the mass flow rate in the atrium without air entrainment into the ends of the free plume \( (m_{X,\text{width}}) \)

This section is based on the calculation method described in Annex E of the BRE-method (see [2]).

It is easily recognized that the variation of the mass flow rate in the atrium without air entrainment into the ends of the spill plume \( (m_{X,\text{width}}) \) as a function of the height of rise of the spill plume can be well approximated by a linear regression that can be written as follows:

\[
m_{X,\text{width}} = K_s X + K_{oo}
\]

Equation 6-1

where

\( K_s \) = slope of the linear regression
\( K_{oo} \) = ordinate at the origin of the linear regression

The approach in the next sections aims to determine the slope \( K_s \) and the ordinate at the origin \( K_{oo} \) as a function of selected parameters.

To achieve this, a sensitivity analysis of \( m_{X,\text{width}} \) was performed with respect to the following parameters:

\( m_B \) = mass flow rate under the balcony [kg/s]
\( Q_C \) = convective part of the heat release rate [kW]
\( W_B \) = width of the smoke flow under the balcony [m]
\( X \) = height of rise of the spill plume in the atrium [m]

When performing the sensitivity analysis with respect to one parameter, the value of the other parameters is set equal to their default value (see Table 3-1, page 25). The default value of \( m_B \) is 50 [kg/s], which is the result of the calculation of Equation 7-5 with default inputs.
6.1.1 Calculation of $m_{X,\text{width}}$ in the case of free spill plumes

The sensitivity analysis of $m_{X,\text{width}}$ with respect to $m_B$ gives the following results:

<table>
<thead>
<tr>
<th>$m_B$ [kg/s]</th>
<th>$X$: height of rise of the spill plume in the atrium [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,0</td>
<td>500                  572                  624                  677</td>
</tr>
<tr>
<td>4,5</td>
<td>287                  342                  394                  431</td>
</tr>
<tr>
<td>7,0</td>
<td>213                  261                  307                  352</td>
</tr>
<tr>
<td>9,5</td>
<td>131                  177                  223                  277</td>
</tr>
<tr>
<td>12,0</td>
<td>88                   136                  184                  230</td>
</tr>
<tr>
<td>14,5</td>
<td>52                   98                   144                  190</td>
</tr>
<tr>
<td>17,0</td>
<td>19,5                 248                  296                  344</td>
</tr>
<tr>
<td>19,5</td>
<td>18,9                 175                  163                  149</td>
</tr>
<tr>
<td>22,0</td>
<td>18,7                 94                   82                   68</td>
</tr>
</tbody>
</table>

Figure 6-1

This results show that the slope of the curves $m_{X,\text{width}} = \text{function}(X)$ hardly varies when $m_B$ changes and that the vertical offset between the curves can be approximated by the value of 1,65 $m_B$. 

Figure 6-2
Therefore can be expressed as:

\[ m_{x,\text{width}} = K_1 X + 1.65 m_B + K_2 \]  

Equation 6-2

The following are the study results of the sensitivity analysis of \( Y \), the modified value of the mass flow rate (see Equation 6-3).

\[ Y = m_{x,\text{width}} - 1.65 m_B = K_1 X + K_2 \]  

Equation 6-3

The sensitivity analysis of \( Y \) with respect to \( m_B \) gives the following results:

![Figure 6-3](image-url)
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
Proposal for a simplified method for sizing smoke ventilation systems in atria

The sensitivity analysis of $Y$ with respect to $Q_c$ gives the following results:

![Graph showing the sensitivity analysis of $Y$ with respect to $Q_c$]

Figure 6-4

![Table showing the sensitivity analysis of $Y$ with respect to $Q_c$]

Figure 6-5
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

Figure 6-6

Slope of Y as a function of $Q_c$

$y = 1.40x^{0.32}$

Figure 6-7
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
Proposal for a simplified method for sizing smoke ventilation systems in atria

The sensitivity analysis of $Y$ with respect to $W_B$ gives the following results:

![Figure 6-8](image)

$y = 0.0036x - 0.11$

![Figure 6-9](image)

$Y = m_{\text{Xvent}} - 1.65 m_2$ [kg/s]
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

Figure 6-10

Variation of the slope of Y as a function of $W_B$

$y = 2.85x^{0.68}$

Figure 6-11
The sensitivity of $Y$ to the parameters $m_B$, $Q_C$ and $W_B$ is summarized in Table 6-1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Slope (K1)</th>
<th>Ordinate at the origin (K2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_B$</td>
<td>Not significantly dependent of $m_B$</td>
<td>Not significantly dependent of $m_B$</td>
</tr>
<tr>
<td>$Q_C$</td>
<td>$\sim$ Proportional to $Q_C^{1/3}$</td>
<td>$\sim$ Proportional to $Q_C$</td>
</tr>
<tr>
<td>$W_B$</td>
<td>$\sim$ Proportional to $W_B^{2/3}$</td>
<td>Not significantly dependent of $W_B$</td>
</tr>
</tbody>
</table>

Based on the performed sensitivity analysis of $Y$ with respect to $m_B$, $Q_C$ and $W_B$, the study observes the following expression of the linear regression of $m_{X,\text{width}}$ as a function of $X$, for free plumes.

$$Y = m_{X,\text{width}} - 1,65 m_B = (0,205 Q_C^{1/3} W_B^{2/3}) X + 0,0033 Q_C$$  
Equation 6-4

Thus:

$$m_{X,\text{width}} = 0,205 Q_C^{1/3} W_B^{2/3} X + 1,65 m_B + 0,0033 Q_C$$  
Equation 6-5

6.1.2 Calculation of $m_{X,\text{width}}$ in the case of adhered spill plumes

The sensitivity analysis of $m_{X,\text{width}}$ with respect to $m_B$ gives the following results:

![Figure 6-12](image)

The results identified in red in the Figure 6-12 were excluded from the calculation of the slope and the ordinate at the origin of the approximation of slope and the ordinate at the origin.
This results show that some parts of the curves are decreasing which is physically quite impossible as this would mean that the mass flow rate decreases when the smoke rises in the atrium. For this reason it is proposed to ignore the ‘abnormal’ parts of the curves and to find the best-fit linear regression to the remaining curves.

If we consider only the linear parts of the curves, we notice their slope hardly varies when \( m_B \) changes and that the vertical offset between the curves can be approximated to the value of 1,50 \( m_B \).

Therefore can be expressed as:

\[
m_{X,\text{width}} = K_1 X + 1,50 m_B + K_2
\]

Equation 6-6

In the following, \( Y \) are the study results of the sensitivity analysis of \( Y \), the modified value of the mass flow rate (see Equation 6-7).

\[
Y = m_{X,\text{width}} - 1,50 m_B = K_1 X + K_2
\]

Equation 6-7
The sensitivity analysis of $Y$ with respect to $m_B$ gives the following results:

<table>
<thead>
<tr>
<th>X</th>
<th>m_B = 150 [kg/s]</th>
<th>m_B = 100 [kg/s]</th>
<th>m_B = 60 [kg/s]</th>
<th>m_B = 25 [kg/s]</th>
<th>m_B = 2 [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>96</td>
<td>86</td>
<td>38</td>
<td>25</td>
<td>22</td>
</tr>
<tr>
<td>4.5</td>
<td>88</td>
<td>60</td>
<td>35</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>7.0</td>
<td>83</td>
<td>57</td>
<td>57</td>
<td>57</td>
<td>59</td>
</tr>
<tr>
<td>9.5</td>
<td>79</td>
<td>74</td>
<td>76</td>
<td>75</td>
<td>77</td>
</tr>
<tr>
<td>12.0</td>
<td>94</td>
<td>91</td>
<td>91</td>
<td>93</td>
<td>95</td>
</tr>
<tr>
<td>14.5</td>
<td>106</td>
<td>111</td>
<td>111</td>
<td>113</td>
<td>113</td>
</tr>
<tr>
<td>17.0</td>
<td>125</td>
<td>130</td>
<td>128</td>
<td>134</td>
<td>130</td>
</tr>
<tr>
<td>19.5</td>
<td>145</td>
<td>154</td>
<td>145</td>
<td>150</td>
<td>148</td>
</tr>
<tr>
<td>22.0</td>
<td>165</td>
<td>160</td>
<td>165</td>
<td>168</td>
<td>166</td>
</tr>
</tbody>
</table>

Slope | y = f(x) | 6.9 | 14 | 6.9 | 9 | 7.4 | 1 | 7.2 | 10 |

Figure 6-14

The results identified in red in the Figure 6-14 were excluded from the calculation of the slope and the ordinate at the origin of the approximation of the linear regression.

The Figure 6-15 shows that the modified value of the mass flow rate ($Y = m_{X,\text{width}} - 1.5 m_B$) can be approximated by a unique linear regression for all the values of $m_B$, neglecting the excluded data.
The sensitivity analysis of $Y$ with respect to $Q_c$ gives the following results:

<table>
<thead>
<tr>
<th>$Q_c$ [kW]</th>
<th>X: height of rise of the spill plume in the atrium [m]</th>
<th>Y = $m_{\text{X,\text{width}}} - 1.50 , m_B$ [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,0</td>
<td>4,5</td>
<td>7,0</td>
</tr>
<tr>
<td>6000 [kW]</td>
<td>50</td>
<td>57</td>
</tr>
<tr>
<td>5000 [kW]</td>
<td>48</td>
<td>52</td>
</tr>
<tr>
<td>4000 [kW]</td>
<td>42</td>
<td>46</td>
</tr>
<tr>
<td>3000 [kW]</td>
<td>38</td>
<td>35</td>
</tr>
<tr>
<td>2000 [kW]</td>
<td>33</td>
<td>30</td>
</tr>
<tr>
<td>1000 [kW]</td>
<td>30</td>
<td>26</td>
</tr>
<tr>
<td>300 [kW]</td>
<td>28</td>
<td>25</td>
</tr>
</tbody>
</table>

The results identified in red in the Figure 6-16 were excluded from the calculation of the slope and the ordinate at the origin of the approximation of the linear regression.
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

**Figure 6-18**

**Slope of Y as a function of** $Q_C$

$y = 0.47x^{0.34}$

$Q_C$: convective part of the heat release rate [kW]

**Figure 6-19**

**Ordinate at the origin of Y as a function of** $Q_C$

$y = 0.003x$

$Q_C$: convective part of the heat release rate [kW]
The sensitivity analysis of $Y$ with respect to $W_B$ gives the following results:

<table>
<thead>
<tr>
<th>$W_B$ [m]</th>
<th>2.0</th>
<th>4.5</th>
<th>7.0</th>
<th>9.5</th>
<th>12.0</th>
<th>14.5</th>
<th>17.0</th>
<th>19.5</th>
<th>22.0</th>
<th>Slope</th>
<th>$y = f(x)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>30</td>
<td>55</td>
<td>87</td>
<td>110</td>
<td>137</td>
<td>165</td>
<td>197</td>
<td>227</td>
<td>251</td>
<td>11.3</td>
<td>3</td>
</tr>
<tr>
<td>25</td>
<td>36</td>
<td>50</td>
<td>76</td>
<td>99</td>
<td>122</td>
<td>145</td>
<td>172</td>
<td>200</td>
<td>227</td>
<td>10.3</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>37</td>
<td>44</td>
<td>66</td>
<td>91</td>
<td>106</td>
<td>127</td>
<td>147</td>
<td>170</td>
<td>194</td>
<td>8.2</td>
<td>13</td>
</tr>
<tr>
<td>15</td>
<td>38</td>
<td>35</td>
<td>54</td>
<td>73</td>
<td>89</td>
<td>106</td>
<td>123</td>
<td>139</td>
<td>158</td>
<td>6.8</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>39</td>
<td>36</td>
<td>44</td>
<td>56</td>
<td>71</td>
<td>87</td>
<td>94</td>
<td>109</td>
<td>122</td>
<td>5.2</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>37</td>
<td>36</td>
<td>35</td>
<td>46</td>
<td>54</td>
<td>64</td>
<td>73</td>
<td>82</td>
<td>3.8</td>
<td>-1</td>
</tr>
<tr>
<td>2</td>
<td>42</td>
<td>40</td>
<td>38</td>
<td>37</td>
<td>36</td>
<td>35</td>
<td>43</td>
<td>45</td>
<td>3.8</td>
<td>-1</td>
<td></td>
</tr>
</tbody>
</table>

The results identified in red in the Figure 6-20 were excluded from the calculation of the slope and the ordinate at the origin of the approximation of the linear regression.
The sensitivity of $Y$ to the parameters $m_B$, $Q_c$ and $W_B$ is summarized in Table 6-2.

Table 6-2 Results of the sensitivity analysis of $Y$ for adhered plumes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Slope (K1)</th>
<th>Ordinate at the origin (K2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_B$</td>
<td>Not significantly dependent of $m_B$</td>
<td>Not significantly dependent of $m_B$</td>
</tr>
<tr>
<td>$Q_c$</td>
<td>~ Proportional to $Q_c^{1/3}$</td>
<td>~ Proportional to $Q_c$</td>
</tr>
<tr>
<td>$W_B$</td>
<td>~ Proportional to $W_B^{2/3}$</td>
<td>Not significantly dependent of $W_B$</td>
</tr>
</tbody>
</table>

Based on the performed sensitivity analysis of $Y$ with respect to $m_B$, $Q_c$ and $W_B$, the study observes the following expression of the linear regression of $m_{X, width}$ as a function of $X$, for adhered plumes.

$$Y = m_{X, width} - 1,50 m_B = 0,078 Q_c^{1/3} W_B^{2/3} X + 0,0033 Q_c$$

Equation 6-8

Thus:

$$m_{X, width} = 0,078 Q_c^{1/3} W_B^{2/3} X + 1,50 m_B + 0,0033 Q_c$$

Equation 6-9
6.2 Calculation of the air entrainment into the ends of the free plume ($m_{X,\text{ends}}$)

This section is based on the calculation method described in Annex E of the BRE-method (see [2]).

It is easily recognised that the variation of the air entrainment into the ends of the spill plume ($m_{X,\text{ends}}$) as a function of the height of rise of the spill plume can be well approximated by a quadratic function with an ordinate at the origin equal to 0 that can be written as follows:

\[ m_{X,\text{ends}} = K_3 X^2 + K_4 X \]

**Equation 6-10**

The purpose of the next sections (6.2.1 and 6.2.2) is to determine the expression of $K_3$ and $K_4$ as a function of the inputs parameters of $m_{X,\text{ends}}$.

To achieve this, a sensitivity analysis of $m_{X,\text{ends}}$ was performed with respect to the following parameters:

$\begin{align*}
  m_B & = \text{mass flow rate under the balcony [kg/s]} \\
  Q_c & = \text{convective part of the heat release rate [kW]} \\
  W_B & = \text{width of the smoke flow under the balcony [m]} \\
  X & = \text{height of rise of the spill plume in the atrium [m]}
\end{align*}$

When performing the sensitivity analysis with respect to one parameter, the value of the other parameters is set equal to their default value (see Table 3-1, page 25). The default value of $m_B$ is equal to 50 [kg/s], which is the result the calculation of Equation 7-5 with default inputs.
6.2.1 Calculation of $m_{X,\text{ends}}$ in the case of free plumes

The sensitivity analysis of $m_{X,\text{ends}}$ with respect to $m_B$ gives the following results:

![Graph showing the sensitivity analysis of $m_{X,\text{ends}}$ with respect to $m_B$. The graph includes multiple lines, each representing different values of $m_B$.](image)

**Figure 6-23**

![Table showing the sensitivities for different values of $X$ and $m_B$.](image)

**Figure 6-24**
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

Figure 6-25

Variation of $K_3$ as a function of $m_B$

Figure 6-26

Variation of $K_4$ as a function of $m_B$
The sensitivity analysis of $m_{X,\text{ends}}$ with respect to $Q_c$ gives the following results:

<table>
<thead>
<tr>
<th>$Q_c$ [kW]</th>
<th>$X$ [m]</th>
<th>$m_{X,\text{ends}}$ [kg/s]</th>
<th>$K_3$</th>
<th>$K_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td>2.0</td>
<td>7</td>
<td>0.216</td>
<td>3.106</td>
</tr>
<tr>
<td>5000</td>
<td>4.5</td>
<td>18</td>
<td>0.203</td>
<td>2.936</td>
</tr>
<tr>
<td>4000</td>
<td>7.0</td>
<td>33</td>
<td>0.188</td>
<td>2.765</td>
</tr>
<tr>
<td>3000</td>
<td>9.5</td>
<td>50</td>
<td>0.171</td>
<td>2.590</td>
</tr>
<tr>
<td>2000</td>
<td>12.0</td>
<td>69</td>
<td>0.150</td>
<td>2.411</td>
</tr>
<tr>
<td>1000</td>
<td>14.5</td>
<td>86</td>
<td>0.121</td>
<td>2.222</td>
</tr>
<tr>
<td>300</td>
<td>17.0</td>
<td>118</td>
<td>0.084</td>
<td>2.077</td>
</tr>
</tbody>
</table>

Figure 6-27

![Figure 6-27](image)

Figure 6-28

![Figure 6-28](image)
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

Figure 6-29

Variation of $K_3$ as a function of $Q_C$

$y = 0.01x^{0.31}$

Figure 6-30

Variation of $K_4$ as a function of $Q_C$

$y = 0.52x^{0.13}$
The sensitivity analysis of $m_{X,\text{ends}}$ with respect to $W_B$ gives the following results:

![Graph showing the sensitivity analysis of $m_{X,\text{ends}}$ with respect to $W_B$.](image)

**Figure 6-31**

<table>
<thead>
<tr>
<th>$W_B$ [m]</th>
<th>2.0</th>
<th>4.5</th>
<th>7.0</th>
<th>9.5</th>
<th>12.0</th>
<th>14.5</th>
<th>17.0</th>
<th>19.5</th>
<th>22.0</th>
<th>$K_1$</th>
<th>$K_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>41</td>
<td>98</td>
<td>160</td>
<td>230</td>
<td>305</td>
<td>374</td>
<td>456</td>
<td>540</td>
<td>629</td>
<td>0.392</td>
<td>19.937</td>
</tr>
<tr>
<td>5</td>
<td>17</td>
<td>42</td>
<td>71</td>
<td>103</td>
<td>137</td>
<td>175</td>
<td>217</td>
<td>264</td>
<td>312</td>
<td>0.279</td>
<td>8.039</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>23</td>
<td>56</td>
<td>80</td>
<td>105</td>
<td>130</td>
<td>159</td>
<td>189</td>
<td>213</td>
<td>0.206</td>
<td>4.070</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>16</td>
<td>43</td>
<td>59</td>
<td>78</td>
<td>98</td>
<td>121</td>
<td>145</td>
<td>165</td>
<td>0.175</td>
<td>2.755</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>13</td>
<td>35</td>
<td>48</td>
<td>64</td>
<td>81</td>
<td>101</td>
<td>122</td>
<td>140</td>
<td>0.157</td>
<td>2.094</td>
</tr>
<tr>
<td>25</td>
<td>4</td>
<td>11</td>
<td>29</td>
<td>41</td>
<td>55</td>
<td>71</td>
<td>88</td>
<td>107</td>
<td>124</td>
<td>0.144</td>
<td>1.694</td>
</tr>
<tr>
<td>30</td>
<td>3</td>
<td>9</td>
<td>17</td>
<td>26</td>
<td>37</td>
<td>49</td>
<td>63</td>
<td>79</td>
<td>97</td>
<td>0.134</td>
<td>1.433</td>
</tr>
</tbody>
</table>

$m_{X,\text{ends}}$ [kg/s]

**Figure 6-32**
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes.

Proposal for a simplified method for sizing smoke ventilation systems in atria.

**Variation of $K_3$ as a function of $W_B$**

$y = 0.52x^{-0.35}$

**Variation of $K_4$ as a function of $W_B$**

$y = 38.72x^{-0.97}$
The sensitivity of $m_{X,\text{ends}}$ to the parameters $m_B$, $Q_C$ and $W_B$ for free plumes is summarized in the next table:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>K3</th>
<th>K4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_B$</td>
<td>Not significantly dependent of $m_B$</td>
<td>$\sim$ Proportional to $m_B$</td>
</tr>
<tr>
<td>$Q_C$</td>
<td>$\sim$ Proportional to $Q_C^{1/3}$</td>
<td>$\sim$ Proportional to $Q_C^{2/15}$</td>
</tr>
<tr>
<td>$W_B$</td>
<td>$\sim$ Proportional to $W_B^{-1/3}$</td>
<td>$\sim$ Proportional to $W_B^{-1}$</td>
</tr>
</tbody>
</table>

Based on the performed sensitivity analysis the study observes the following expression of a quadratic function of $m_{X,\text{width}}$ as a function of $X$, for free plumes.

$$m_{X,\text{ends}} = 0.03 \left( \frac{Q_C}{W_B} \right)^{1/3} X^2 + \frac{0.4 m_B Q_C^{2/15}}{W_B} X$$

Equation 6-11
6.2.2 Calculation of $m_{X,\text{ends}}$ in the case of adhered spill plumes

The sensitivity analysis of $m_{X,\text{ends}}$ with respect to $m_B$ gives the following results:

![Graph showing the relationship between $m_{X,\text{ends}}$ and $X$ for different values of $m_B$.]

**Figure 6-35**

![Table showing $m_{X,\text{ends}}$ values for different $m_B$ values.]

**Figure 6-36**
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
Proposal for a simplified method for sizing smoke ventilation systems in atria

Variation of $K_3$ as a function of $m_B$

Variation of $K_4$ as a function of $m_B$

Figure 6-37

Figure 6-38
The sensitivity analysis of $m_{X,\text{ends}}$ with respect to $Q_C$ gives the following results:

![Graph showing $m_{X,\text{ends}}$ vs. $X$ for different values of $Q_C$.]

**Figure 6-39**

| $X$ : height of rise of the spill plume in the atrium [m] | $m_{X,\text{ends}}$ [kg/s] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| QC = 6000 [kW] | 3 | 8 | 13 | 19 | 25 | 32 | 39 | 47 | 56 | 0.046 | 1.508 |
| QC = 5000 [kW] | 3 | 7 | 12 | 18 | 24 | 31 | 37 | 45 | 52 | 0.044 | 1.428 |
| QC = 4000 [kW] | 3 | 7 | 12 | 17 | 23 | 29 | 35 | 42 | 49 | 0.041 | 1.347 |
| QC = 3000 [kW] | 3 | 6 | 11 | 16 | 21 | 27 | 33 | 39 | 46 | 0.037 | 1.267 |
| QC = 2000 [kW] | 3 | 6 | 10 | 15 | 20 | 25 | 30 | 36 | 42 | 0.033 | 1.188 |
| QC = 1000 [kW] | 2 | 5 | 9 | 13 | 18 | 22 | 27 | 32 | 37 | 0.027 | 1.109 |
| QC = 300 [kW] | 2 | 5 | 8 | 12 | 15 | 20 | 24 | 29 | 33 | 0.019 | 1.056 |

**Figure 6-40**

Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
Proposal for a simplified method for sizing smoke ventilation systems in atria
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

Figure 6-41

Variation of $K_3$ as a function of $Q_C$

$y = 0.00x^{0.30}$

Figure 6-42

Variation of $K_4$ as a function of $Q_C$

$y = 0.52x^{0.12}$
The sensitivity analysis of $m_{X,\text{ends}}$ with respect to $W_B$ gives the following results:

![Graph showing the sensitivity analysis of $m_{X,\text{ends}}$ with respect to $W_B$.](image)

**Figure 6-43**

<table>
<thead>
<tr>
<th>$W_B$ [m]</th>
<th>2.0</th>
<th>4.5</th>
<th>7.0</th>
<th>9.5</th>
<th>12.0</th>
<th>14.5</th>
<th>17.0</th>
<th>19.5</th>
<th>22.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>21</td>
<td>48</td>
<td>75</td>
<td>103</td>
<td>131</td>
<td>160</td>
<td>190</td>
<td>226</td>
<td>260</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>10</td>
<td>16</td>
<td>24</td>
<td>32</td>
<td>41</td>
<td>48</td>
<td>57</td>
<td>67</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>7</td>
<td>12</td>
<td>17</td>
<td>22</td>
<td>26</td>
<td>35</td>
<td>41</td>
<td>48</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>5</td>
<td>9</td>
<td>14</td>
<td>18</td>
<td>22</td>
<td>27</td>
<td>33</td>
<td>39</td>
</tr>
<tr>
<td>25</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>11</td>
<td>16</td>
<td>19</td>
<td>23</td>
<td>28</td>
<td>33</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>4</td>
<td>7</td>
<td>9</td>
<td>13</td>
<td>16</td>
<td>20</td>
<td>24</td>
<td>28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$W_B$ [m]</th>
<th>$K_2$</th>
<th>$K_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.063</td>
<td>10.451</td>
</tr>
<tr>
<td>10</td>
<td>0.045</td>
<td>2.037</td>
</tr>
<tr>
<td>15</td>
<td>0.038</td>
<td>1.353</td>
</tr>
<tr>
<td>20</td>
<td>0.034</td>
<td>1.011</td>
</tr>
<tr>
<td>25</td>
<td>0.031</td>
<td>0.807</td>
</tr>
<tr>
<td>30</td>
<td>0.028</td>
<td>0.673</td>
</tr>
</tbody>
</table>

**Figure 6-44**
The sensitivity of $m_{X\text{ends}}$ to the parameters $m_B, Q_C$ and $W_B$ for adhered plumes is summarized in Table 6-4.
### Table 6-4 Results of the sensitivity analysis of $m_{X,ends}$ for adhered plumes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>K3</th>
<th>K4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_B$</td>
<td>Not significantly dependent of $m_B$</td>
<td>~ Proportional to $m_B$</td>
</tr>
<tr>
<td>$Q_C$</td>
<td>~ Proportional to $Q_C^{1/3}$</td>
<td>~ Proportional to $Q_C^{2/15}$</td>
</tr>
<tr>
<td>$W_B$</td>
<td>~ Proportional to $W_B^{1/3}$</td>
<td>~ Proportional to $W_B^{-1}$</td>
</tr>
</tbody>
</table>

Based on the performed sensitivity analysis the study observes the following expression of a quadratic function of $m_{X,\text{width}}$ as a function of $X$, for adhered plumes.

$$m_{X,\text{ends}} = 0.006 \left( \frac{Q_C}{W_B} \right)^{1/3} X^2 + \frac{0.19 m_B Q_C^{2/15}}{W_B} X$$

Equation 6-12

### 6.3 Conclusions on the advanced numerical analysis

Given the decomposition of the calculation flow discussed in Chapter 5, the development of a proposal for a simplified BRE-method is based on a 2-step calculation process:

STEP 1: the calculation of the mass flow rate under the balcony ($m_B$);

STEP 2: the calculation of the mass flow rate in the spill plume ($m_X$) which can be decomposed as follows:

- **STEP 2.1**: the calculation of the air entrainment along the width of the spill plume ($m_{X,\text{width}}$);
- **STEP 2.2**: the calculation of the air entrainment within the ends of the spill plume ($m_{X,\text{ends}}$).

Formally, only STEP 2 is considered in this section since the calculation process of STEP 1 included in the BRE-method is considered to be simple enough.

Basic analysis of the graphs of $m_X$ as a function of $X$ clearly shows that:

- $m_{X,\text{width}}$ is a linear function of $X$ and can be expressed as: $m_{X,\text{width}} = K_1 X + K_2 + K_{mB} m_B$
- $m_{X,\text{ends}}$ is a quadratic function of $X$ that passes through the origin and can be expressed as: $m_{X,\text{ends}} = K_3 X^2 + K_4 X$

A detailed sensitivity analysis has given the value of $K_1, K_2, K_{mB}, K_3$ and $K_4$ as a function of the parameters $m_B, Q_C$ and $W_B$. 

---

Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
Proposal for a simplified method for sizing smoke ventilation systems in atria
Finally the value of $m_{X,\text{width}}$ and $m_{X,\text{ends}}$ can be expressed by the following:

- For free plumes:

$$m_{X,\text{width}} = 0.205 \, Q_c^{1/3} \, W_B^{2/3} \, X + 1.65 \, m_B + 0.0033 \, Q_c$$

$$m_{X,\text{ends}} = 0.03 \left( \frac{Q_c}{W_B} \right)^{1/3} \, X^2 + 0.4 \, m_B \, \frac{Q_c^{2/15}}{W_B} \, X$$

- For adhered plumes:

$$m_{X,\text{width}} = 0.078 \, Q_c^{1/3} \, W_B^{2/3} \, X + 1.50 \, m_B + 0.0033 \, Q_c$$

$$m_{X,\text{ends}} = 0.006 \left( \frac{Q_c}{W_B} \right)^{1/3} \, X^2 + 0.19 \, m_B \, \frac{Q_c^{2/15}}{W_B} \, X$$
Proposal for a simplified BRE-method

This chapter aimed to propose a simplified calculation method where the results show a good agreement with the BRE-method.

In this proposal for a simplified BRE-method, the calculation process includes 3 main steps:

- **STEP 1**: calculation of the mass flow rate under the balcony ($m_B$);
- **STEP 2**: calculation of the smoke flow rising in the atrium;
- **STEP 3**: sizing of the SHEVS.

There are also a series of optional steps for determining 'useful' intermediate parameters:

- The depth of the smoke flow under the balcony (design of the channelling screens);
- The temperature after rotation at the spill edge (required performance of the lowest edge of the façade);
- The temperature of the spill plume at different heights (required performance of the façade, depending on the height).

The first step (STEP 1) includes formulas from the BRE-method itself. Some simplification and rearrangement of the existing formulas are proposed.

The second step (STEP 2) is the actual proposal for a simplified BRE-method that results from the analysis performed in Chapter 6.

**7.1 STEP 1: Calculation of the mass flow rate under the balcony ($m_B$)**

For this part of the calculation process, the BRE-method proposes a calculation method that is sufficiently simple to negate any requirement for a comprehensive study based on a sensitivity analysis. This section aims to rewrite the formulae of the BRE-method in order to facilitate their practical use.

The value of the mass flow rate at the opening of the fire room can be evaluated in accordance with the BRE-method (see Equation 7-1).

$$m_W = \frac{C_e P W_W H_W^{3/2}}{W_W^{2/3} + \frac{1}{C_d} (\frac{C_e P}{2})^{2/3}}^{3/2}$$

Equation 7-1

where

- $m_W$ = mass flow rate at the opening of the fire room [kg/s]
- $C_e$ = coefficient of entrainment in the fire room
  - = 0.19 for large rooms
  - = 0.337 for small rooms
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
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\[ P = \text{perimeter of the fire [m]} \]

\[ C_d = \text{coefficient of discharge of the opening} = 0.65 \ldots 1 \]

The Equation 7-1 can be rewritten taking into account the following points:

- \( C_d = 1 \), because the sensitivity analysis has shown that this assumption is maximizing the mass flow and thus the depth of the smoke flow rate under the balcony.
- A new dimensionless factor is introduced: \( C_{LR} = (C_e)^{-2/3} \), which can be rounded down as this will maximize the mass flow and thus the depth of the smoke flow rate under the balcony.
  - \( C_{LR} = 2.06 \approx 2 \) for small rooms.
  - \( C_{LR} = 3.03 \approx 3 \) for large rooms.

Thus:

\[
m_W = \left[ \frac{H_W}{C_{LR} P^{-2/3} + 0.63 W_W^{-2/3}} \right]^{3/2}
\]

where

\[ C_{LR} = 2 \text{ for small rooms} \]

\[ C_{LR} = 3 \text{ for large rooms} \]

Equation 7-2

The mass flow rate under the balcony can then easily be evaluated in accordance with the BRE-method (see Equation 7-3 and Equation 7-4)

\[ m_B = m_W \text{ when the balcony is flat with the opening of the fire room} \]

Equation 7-3

\[ m_B = 2 m_W \text{ when the smoke rises after the opening of the fire room} \]

Equation 7-4

Finally, the mass flow rate under the balcony can be evaluated as follows:

\[
m_B = C_{RAW} \left[ \frac{H_W}{C_{LR} P^{-2/3} + 0.63 W_W^{-2/3}} \right]^{3/2}
\]

Equation 7-5
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

$C_{raw} = 1$ when the underside of balcony is flat with the opening of the fire room

$= 2$ when the underside of the balcony is higher than the opening of the fire room

(the smoke rises after the opening)

$C_{LR} = 2$ for small rooms

$= 3$ for large rooms

7.2 STEP 2: Calculation of the mass flow rate in the spill plume

- For spill plumes where air entrainment occurs into the ends of the plume:

\[ m_x = m_{x, width} + m_{x, ends} \]

Equation 7-6

- For spill plumes where no air entrainment occurs into the ends of the plume:

\[ m_x = m_{x, width} \]

Equation 7-7

7.2.1 Free plumes

\[ m_{x, width} = 0.205 Q_C^{1/3} W_B^{2/3} X + 1.65 m_B + 0.0033 Q_C \]

Equation 7-8

\[ m_{x, ends} = 0.03 \left( \frac{Q_C}{W_B} \right)^{1/3} X^2 + \frac{0.4 m_B Q_C^{2/15}}{W_B} X \]

Equation 7-9

7.2.2 Adhered spill plumes

\[ m_{x, width} = 0.078 Q_C^{1/3} W_B^{2/3} X + 1.50 m_B + 0.0033 Q_C \]

Equation 7-10

\[ m_{x, ends} = 0.006 \left( \frac{Q_C}{W_B} \right)^{1/3} X^2 + \frac{0.19 m_B Q_C^{2/15}}{W_B} X \]

Equation 7-11
7.3 STEP 3: Sizing of the SHEVS

7.3.1 Calculation of the mass flow rate entering the smoke layer \((m_L)\)

Since a steady state situation is considered, the mass flow rate to extract from the building is equal to the mass flow rate entering the smoke layer \((m_L)\).

The study of Harrison (see Section 2.9) has shown that the BRE-method gives a reasonably good agreement with the experimental data provided that the height of rise in the atrium is measured with respect to the visible layer base.

Consequently, the sizing of the SHEVS can be based on the value of \(m_X\) (see the equations of the Section 7.2), with \(X\) = the height of rise of the spill plume, measured between the spill edge and the visible base layer in the atrium.

7.3.2 Sizing of a mechanical SHEVS

The required ventilation rate (fan capacity) can be calculated as follows:

\[
V_L = \frac{m_L}{\rho_L}
\]

\text{Equation 7-12}

with

\[
\rho_L = \frac{\rho_0 \cdot 288}{T_L} \approx \frac{355}{T_L}
\]

\text{Equation 7-13}

and

\[
T_L = 288 + \frac{Q_c}{m_L}
\]

\text{Equation 7-14}

where

\(V_L\) = required ventilation rate \([\text{m}^3/\text{s}]\)

\(\rho_L\) = density of the smoke layer \([\text{kg/m}^3]\)

\(T_L\) = absolute temperature of the smoke layer \([\text{K}]\)

\(\rho_0\) = density of the ambient \(\approx 1,293\) \([\text{kg/m}^3]\)
7.3.3 Sizing of a natural SHEVS

The area of the opening in the roof can be determined by using the formula (5.15a) of the BR368 [2]:

\[
A_V C_V = \frac{m_L T_L}{\left[2 g \rho_0^2 D_L \theta_L T_0 - \left(\frac{T_L T_0}{A_I^2} \frac{m_I^2}{C_I^2}\right)\right]^{1/2}}
\]

Equation 7-15

where

- \(A_V\) = throat area of the opening in the roof of the atrium \([m^2]\)
- \(C_V\) = coefficient of discharge of the vents
- \(A_I\) = area of the inlets \([m^2]\)
- \(C_I\) = coefficient of discharge of the inlets
- \(\rho_0\) = density of the ambient \([kg/m^3]\)
- \(\theta_L\) = temperature of the smoke layer above the ambient \([K]\)

7.4 Optional STEPS

7.4.1 Calculation of the depth of the smoke flow under the balcony (\(D_B\))

The depth of the smoke flow under the balcony can be evaluated in accordance with the BRE-method:

\[
D_B = 0.36 \left(\frac{m_B T_B}{\sqrt{\theta_B T_0}}\right)^{2/3}
\]

Equation 7-16

where

- \(T_B\) = temperature of the smoke flow under the balcony \([K]\)
- \(\theta_B\) = temperature elevation of the smoke under the balcony \([K]\)

Considering a new parameter \(C_{DB}\):

\[
C_{DB} = 0.36 \left(\frac{m_B T_B}{\sqrt{\theta_B T_0}}\right)^{2/3}
\]

Equation 7-17
We can write:

\[ D_B = C_{DB} W_B^{-2/3} \]  

Equation 7-18

Since:

\[ \theta_B = \frac{Q_C}{m_B} \]  

Equation 7-19

\[ T_B = 288 + \theta_B \]  

Equation 7-20

We can see that \( C_{DB} \) is only dependant of \( m_B \) and \( Q_C \):

\[ C_{DB} = 0.0545 \left( m_B \left( 288 + \frac{Q_C}{m_B} \right)^{2/3} \left( \frac{Q_C}{m_B} \right)^{-1/3} \right) \]  

Equation 7-21

The following figure provides a direct reading of the value of \( C_{DB} \) as a function of \( m_B \) and \( Q_C \).

![Figure 7-1 \( C_{DB} \) as a function of \( m_B \) and \( Q_C \)]
7.4.2 Calculation of the temperature of the smoke after rotation \( (t_R) \)

To simplify the calculation process (see Figure 5-8), a sensitivity analysis of \( m_R \) was performed with respect to the following parameters:

\[
\begin{align*}
    m_B & = \text{mass flow rate under the balcony [kg/s]} \\
    Q_C & = \text{convective part of the heat release rate [kW]} \\
    W_B & = \text{width of the smoke flow under the balcony [m]}
\end{align*}
\]

The sensitivity analysis of \( m_R \) with respect to \( Q_C \) gives the following results:

![Figure 7-2](image)

The results of this analysis (see Figure 7-2) show that:

- The slope of \( m_R = \text{function}(m_B) \) is independent of \( Q_C \).
- The ordinate at the origin of \( m_R = \text{function}(m_B) \) can be approximated by the value of 0,00402 \( Q_C \).

The sensitivity analysis of \( m_R \) with respect to \( W_B \) gives the following results:

![Figure 7-3](image)
The results of this analysis (see Figure 7-3) show that:

- The slope of $m_R = \text{function}(m_B)$ is independent of $W_B$;
- The ordinate at the origin of $m_R = \text{function}(m_B)$ is independent of $W_B$.

Consequently the value of $m_R$ can be approximated by the following expression:

$$m_R = 1,846 \, m_B + 0,00402 \, Q_C$$

Equation 7-22

where:

- $m_R = \text{mass flow rate after rotation} \, [\text{kg/s}]$

Since:

$$\theta_R = \frac{Q_C}{m_R}$$

Equation 7-23

and

$$t_R = 15 + \theta_R$$

Equation 7-24

Thus the simplified expression:

$$t_R = 15 + \left[ \frac{1,846 \, m_B}{Q_C} + 0,00402 \right]^{-1}$$

Equation 7-25

### 7.5 Conclusions on the proposal for a simplified method

The proposal for a simplified BRE-method allows the sizing of a mechanical or natural SHEVS in an atrium. The proposed 3-step calculation process provides a much lower level of complexity than the original BRE-method.

It should be noted that the proposed method addresses only spill plumes, i.e. smoke flows coming from adjacent fire rooms. Fires located on the atrium floor correspond to axisymmetric plumes which goes beyond the scope of this study.
8 Numerical comparison between the original BRE-method and the simplified BRE-method

A comparison between the results of the original BRE-method and the simplified BRE-method (also called 'new' simplified method) has been conducted with respect to the 4 design fires and corresponding geometry described in the following table.

<table>
<thead>
<tr>
<th>Case n°</th>
<th>Type of occupancy</th>
<th>Fire perimeter ( P ) [m]</th>
<th>Convective heat release rate ( Q_c ) [kW]</th>
<th>Height under the balcony [m]</th>
<th>Width of the opening [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hotel bedroom with standard sprinklers</td>
<td>6</td>
<td>300</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Office with standard response sprinklers</td>
<td>14</td>
<td>1000</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Shop with fast response sprinkler</td>
<td>9</td>
<td>2500</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>Shop with standard response sprinkler</td>
<td>12</td>
<td>5000</td>
<td>5</td>
<td>12</td>
</tr>
</tbody>
</table>

In all cases, it is considered that there is no downstand at the opening of the fire room and that the balcony is flat with this opening. Furthermore, the cases 1 and 2 are treated like ‘small rooms’ (entrainment coefficient of the BRE-method = 0.337) whereas the cases 3 and 4 are treated like 'large rooms' (entrainment coefficient of the BRE-method = 0.19).

The results of this numerical comparison can be found in the Appendix C and are summarized in the Table 8-2. This table gives the relative difference [%] between the result of the calculation with the original BRE-method and its result with the simplified BRE-method.

We see that the simplified BRE-method shows a good agreement with the original BRE-method:

- the largest observed relative difference is less than 8%;
- the average relative difference for free plumes is less than 1%;
- the average relative difference for adhered plumes is less than 2%.
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
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Table 8-2 Summary of the numerical comparison between the original BRE-method and the simplified BRE-method

<table>
<thead>
<tr>
<th>Air entrainment into the ends of the spill plume?</th>
<th>Free plumes</th>
<th></th>
<th>Adhered plumes</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hotel bedroom with standard sprinklers</td>
<td>No</td>
<td>2.9%</td>
<td>Yes</td>
<td>2.1%</td>
</tr>
<tr>
<td>Office with standard response sprinklers</td>
<td>1.5%</td>
<td>Yes</td>
<td>2.5%</td>
<td>7.8%</td>
</tr>
<tr>
<td>Shop with fast response sprinkler</td>
<td>1.7%</td>
<td>1.6%</td>
<td>3.8%</td>
<td>3.7%</td>
</tr>
<tr>
<td>Shop with standard response sprinkler</td>
<td>1.1%</td>
<td>1.8%</td>
<td>5.0%</td>
<td>3.8%</td>
</tr>
</tbody>
</table>
9 Conclusions and recommendations for future work

The starting point of this study was the unnecessary complexity of the BRE-method and the resulting problems: a high risk of miscalculation and no possibility of quick check by the authorities.

The comparison between the BRE-method and the existing simplified methods has shown that none of those simplified methods could serve as an acceptable alternative. Indeed, their results are not in agreement with the BRE-method and their fields of application is always limited.

However, the proposal for a simplified BRE-method developed in this study meets these requirements:

- the largest observed relative difference between the original and the simplified method is less than 8%;
- the average relative difference for free plumes is less than 1%;
- the average relative difference for adhered plumes is less than 2%.

An important question remains; this concerns the reliability of calculation results obtained by using the BRE-method or its simplified version.

The validation of the BRE-method by full-scale testing was satisfactory but did not cover the full scope of the method.

The CFD modelling studies conducted by Harrison and Tilley have provided interesting information but didn't result in a satisfactory alternative to the BRE-method, particularly because their conclusions didn't cover all common situations.

It would be desirable to carry out a broad campaign of CFD-modelling that covers all types of spill plumes and a wide range of geometry. This campaign should ideally result in a simple and practical calculation method.
Appendix A: Results of the global sensitivity analysis of the BRE-method
A1 Global sensitivity analysis: $m_X$, parameter $P$

![Table of mass flow rate $m_X$ at height $X$ [kg/s] and perimeter of the fire $P$ [m].]

![Graph showing mass flow rate $m_X$ at different perimeters $P$.]

Figure A-1 Mass flow rate $m_X$, parameter $P$
Global sensitivity analysis: $m_X$, parameter $Q_C$

| $Q_C$ : convective part of the heat release rate [kW] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 300             | 500             | 1000            | 2000            | 3000            | 4000            | 6000            |
| maximising input data | 488             | 556             | 675             | 793             | 885             | 959             | 1023            | 1080            | 488             | 1080            | 592             | 55%             |
| default input data | 175             | 200             | 244             | 290             | 327             | 358             | 385             | 409             | 175             | 409             | 234             | 57%             |
| minimizing input data | 3.3             | 4.2             | 6.5             | 11.2            | 15.6            | 20.2           | 24.8            | 29.4            | 3.3             | 29.4            | 26.1            | 89%             |

Figure A-2 Mass flow rate $m_X$, parameter $Q_C$
A3 Global sensitivity analysis: $m_X$, parameter $H_W$

**Figure A-3** Mass flow rate $m_X$, parameter $H_W$
A4 Global sensitivity analysis: $m_X$, parameter $D_D$

![Table and graph showing global sensitivity analysis for $m_X$ and $D_D$](image)

Figure A-4 Mass flow rate $m_X$, parameter $D_D$
A5 Global sensitivity analysis: $m_X$, parameter $W_B$

<table>
<thead>
<tr>
<th>$W_B$ : width of the smoke flow at the spill edge [m]</th>
<th>min</th>
<th>max</th>
<th>delta</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximizing input data</td>
<td>781</td>
<td>1080</td>
<td>299</td>
<td>28%</td>
</tr>
<tr>
<td>default input data</td>
<td>250</td>
<td>431</td>
<td>181</td>
<td>42%</td>
</tr>
<tr>
<td>minimizing input data</td>
<td>3.3</td>
<td>12.7</td>
<td>9.4</td>
<td>74%</td>
</tr>
</tbody>
</table>

$W_B$ : width of the smoke flow at the spill edge [m]

$W_B$ : width of the smoke flow at the spill edge [m]

Figure A-5 Mass flow rate $m_X$, parameter $W_B$
A6 Global sensitivity analysis: $m_x$, parameter $X$

![Figure A-6 Mass flow rate $m_x$, parameter $X$](image)

The table shows the mass flow rate $m_x$ at different heights of rise of the spill plume in the atrium. The graph illustrates the trend of $m_x$ as a function of the height of rise $X$. The three lines represent different input data scenarios: maximizing, default, and minimizing. The percentage change (%) is also indicated for each scenario.
A7  Global sensitivity analysis: $m_X$, parameter $L.R.$.

<table>
<thead>
<tr>
<th>$X$ : height of rise of the spill plume in the atrium [m]</th>
<th>2.00</th>
<th>4.50</th>
<th>7.00</th>
<th>9.50</th>
<th>12.00</th>
<th>14.50</th>
<th>17.00</th>
<th>19.50</th>
<th>22.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>small room</td>
<td>138</td>
<td>193</td>
<td>251</td>
<td>320</td>
<td>378</td>
<td>508</td>
<td>576</td>
<td>647</td>
<td>$m_X$</td>
</tr>
<tr>
<td>large room</td>
<td>108</td>
<td>159</td>
<td>222</td>
<td>277</td>
<td>337</td>
<td>464</td>
<td>530</td>
<td>596</td>
<td>$[\text{kg/s}]$</td>
</tr>
<tr>
<td>delta</td>
<td>10</td>
<td>14</td>
<td>18</td>
<td>22</td>
<td>26</td>
<td>30</td>
<td>34</td>
<td>38</td>
<td>42</td>
</tr>
<tr>
<td>%</td>
<td>22%</td>
<td>18%</td>
<td>12%</td>
<td>13%</td>
<td>11%</td>
<td>9%</td>
<td>8%</td>
<td>8%</td>
<td>22%</td>
</tr>
</tbody>
</table>

Figure A-7 Mass flow rate $m_X$, parameter $L.R.$.
A8  Global sensitivity analysis: $m_X$, parameter $R.A.W.$.

<table>
<thead>
<tr>
<th>$X$ : height of rise of the spill plume in the atrium [m]</th>
<th>2.00</th>
<th>4.50</th>
<th>7.00</th>
<th>9.50</th>
<th>12.00</th>
<th>14.50</th>
<th>17.00</th>
<th>19.50</th>
<th>22.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>rise after window</td>
<td>138</td>
<td>193</td>
<td>251</td>
<td>320</td>
<td>378</td>
<td>442</td>
<td>508</td>
<td>576</td>
<td>647</td>
</tr>
<tr>
<td>no rise after window</td>
<td>93</td>
<td>147</td>
<td>204</td>
<td>262</td>
<td>321</td>
<td>382</td>
<td>448</td>
<td>511</td>
<td>579</td>
</tr>
<tr>
<td>delta</td>
<td>45</td>
<td>46</td>
<td>47</td>
<td>59</td>
<td>57</td>
<td>60</td>
<td>63</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>%</td>
<td>33%</td>
<td>24%</td>
<td>19%</td>
<td>18%</td>
<td>15%</td>
<td>14%</td>
<td>12%</td>
<td>11%</td>
<td>11%</td>
</tr>
</tbody>
</table>

Figure A-8 Mass flow rate $m_X$ parameter $R.A.W.$.
A9  Global sensitivity analysis: \( m_X \), parameter \( A.P. \).

<table>
<thead>
<tr>
<th>( X ) : height of rise of the spill plume in the atrium [m]</th>
<th>2.00</th>
<th>4.50</th>
<th>7.00</th>
<th>9.50</th>
<th>12.00</th>
<th>14.50</th>
<th>17.00</th>
<th>19.50</th>
<th>22.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>non adherent plume</td>
<td>138</td>
<td>193</td>
<td>251</td>
<td>320</td>
<td>378</td>
<td>442</td>
<td>508</td>
<td>576</td>
<td>647</td>
</tr>
<tr>
<td>adherent plume</td>
<td>117</td>
<td>117</td>
<td>144</td>
<td>168</td>
<td>189</td>
<td>214</td>
<td>237</td>
<td>260</td>
<td>287</td>
</tr>
<tr>
<td>delta</td>
<td>22</td>
<td>76</td>
<td>108</td>
<td>152</td>
<td>189</td>
<td>229</td>
<td>271</td>
<td>316</td>
<td>360</td>
</tr>
<tr>
<td>%</td>
<td>16%</td>
<td>39%</td>
<td>43%</td>
<td>47%</td>
<td>50%</td>
<td>52%</td>
<td>53%</td>
<td>55%</td>
<td>56%</td>
</tr>
</tbody>
</table>

\[ m_X \]: mass flow rate at height \( X \) [kg/s]

\( X \): height of rise of the spill plume in the atrium [m]

Figure A-9 Mass flow rate \( m_X \), parameter \( A.P. \).
A10 Global sensitivity analysis: $m_X$, parameter $F.E.$

Figure A-10 Mass flow rate $m_X$, parameter $F.E.$
Appendix B: Results of the numerical comparison between the BRE-method and the existing simplified methods
B1  Numerical comparison for free plumes with air entrainment into the ends of the plume

B1.1 Hotel bedroom (with standard sprinklers)

![Table showing numerical comparison for free plumes with air entrainment into the ends of the plume]

**Figure B-1**
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
Proposal for a simplified method for sizing smoke ventilation systems in atria

Figure B-2
B1.2  Office (with standard sprinklers)

Figure B-3
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

Figure B-4
B1.3 Shop with fast response sprinklers

```
<table>
<thead>
<tr>
<th>Method</th>
<th>X: height of rise of the spill plume in the atrium [m]</th>
<th>m_x [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRE</td>
<td>2.00 4.50 7.00 9.50 12.00 14.50 17.00 19.50 22.00</td>
<td>66 111 155 202 250 301 355 410 467</td>
</tr>
<tr>
<td>LAW-95</td>
<td>72 127 182 237 292 347 402 458 513</td>
<td></td>
</tr>
<tr>
<td>CIBSE</td>
<td>83 147 211 275 339 403 467 531 595</td>
<td></td>
</tr>
<tr>
<td>THOMAS-98</td>
<td>49 78 108 138 168 197 227 257 287</td>
<td></td>
</tr>
<tr>
<td>HARRISON</td>
<td>55 91 126 162 198 233 269 304 340</td>
<td></td>
</tr>
<tr>
<td>NFPA-09</td>
<td>83 147 211 275 339 403 502 538 573</td>
<td></td>
</tr>
</tbody>
</table>

Relative difference between BRE-method and simplified method

<table>
<thead>
<tr>
<th>Method</th>
<th>8% 15% 18% 18% 17% 15% 13% 12% 10%</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAW-95</td>
<td></td>
<td>18%</td>
</tr>
<tr>
<td>CIBSE</td>
<td>26% 33% 36% 37% 36% 34% 32% 30% 27%</td>
<td>37%</td>
</tr>
<tr>
<td>THOMAS-98</td>
<td>27% 29% 30% 32% 33% 34% 36% 37% 39%</td>
<td>39%</td>
</tr>
<tr>
<td>HARRISON</td>
<td>16% 18% 18% 20% 21% 23% 24% 26% 27%</td>
<td>27%</td>
</tr>
<tr>
<td>NFPA-09</td>
<td>26% 33% 36% 37% 36% 34% 42% 31% 23%</td>
<td>42%</td>
</tr>
</tbody>
</table>

P = 9 [m]  | Free plume? yes          
QC = 2500 [kW]  | With air entrainment at the ends? yes  
HB = 5 [m]  | Large room? yes          
WB = 12 [m]  |
```

Figure B-5
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

Figure B-6
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

B1.4 Shop with standard sprinklers

![Comparison of existing methods for smoke spill plumes](image)

**Figure B-7**
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes.

Proposal for a simplified method for sizing smoke ventilation systems in atria.

Figure B-8
B2  Numerical comparison for free plumes without air entrainment into the ends of the plume

B2.1  Hotel bedroom (with standard sprinklers)

Figure B-9

Figure B-10
B2.2  Office (with standard sprinklers)

![Diagram of smoke spill plume](image)

**Table B-11**

<table>
<thead>
<tr>
<th>BRE</th>
<th>POREH</th>
<th>THOMAS-98</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,00</td>
<td>50</td>
<td>66</td>
</tr>
<tr>
<td>4,50</td>
<td>50</td>
<td>74</td>
</tr>
<tr>
<td>7,00</td>
<td>60</td>
<td>62</td>
</tr>
<tr>
<td>9,50</td>
<td>81</td>
<td>86</td>
</tr>
<tr>
<td>12,00</td>
<td>110</td>
<td>97</td>
</tr>
<tr>
<td>14,50</td>
<td>125</td>
<td>83</td>
</tr>
<tr>
<td>17,00</td>
<td>140</td>
<td>110</td>
</tr>
<tr>
<td>19,50</td>
<td>155</td>
<td>121</td>
</tr>
</tbody>
</table>

**Figure B-11**

- BRE: 24%
- POREH: 24%
- THOMAS-98: 24%

**Figure B-12**

Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
Proposal for a simplified method for sizing smoke ventilation systems in atria
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

B2.3 Shop with fast response sprinklers

Table B-1: Comparison of existing empirical methods for air entrainment in smoke spill plumes

<table>
<thead>
<tr>
<th>Method</th>
<th>2.00</th>
<th>4.50</th>
<th>7.00</th>
<th>9.50</th>
<th>12.00</th>
<th>14.50</th>
<th>17.00</th>
<th>19.50</th>
<th>22.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRE</td>
<td>63</td>
<td>100</td>
<td>136</td>
<td>172</td>
<td>208</td>
<td>244</td>
<td>280</td>
<td>316</td>
<td>352</td>
</tr>
<tr>
<td>POREH</td>
<td>46</td>
<td>74</td>
<td>103</td>
<td>131</td>
<td>159</td>
<td>188</td>
<td>216</td>
<td>245</td>
<td>273</td>
</tr>
<tr>
<td>THOMAS-98</td>
<td>47</td>
<td>76</td>
<td>104</td>
<td>133</td>
<td>161</td>
<td>190</td>
<td>218</td>
<td>247</td>
<td>275</td>
</tr>
</tbody>
</table>

$X$ : height of rise of the spill plume in the atrium [m]

$\dot{m}_X$ [kg/s]

<table>
<thead>
<tr>
<th>Method</th>
<th>Relative difference with BRE-method</th>
</tr>
</thead>
<tbody>
<tr>
<td>POREH</td>
<td>27%</td>
</tr>
<tr>
<td>THOMAS-98</td>
<td>24%</td>
</tr>
</tbody>
</table>

Figure B-13

Figure B-14

$X$ : height of rise of the spill plume in the atrium [m]

$\dot{m}_X$ : mass flow rate at height $X$ [kg/s]
B2.4 Shop with standard sprinklers

<table>
<thead>
<tr>
<th></th>
<th>BRE</th>
<th>4.50</th>
<th>7.00</th>
<th>9.50</th>
<th>12.00</th>
<th>14.50</th>
<th>17.00</th>
<th>19.50</th>
<th>22.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRE</td>
<td>85</td>
<td>131</td>
<td>179</td>
<td>224</td>
<td>269</td>
<td>315</td>
<td>360</td>
<td>405</td>
<td>450</td>
</tr>
<tr>
<td>POREH</td>
<td>59</td>
<td>95</td>
<td>131</td>
<td>167</td>
<td>203</td>
<td>238</td>
<td>274</td>
<td>310</td>
<td>346</td>
</tr>
<tr>
<td>THOMAS-98</td>
<td>64</td>
<td>100</td>
<td>136</td>
<td>171</td>
<td>207</td>
<td>243</td>
<td>279</td>
<td>315</td>
<td>351</td>
</tr>
</tbody>
</table>

Relative difference between BRE-method and simplified method

<table>
<thead>
<tr>
<th></th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>POREH</td>
<td>31%</td>
</tr>
<tr>
<td>THOMAS-98</td>
<td>25%</td>
</tr>
</tbody>
</table>

\[ m_x \text{ [kg/s]} \]

<table>
<thead>
<tr>
<th>P</th>
<th>12 [m]</th>
<th>Free plume?</th>
<th>yes</th>
<th>With air entrainment at the ends?</th>
<th>no</th>
<th>Large room?</th>
<th>yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>QC</td>
<td>5000 [kW]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HB</td>
<td>5 [m]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WB</td>
<td>12 [m]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure B-15

Figure B-16
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

B3. Numerical comparison for adhered spill plume without air entrainment into the ends of the plume

B3.1 Hotel bedroom (with standard sprinklers)

Figure B-17

Table of mass flow rate at height X [kg/s]

<table>
<thead>
<tr>
<th>Method</th>
<th>X: height of rise of the spill plume in the atrium [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.00</td>
</tr>
<tr>
<td>BRE</td>
<td>14</td>
</tr>
<tr>
<td>POREH</td>
<td>10</td>
</tr>
<tr>
<td>TILLEY - Hs15</td>
<td>10</td>
</tr>
<tr>
<td>TILLEY - Hs25</td>
<td>10</td>
</tr>
<tr>
<td>TILLEY - Hs35</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Method</th>
<th>Relative difference between BRE-method and simplified method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>max</td>
</tr>
<tr>
<td>POREH</td>
<td>25%</td>
</tr>
<tr>
<td>TILLEY - Hs15</td>
<td>16%</td>
</tr>
<tr>
<td>TILLEY - Hs25</td>
<td>14%</td>
</tr>
<tr>
<td>TILLEY - Hs35</td>
<td>12%</td>
</tr>
</tbody>
</table>

Figure B-18

Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
Proposal for a simplified method for sizing smoke ventilation systems in atria
B3.2 Office (with standard sprinklers)

![Figure B-19]

![Figure B-20]

Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
Proposal for a simplified method for sizing smoke ventilation systems in atria
B3.3 Shop with fast response sprinklers

### Table

<table>
<thead>
<tr>
<th></th>
<th>2.00</th>
<th>4.50</th>
<th>7.00</th>
<th>9.50</th>
<th>12.00</th>
<th>14.50</th>
<th>17.00</th>
<th>19.50</th>
<th>22.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRE</td>
<td>40</td>
<td>54</td>
<td>68</td>
<td>82</td>
<td>96</td>
<td>113</td>
<td>125</td>
<td>139</td>
<td>153</td>
</tr>
<tr>
<td>POREH</td>
<td>30</td>
<td>43</td>
<td>57</td>
<td>71</td>
<td>85</td>
<td>98</td>
<td>112</td>
<td>126</td>
<td>139</td>
</tr>
<tr>
<td>TILLEY - Hs15</td>
<td>30</td>
<td>45</td>
<td>59</td>
<td>73</td>
<td>87</td>
<td>101</td>
<td>120</td>
<td>165</td>
<td>210</td>
</tr>
<tr>
<td>TILLEY - Hs25</td>
<td>30</td>
<td>45</td>
<td>59</td>
<td>73</td>
<td>87</td>
<td>101</td>
<td>116</td>
<td>130</td>
<td>144</td>
</tr>
<tr>
<td>TILLEY - Hs35</td>
<td>30</td>
<td>45</td>
<td>59</td>
<td>73</td>
<td>87</td>
<td>101</td>
<td>116</td>
<td>130</td>
<td>144</td>
</tr>
</tbody>
</table>

### Figure B-21

- **POREH**
  - 26% 20% 16% 13% 12% 13% 11% 10% 9% 26%
- **TILLEY - Hs15**
  - 25% 18% 13% 10% 67% 136% 100% 100% 100% 136%
- **TILLEY - Hs25**
  - 25% 18% 13% 10% 9% 10% 4% 19% 37% 37%
- **TILLEY - Hs35**
  - 26% 18% 13% 10% 9% 10% 8% 7% 6% 25%

### Figure B-22
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
Proposal for a simplified method for sizing smoke ventilation systems in atria

**B3.4 Shop with standard sprinklers**

<table>
<thead>
<tr>
<th>BRE</th>
<th>POREH</th>
<th>TILLEY - Hs15</th>
<th>TILLEY - Hs25</th>
<th>TILLEY - Hs35</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>38</td>
<td>39</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>73</td>
<td>56</td>
<td>57</td>
<td>57</td>
<td>57</td>
</tr>
<tr>
<td>93</td>
<td>73</td>
<td>75</td>
<td>75</td>
<td>75</td>
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<tr>
<td>108</td>
<td>90</td>
<td>93</td>
<td>93</td>
<td>93</td>
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<tr>
<td>124</td>
<td>107</td>
<td>111</td>
<td>111</td>
<td>111</td>
</tr>
<tr>
<td>144</td>
<td>125</td>
<td>129</td>
<td>129</td>
<td>129</td>
</tr>
<tr>
<td>164</td>
<td>142</td>
<td>152</td>
<td>152</td>
<td>147</td>
</tr>
<tr>
<td>183</td>
<td>159</td>
<td>209</td>
<td>209</td>
<td>165</td>
</tr>
<tr>
<td>199</td>
<td>176</td>
<td>266</td>
<td>266</td>
<td>183</td>
</tr>
</tbody>
</table>

\[ m_X [\text{kg/s}] \]

**Figure B-23**

**Figure B-24**

\[ P = 12 \, [\text{m}] \quad \text{Free plume? no} \]
\[ Q_C = 5000 \, [\text{kW}] \quad \text{With air entrainment at the ends? no} \]
\[ H_B = 5 \, [\text{m}] \quad \text{Large room? yes} \]
\[ W_B = 12 \, [\text{m}] \]

Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
Proposal for a simplified method for sizing smoke ventilation systems in atria
Appendix C: Results of the numerical comparison between the original BRE-method and the proposal for simplified BRE-method
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

C1 Numerical comparison for free plumes

C1.1 Hotel bedroom (with standard sprinklers)

<table>
<thead>
<tr>
<th>Hotel bedroom with standard sprinklers</th>
<th>X: height of rise of the spill plume in the atrium [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRE - mX</td>
<td>22.0 35.2 51.7 68.1 86.4 106.3 127.6 150.5 174.9</td>
</tr>
<tr>
<td>NEW - mX</td>
<td>21.6 35.7 51.4 68.6 87.5 107.9 129.9 153.5 178.6</td>
</tr>
<tr>
<td>BRE - mX,width</td>
<td>16.9 26.9 36.3 44.5 53.0 61.5 70.1 78.6 87.1</td>
</tr>
<tr>
<td>NEW - mX,width</td>
<td>18.4 27.0 35.7 44.3 53.0 61.6 70.2 78.9 87.5</td>
</tr>
</tbody>
</table>

| Relative difference mX | 1.9% 1.3% 0.6% 0.8% 1.2% 1.5% 1.8% 2.0% 2.1% |
| Relative difference mX, width | 2.9% 0.4% 1.8% 0.4% 0.1% 0.1% 0.3% 0.4% 0.5% 2.9% |

Figure C-1

Figure C-2
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

C1.2 Office (with standard sprinklers)

<table>
<thead>
<tr>
<th>X [m]</th>
<th>BRE - mX</th>
<th>NEW - mX</th>
<th>BRE - mX, width</th>
<th>NEW - mX, width</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00</td>
<td>40.6</td>
<td>40.7</td>
<td>35.6</td>
<td>35.2</td>
</tr>
<tr>
<td>4.50</td>
<td>63.3</td>
<td>64.6</td>
<td>50.0</td>
<td>50.1</td>
</tr>
<tr>
<td>7.00</td>
<td>90.2</td>
<td>90.7</td>
<td>68.1</td>
<td>65.1</td>
</tr>
<tr>
<td>9.50</td>
<td>117.5</td>
<td>118.9</td>
<td>80.8</td>
<td>80.1</td>
</tr>
<tr>
<td>12.00</td>
<td>147.0</td>
<td>149.4</td>
<td>95.5</td>
<td>95.1</td>
</tr>
<tr>
<td>14.50</td>
<td>178.6</td>
<td>182.1</td>
<td>110.3</td>
<td>110.1</td>
</tr>
<tr>
<td>17.00</td>
<td>212.2</td>
<td>216.9</td>
<td>125.1</td>
<td>125.1</td>
</tr>
<tr>
<td>19.50</td>
<td>248.0</td>
<td>254.0</td>
<td>139.8</td>
<td>139.8</td>
</tr>
<tr>
<td>22.00</td>
<td>286.9</td>
<td>293.2</td>
<td>154.6</td>
<td>154.6</td>
</tr>
</tbody>
</table>

Relative difference mX: 0.3% 2.0% 0.5% 1.3% 1.7% 2.0% 2.2% 2.4% 2.5% 2.5%
Relative difference mX, width: 1.2% 0.3% 1.5% 0.8% 0.4% 0.2% 0.0% 0.2% 0.3% 1.5%

Figure C-3

Figure C-4
C1.3 Shop with fast response sprinklers

Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

Figure C-5

Figure C-6
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

C1.4 Shop with standard sprinklers

<table>
<thead>
<tr>
<th>(X) : height of rise of the spill plume in the atrium [m]</th>
<th>2.00</th>
<th>4.50</th>
<th>7.00</th>
<th>9.50</th>
<th>12.00</th>
<th>14.50</th>
<th>17.00</th>
<th>19.50</th>
<th>22.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRE - (m_X)</td>
<td>90.7</td>
<td>145.7</td>
<td>205.4</td>
<td>265.5</td>
<td>328.3</td>
<td>393.8</td>
<td>462.0</td>
<td>532.9</td>
<td>606.6</td>
</tr>
<tr>
<td>NEW - (m_X)</td>
<td>89.8</td>
<td>144.4</td>
<td>201.7</td>
<td>259.7</td>
<td>324.8</td>
<td>390.6</td>
<td>459.1</td>
<td>530.5</td>
<td>604.7</td>
</tr>
<tr>
<td>BRE - (m_X,\text{width})</td>
<td>85.4</td>
<td>131.1</td>
<td>178.7</td>
<td>224.0</td>
<td>269.3</td>
<td>314.6</td>
<td>359.9</td>
<td>405.1</td>
<td>450.4</td>
</tr>
<tr>
<td>NEW - (m_X,\text{width})</td>
<td>84.9</td>
<td>130.9</td>
<td>176.8</td>
<td>222.7</td>
<td>268.7</td>
<td>314.6</td>
<td>360.5</td>
<td>406.5</td>
<td>452.4</td>
</tr>
</tbody>
</table>

Relative difference \(m_X\) | 1.0% | 0.9% | 1.8% | 1.4% | 1.1% | 0.8% | 0.6% | 0.5% | 0.3% | 1.8% |
Relative difference \(m_X,\text{width}\) | 0.6% | 0.2% | 1.1% | 0.6% | 0.2% | 0.0% | 0.2% | 0.3% | 0.4% | 1.1% |

**Figure C-7**

**Figure C-8**
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

C2.1 Hotel bedroom (with standard sprinklers)

![Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes](image)

<table>
<thead>
<tr>
<th>X : height of rise of the spill plume in the atrium [m]</th>
<th>BRE - mX</th>
<th>NEW - mX</th>
<th>BRE - mX, width</th>
<th>NEW - mX, width</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00</td>
<td>15.1</td>
<td>14.5</td>
<td>13.7</td>
<td>13.1</td>
</tr>
<tr>
<td>4.50</td>
<td>19.5</td>
<td>19.8</td>
<td>16.1</td>
<td>16.4</td>
</tr>
<tr>
<td>7.00</td>
<td>25.9</td>
<td>25.5</td>
<td>19.9</td>
<td>19.7</td>
</tr>
<tr>
<td>9.50</td>
<td>31.2</td>
<td>31.4</td>
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<td>23.0</td>
</tr>
<tr>
<td>12.00</td>
<td>37.4</td>
<td>37.7</td>
<td>26.0</td>
<td>26.3</td>
</tr>
<tr>
<td>14.50</td>
<td>44.1</td>
<td>44.3</td>
<td>29.4</td>
<td>29.6</td>
</tr>
<tr>
<td>17.00</td>
<td>51.5</td>
<td>51.1</td>
<td>33.2</td>
<td>32.9</td>
</tr>
<tr>
<td>19.50</td>
<td>59.1</td>
<td>58.4</td>
<td>36.9</td>
<td>36.2</td>
</tr>
<tr>
<td>22.00</td>
<td>65.7</td>
<td>65.9</td>
<td>39.7</td>
<td>39.5</td>
</tr>
</tbody>
</table>

Relative difference mX

<table>
<thead>
<tr>
<th>Relative difference mX</th>
<th>3.5%</th>
<th>2.0%</th>
<th>1.7%</th>
<th>0.6%</th>
<th>0.7%</th>
<th>0.4%</th>
<th>0.6%</th>
<th>1.2%</th>
<th>0.3%</th>
<th>3.5%</th>
</tr>
</thead>
</table>

Relative difference mX, width

<table>
<thead>
<tr>
<th>Relative difference mX, width</th>
<th>4.3%</th>
<th>2.3%</th>
<th>1.0%</th>
<th>1.4%</th>
<th>1.3%</th>
<th>0.8%</th>
<th>0.8%</th>
<th>1.9%</th>
<th>0.7%</th>
<th>4.3%</th>
</tr>
</thead>
</table>

Figure C-9

![Figure C-9](image)

Figure C-10

![Figure C-10](image)
C2.2 Office (with standard sprinklers)

<table>
<thead>
<tr>
<th>X : height of rise of the spill plume in the atrium [m]</th>
<th>2.00</th>
<th>4.50</th>
<th>7.00</th>
<th>9.50</th>
<th>12.00</th>
<th>14.50</th>
<th>17.00</th>
<th>19.50</th>
<th>22.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRE - mX</td>
<td>30.4</td>
<td>36.0</td>
<td>46.4</td>
<td>55.7</td>
<td>66.2</td>
<td>76.9</td>
<td>88.0</td>
<td>100.4</td>
<td>113.5</td>
</tr>
<tr>
<td>NEW - mX</td>
<td>28.4</td>
<td>37.5</td>
<td>47.1</td>
<td>57.1</td>
<td>67.6</td>
<td>78.5</td>
<td>89.6</td>
<td>101.6</td>
<td>113.8</td>
</tr>
<tr>
<td>BRE - mX, width</td>
<td>28.1</td>
<td>30.5</td>
<td>38.6</td>
<td>41.9</td>
<td>47.8</td>
<td>53.5</td>
<td>59.2</td>
<td>65.7</td>
<td>72.4</td>
</tr>
<tr>
<td>NEW - mX, width</td>
<td>25.9</td>
<td>31.6</td>
<td>37.3</td>
<td>43.0</td>
<td>48.7</td>
<td>54.4</td>
<td>60.1</td>
<td>65.8</td>
<td>71.5</td>
</tr>
</tbody>
</table>

Relative difference mX: 6.8%, 4.1%, 1.8%, 2.5%, 2.0%, 2.1%, 2.1%, 1.2%, 0.3%, 6.8%
Relative difference mX, width: 7.8%, 3.7%, 1.5%, 2.7%, 1.9%, 1.8%, 1.5%, 0.2%, 1.2%, 7.8%

**Figure C-11**

![Graph showing the mass flow rate at a height X (kg/s) vs. height of rise of the spill plume in the atrium (m)]

**Figure C-12**

![Graph comparing BRE - mX, NEW - mX, BRE - mX, width, NEW - mX, width]
C2.3 Shop with fast response sprinklers

<table>
<thead>
<tr>
<th>X : height of rise of the spill plume in the atrium [m]</th>
<th>BRE - mX</th>
<th>NEW - mX</th>
<th>BRE - mX, width</th>
<th>NEW - mX, width</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00</td>
<td>41.9</td>
<td>43.5</td>
<td>40.4</td>
<td>42.0</td>
</tr>
<tr>
<td>4.50</td>
<td>58.5</td>
<td>59.6</td>
<td>54.5</td>
<td>55.8</td>
</tr>
<tr>
<td>7.00</td>
<td>74.6</td>
<td>76.2</td>
<td>67.8</td>
<td>69.7</td>
</tr>
<tr>
<td>9.50</td>
<td>91.6</td>
<td>93.2</td>
<td>81.6</td>
<td>83.6</td>
</tr>
<tr>
<td>12.0</td>
<td>109.9</td>
<td>110.7</td>
<td>96.3</td>
<td>97.4</td>
</tr>
<tr>
<td>14.50</td>
<td>130.7</td>
<td>128.6</td>
<td>112.9</td>
<td>111.3</td>
</tr>
<tr>
<td>17.00</td>
<td>147.2</td>
<td>147.0</td>
<td>125.2</td>
<td>125.2</td>
</tr>
<tr>
<td>19.50</td>
<td>165.6</td>
<td>165.8</td>
<td>139.2</td>
<td>139.1</td>
</tr>
<tr>
<td>22.00</td>
<td>184.5</td>
<td>185.0</td>
<td>153.1</td>
<td>152.9</td>
</tr>
</tbody>
</table>

Relative difference mX: 3.7% 1.9% 2.1% 1.8% 0.7% 1.6% 0.1% 0.1% 0.3% 3.7%

Relative difference mX, width: 3.8% 2.5% 2.6% 2.4% 1.2% 1.4% 0.1% 0.1% 0.1% 3.8%

Figure C-13

Figure C-14
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes

Proposal for a simplified method for sizing smoke ventilation systems in atria

**C2.4 Shop with standard sprinklers**

<table>
<thead>
<tr>
<th>BRE - mX</th>
<th>NEW - mX</th>
<th>BRE - mX, width</th>
<th>NEW - mX, width</th>
</tr>
</thead>
<tbody>
<tr>
<td>62.1</td>
<td>78.9</td>
<td>103.8</td>
<td>122.7</td>
</tr>
<tr>
<td>61.3</td>
<td>81.9</td>
<td>103.0</td>
<td>124.7</td>
</tr>
<tr>
<td>59.8</td>
<td>73.1</td>
<td>93.4</td>
<td>108.0</td>
</tr>
<tr>
<td>59.3</td>
<td>76.8</td>
<td>94.2</td>
<td>111.7</td>
</tr>
</tbody>
</table>

Relative difference mX: 0.8% 5.0% 0.9% 3.4% 3.8% 2.0% 0.1% 0.7% 0.3% 5.0%

Relative difference mX, width: 1.2% 3.8% 0.7% 1.7% 2.0% 0.3% 1.3% 1.9% 0.8% 3.8%

| P = 12 [m] | WB = 12 [m] |
| QC = 5000 [kW] | Free plume? no |
| HB = 5 [m] | Large room? yes |

Figure C-15

![Figure C-15](image)

**Figure C-16**

![Figure C-16](image)
Appendix D: BRE spill-plume calculations

This appendix contains the set of equations given in the Annex E of the BRE report 368 [2].

**E.4.2 Determining remaining approach-flow parameters**

Select from the following Eqs (from [27]) to determine the remaining parameters for the approach flow from the initial known parameters.

Calculate the mean layer temperature ($\bar{\theta}_w$):

$$\bar{\theta}_w = \frac{Q_w}{M_w c} \quad (\text{K}) \quad (E.1)$$

Calculate the mass flow rate ($M_w$) at the opening ([32]):

$$M_w = \frac{2}{3} C_d^{3/2} (2 g \theta_{cw} T_{cw})^{1/2} \frac{W D_o}{T_{cw}} d_w^{3/2} \kappa_M \quad \text{(kg s}^{-1}) \quad (E.2)$$

where:
- $\rho_o = 1.22 \text{ kg m}^{-3}$ for an ambient temperature $T_o$ of 288 K,
- $C_d = 0.6$ for opening with a deep downstand or 1.0 for no downstand,
- $g = 9.81 \text{ m s}^{-2}$,
- $\kappa_M = 1.3$ for most typical flowing layers.

The depth of the layer ($d_w$) at the opening is then given by ([32]):

$$d_w = \left[ \frac{3 M_w T_{cw}}{2 C_d^{3/2} \kappa_M W \rho_o (2 g \theta_{cw} T_{cw})^{1/2}} \right]^{2/3} \quad (\text{m}) \quad (E.3)$$

The mass-weighted average temperature $\bar{\theta}_w$ of the gas layer is ([51]):

$$\bar{\theta}_w = \frac{\kappa}{\kappa_M} \theta_{cw} \quad (\text{K}) \quad (E.4)$$
where $\kappa_0 = 0.95$ for most typical flowing layers.

Greater accuracy can be achieved by calculating the values of the profile correction factor $\kappa_M$ and $\kappa_0$ using the temperature-dependent formulae in, although this is usually unnecessary for most practical designs.

The layer's characteristic velocity ($v$) is given by:

$$v = 0.96 \frac{C_d \kappa_M}{\kappa_0^{1/3}} \left[ \frac{gQ_{cw}T_{cw}}{c\rho_0WT^2_0} \right]^{1/3} \text{ (m s}^{-1}\text{)} \quad (E.5)$$

For a deep downstand, where $C_d = 0.6$, this becomes:

$$v = 0.76 \left[ \frac{gQ_{cw}T_{cw}}{c\rho_0WT^2_0} \right]^{1/3} \text{ (m s}^{-1}\text{)} \quad (E.6)$$

With no downstand at the opening, $C_d = 1.0$, and

$$v = 1.27 \left[ \frac{gQ_{cw}T_{cw}}{c\rho_0WT^2_0} \right]^{1/3} \text{ (m s}^{-1}\text{)} \quad (E.7)$$

Calculate the horizontal flux ($B$) of vertical buoyant potential energy$^{[27,25]}$ (relative to the void edge):

$$B = \frac{\rho_0 \theta_{cw} gvd_w^2}{2 T_{cw}} \text{ (W m}^{-1}\text{)} \quad (E.8)$$

**E.4.3 Calculate the mass flux ($M_y$) rising past the void edge$^{[27]}$:**

$$M_y = \frac{2}{3} \rho_0 W \alpha' \left(2 g \frac{\theta}{T_0} \right)^{1/2} d_w \frac{M_w}{\alpha} + M_w \text{ (kg s}^{-1}\text{)} \quad (E.9)$$

where the entrainment constant $\alpha' = 1.1$.

*Note: $\alpha'$ takes such a large value as a result of treating all
anomalous entrainment above the spill edge as if it occurred in the rotation region.

If the line plume is single-sided go to E.4.7 after completion of this step.

**E.4.4 Calculate the Equivalent Gaussian Source:**
First convert \(Q\) and \(M_0\) into the corresponding parameters per unit length of plume (ie divide by the channel width \((W)\) to give \(Q_0\) and \(A\)). Then solve the following Eqns:

\[
\xi = \left[ A + \frac{Q_0}{T_0C} \right] \frac{1}{\rho_0 \sqrt{\pi}} \tag{E.10}
\]

\[
\frac{[\theta]}{[T]_g} = \frac{Q_0 \sqrt{1 + \lambda^2}}{T_0C \lambda \left[ A + \frac{Q_0}{T_0C} \right]} \tag{E.11}
\]

where the empirical thermal constant \(\lambda = 0.9\):

\[
\zeta = \frac{2B}{\rho_0 \sqrt{3} \left( \frac{\theta}{[T]_g} \right) \frac{\lambda}{\sqrt{1 + 3 \lambda^2}} \sqrt{\pi}} \tag{E.12}
\]

\[
U_g = \frac{\sqrt{\xi}}{\sqrt{\zeta}} \tag{E.13}
\]

and

\[
b_g = \frac{\xi}{u_g} \tag{E.14}
\]

where \([\theta][T]_g\), \(u_g\) and \(b_g\) are parameters of the Equivalent Gaussian Source.
E.4.5 Calculate the entrainment into the rising plume:
The Source Froude number (F) for the line plume is\(^{(25)}\):

\[
F = \left[ \frac{2}{\pi} \right]^{1/4} \left[ \frac{\alpha}{\theta} \right] \left[ \frac{\lambda}{\theta g} \right]^{1/2} \frac{u_g}{(gb_g)^{1/2}} \tag{E.15}
\]

where \( \alpha = 0.16 \) for double-sided\(^{(102)}\) and 0.077 for single-sided\(^{(63)}\) line plumes. Calculate the transformed parameter \((v_g)\) for the Equivalent Gaussian Source:

\[
v_g = \frac{1}{(1 - F^2)^{1/4}} \tag{E.16}
\]

Determine the value of \(I_1(v_g)\) by using the following procedure (or the alternative procedure of E.6 below):

- \(v_g\) represents a value on the vertical axis of Figure E1. Look across to the middle solid curve and find the corresponding value of \(I_1(v_g)\) on the other axis.
- Calculate the transformed height parameter of \(x'\)
corresponding to the desired plume height \( x \), noting that \( x \) must be set equal to the appropriate effective height of rise identified in section 6.1 of Chapter 6 of this book.

\[
x' = \frac{2}{\sqrt{\pi}} \frac{x}{b_g}
\]  

(E.17)

Next calculate \( \Delta I_1(\nu) \):

\[
\Delta I_1(\nu) = \frac{x'}{\left[ F^2 (1 - F^2) \right]^{\nu/3}}
\]  

(E.18)

and

\[
I_1(\nu) = I_1(\nu_0) + \Delta I_1(\nu)
\]  

(E.19)

Determine values of \( b', p' \) and \( u' \) corresponding to the calculated value of \( I_1(\nu) \) using the following method or an alternative procedure which is set out in E.7 below.

\( I_1(\nu) \) represents a value on the horizontal axis of Figure E.1. Using this value find the corresponding values (from all three curves) for \( u', p' \) and \( b' \). Then use the following equations to determine \( u', p' \) and \( b' \):

\[
u' = u'' F^{\nu/3}
\]  

(E.20)

\[
p' = \frac{1}{(1 - F^2)^{\nu/3}} p''
\]  

(E.21)

\[
b' = b'' (F^2 (1 - F^2))^{\nu/3}
\]  

(E.22)

Next determine the characteristic half-width (b) of the line plume at height \( x \):

\[
b = b' b_g
\]  

(E.23)

Then calculate the axial vertical velocity component (u) of the gases at height \( x \):

\[
u = \frac{u' u_0}{F}
\]  

(E.24)

Calculate the mass flow per unit plume length (m) passing the chosen height \( x \):

\[
m = \sqrt{\pi \rho \mu b} \left[ 1 - p \left[ \frac{\Theta}{T_0} \frac{\lambda}{(1 + \lambda)^{3/2}} \right] \right] (kg \cdot m^{-1})
\]  

(E.25)

Convert to the total mass flow in the line plume (ignoring end-effects) by multiplying Eqn (E.25) by the channel width (ie \( m, W \)).
E.4.6 Calculate the entrainment $\delta M_r$\cite{25,62} into the free ends of the line plume

The width of the line plume (and also its axial velocity) can be taken as being approximately constant for most of its height as a first-order approximation, and equal to the mean of the values at the Equivalent Gaussian Source and at the chosen height $x$.

The entrainment $\delta M_r$ into both ends of the line plume is then\cite{60}:

$$\delta M_r = 4\bar{b} \bar{u} \alpha x \rho_0 \quad \text{(kg s$^{-1}$)} \quad \text{(E.26)}$$

where:

$$\bar{b} = \left( \frac{b_a + b}{} \right) \quad \text{(m)} \quad \text{(E.27)}$$

$$\bar{u} = \left( \frac{u_a + u}{} \right) \quad \text{(m)} \quad \text{(E.28)}$$

Note that while the original derivation was semi-empirical, this treatment is equivalent to regarding the free ends of the line plume as if they were themselves line plumes of length $2\bar{b}$ at each end, although the parameter $b$ takes its values from the properties of the main line plume itself.

Add this to the plume entrainment result from E.4.5 to obtain the total mass flow $M_r$ of smoky gases rising past the specified height ($x$), i.e:

$$M_r = m_W + \delta M_r \quad \text{(kg s$^{-1}$)} \quad \text{(E.29)}$$

It should be noted that where both ends of a plume are bounded by side walls (e.g., as in a shaft) then $\delta M_r = 0$.

E.4.7 Modifications to the above procedure for single-sided\cite{27,83} (or adhered) line plumes

Convert both the Equivalent Gaussian Source and the plume into a composite of a real and an imaginary half, such that the centre line of the composite lies along the vertical wall to which the plume is adhering. This is done by doubling values for $B$, $M_r$ (and hence $A$), and $Q$ from E.4.3) before returning to E.4.4–E.4.6 above. Note that experiments\cite{61} show that the value of $\alpha$ needed in E.4.4–E.4.6 should change value from 0.16 (valid for a free- or double-sided plume) to 0.077 for the adhered plume.

On completing E.4.6, halve the final value of mass flow $M_r$ rising past the desired plume height ($x$).
Comparison of existing empirical methods to quantify the air entrainment in smoke spill plumes
Proposal for a simplified method for sizing smoke ventilation systems in atria

References


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