New Guidance for the Spill Plume in Smoke Control Design

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Smoke control systems may have several objectives, such as:

- Removing smoke from the building for means of escape
- Maintaining tenable conditions in the area of fire origin or areas adjoining the fire for means of escape
- Removing smoke during or post fire-fighting operations
- Minimising the risk of smoke spread to adjoining parts of the building
The Thermal Spill Plume

- Determine mass flow rate of gases produced
- Dependent on entrainment of air into plume
- 2-D plumes do not include end entrainment
- 3-D plumes include end entrainment
Calculation Methods

– Simple spill plume formulae (based on empirical correlations)
  – Commonly used (e.g. CIBSE Guide E, PD 7974-2, NFPA 92)
  – Useful in early design stages to inform more complex methods

– Analytical methods or theories (utilises empirical data)
  – The BRE spill plume method [BR 368], etc.

– Computational Fluid Dynamics (CFD) modelling
  – More versatile, can be used for novel designs

– Uncertainties and limitations in some calculation methods
  – Supporting experimental data has been sparse
  – Can be large differences predicted smoke production rates
  – Scenarios where design guidance does not exist
Aims and Objectives

– Provide a better understanding of spill plume entrainment

– Produce new data to provide options to Fire Engineers for design purposes in the form of:
  – A range of new and improved simplified design formulae for a variety of spill plume scenarios
  – Improvements to the existing analytical methods (i.e. the empirical elements)
  – An initial assessment of CFD modelling with recommendations for appropriate use (e.g. grid size)
– Alcohol fires in a 1/10th physical scale model
– Designed to satisfy the scaling laws (i.e. turbulent flow on full and model scale)
– Measure temperature, velocity, mass flow, etc
– Over 300 experiments carried out
- CFD used to model the experiment for validation
- Examine plumes at high heights of rise
- Fire Dynamics Simulator (FDS 5) mainly used
**Terminology**

\[ W_s \] = width of plume at the spill edge (m)

\[ d_s \] = depth of the layer below the spill edge (m)

\[ z_s \] = height of rise of plume above the spill edge (m)

\[ \dot{Q}_c \] = convective heat flow of the layer below the spill edge (kW)

\[ \dot{m}_s \] = mass flow rate of the layer below the spill edge (kg/s)
Experiments

- Parameter variation
  - Fire size, compartment opening width and height of rise of plume varied
  - 2-D and 3-D plumes
  - Balcony and adhered plumes
3-D Balcony Spill Plume

\[ \frac{m'_{3-D} - m'_{2-D}}{Q'_{c}} \] (kg kW\(^{-1}\) s\(^{-1}\))

\[ z_{c}/Q'^{2/3} \] (m\(^{3/3}\) kW\(^{-2/3}\))

- $W_1 = 1.0 \text{ m, } Q'_{c} = 3.6 \text{ to } 12.2 \text{ kW}$
- $W_2 = 0.8 \text{ m, } Q'_{c} = 3.7 \text{ to } 12.8 \text{ kW}$
- $W_3 = 0.6 \text{ m, } Q'_{c} = 3.9 \text{ to } 12.3 \text{ kW}$
- $W_4 = 0.4 \text{ m, } Q'_{c} = 3.6 \text{ to } 10.9 \text{ kW}$
- $W_5 = 0.2 \text{ m, } Q'_{c} = 3.4 \text{ to } 9.9 \text{ kW}$
3-D Balcony Spill Plume

\[
\frac{\dot{m}_{3D} - \dot{m}_{2D}}{\dot{Q}_s} (\text{kg kW}^{-1} \text{s}^{-1})
\]

\[
z_s/Q_{s}^{1/3} (\text{m}^{3/3} \text{ kW}^{-2/3})
\]

NFPA92
CIBSE E / PD7974-2
HARRISON AND SPEARPOINT (2004)

\[
\dot{W}_s = 1.0 \text{ m}
\]
\[
\dot{W}_s = 0.8 \text{ m}
\]
\[
\dot{W}_s = 0.6 \text{ m}
\]
\[
\dot{W}_s = 0.4 \text{ m}
\]
\[
\dot{W}_s = 0.2 \text{ m}
\]
– General expression developed by decoupling and characterising key entrainment regions
– Experimental data collapse to a single general relationship
Sum of entrainment into the decoupled flows

\[
\dot{m}_{p,2D} = 0.16 \dot{Q}_c^{1/3} W_s^{2/3} z_s + 1.34 \dot{m}_s
\]

\[
\dot{m}_{p,3D} = 0.16 \dot{Q}_c^{1/3} \left( W_s^{2/3} + 1.56 d_s^{2/3} \right) z_s + 1.34 \dot{m}_s
\]
- Grid sensitivity analysis carried out using the scale model data
- Guidance on appropriate grid for design purposes
- FDS5 provided a very good prediction of plume behaviour and entrainment
- FDS5 then used extrapolate the analysis (i.e. higher heights of rise)
3-D Balcony Plume to Axisymmetric

– New empirical design formula exhibits linearity
– The spill plume will eventually behave like an axisymmetric plume at high heights of rise (a power law)
– By matching the new design formula with an axisymmetric plume formula

\[ z_{\text{trans}} = 3.4 \left( W_s^{2/3} + 1.56 d_s^{2/3} \right)^{3/2} \]

For \( z_s > z_{\text{trans}} \)

\[ \dot{m}_{p,3D} = 0.071 \dot{Q}^{1/3} z_s^{5/3} \]
3-D Balcony Plume to Axisymmetric

FDS modelling at higher plume heights than in experiments

Increasing height of rise
3-D Balcony Plume to Axisymmetric

$W = 2\, \text{m} \text{ (full-scale equivalent)}$

$\dot{m}_p \text{ (kg s}^{-1}\text{)}$

$z \text{ (m) (full-scale equivalent)}$

FDS prediction

Linear equation based on experiment
3-D Balcony Plume to Axisymmetric

$W = 10 \, \text{m (full-scale equivalent)}$

$FDS \text{ prediction}$

Linear equation based on experiment
3-D Adhered Plume

Wide opening  Intermediate opening  Narrow opening
3-D Adhered Plume
Adhered Spill Plume Formulae

- General expression developed by decoupling and characterising key entrainment regions
- Experimental data collapse to a single relationship

\[ m_{p,2D} = 0.08 \hat{Q}_c^{1/3} W_s^{2/3} z_s + 1.34 m_s \]

\[ m_{p,3D} = 0.3 \hat{Q}_c^{1/3} W_s^{1/6} d_s^{1/2} z_s + 1.34 m_s \]
3-D Adhered Plume

Wide opening

Intermediate opening

Narrow opening
To assess guidance with full scale ‘Hot Smoke Test’ data
Implementation

- CIBSE Guide E (Fire Engineering)
  - Included in next revision, late 2018

- PD 7974 Part 2 (Application of fire safety engineering principles to the design of buildings - Spread of smoke and toxic gases within and beyond the enclosure of origin)
  - Full revision of this standard
  - Late 2018

- BS EN 12101 (Guidelines on functional recommendations and calculation methods for smoke and heat exhaust ventilation systems)
  - Ongoing
Forms the spill plume entrainment model in B-RISK, a next generation version of the BRANZFIRE fire zone model.
Experimental data used for FDS6 validation guide:
Further Reading


Further Reading


Summary

– New guidance has been developed in the form of:
  – A range of new simplified design formulae for balcony and adhered plumes that apply more generally than existing methods
  – A simplified formula for when a balcony plume becomes an axisymmetric plume
  – An assessment on the use of numerical modelling
  – Being implemented into standards and models
Thank you

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