Use of algebraic equations for atrium smoke management analysis

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Use of Algebraic Equations for Atrium Smoke Management Analysis

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Outline

- Design parameters
  - Fire scenarios
  - Design fire size
  - Design height
- Smoke management options
  - Smoke-filling
  - Mechanical exhaust
  - Make-up air
  - Ceiling jet and Plugholing
  - Plume diameter
- Opposed airflow

References

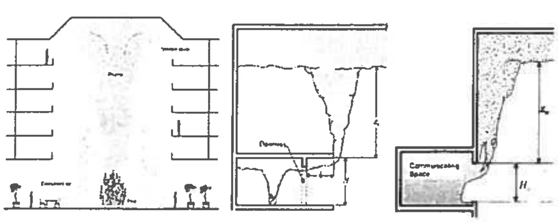
- NFPA 92B, Standard for Smoke Management Systems in Malls, Atria and Large Spaces, National Fire Protection Association, Quincy, MA, 2005.
- Klote, J.H. and Milke, J.A., Principles of Smoke Management, ASHRAE, Atlanta, Georgia.
- ASHRAE Handbook, HVAC Applications, Chapter 52.
- Building codes
  - International Building Code.
  - Local Code.

Design Objective

- Management of smoke within the large volume space and any communicating spaces open to the large volume space.
  - Maintain the smoke layer interface height to a predetermined elevation.
  - Maintain a tenable environment in all exit excess and area or refuge paths for the time necessary to allow occupants to reach safety.
- Design time
  - Prescribed by code.
  - Egress analysis.

Fire Scenario

- Fire scenarios
- Design height



Axisymmetric plume | Balcony spill plume | Window plume

Design Fires

- Steady state fires with constant heat release rate, Q (kW), frequently used as conservative design fire.

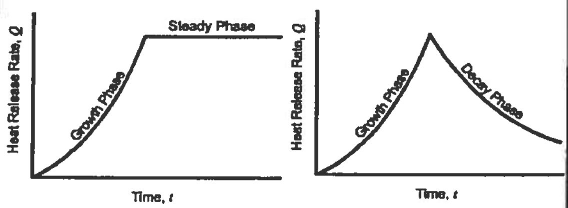
Fuel loading	Design fire (MW)
Low (minimum fire for fuel-restricted atrium)	2
Typical (minimum fire for atrium with combustibles)	5
High (large fires)	25

- Unsteady fires (t-squared fires)
  - Q = heat release of fire (kW)
  - t = time (s), t_g = growth constant (s)
  - t_g=150 (Fast); t_g= 300 (Medium); t_g=600 (Slow);

$$Q = 1055\left(\frac{t}{t_g}\right)^2$$

Other Design Fires

- Fire test data
- Engineering analysis of fire growth, sprinkler response and effect of sprinkler at prevailing ceiling height



Smoke Filling – Steady Fire

- Large volume to contain smoke; no exhaust

$$\frac{z}{H} = 1.11 - 0.28 \ln \left[\frac{t \dot{Q}^{1/3} H^{-4/3}}{\frac{A}{H^2}} \right]$$

Appropriate for a constant cross sectional A, for A/H² from 0.9 to 14 and for z values ≥ to 20% of H

z = height of the first indication of smoke above the fire surface (m)
H = ceiling height above the fire (m)
A = area of atrium (m^2)
t = time (s)
$\dot{Q}$ = heat release rate from steady fire (kW)

Smoke Filling – Unsteady Fire

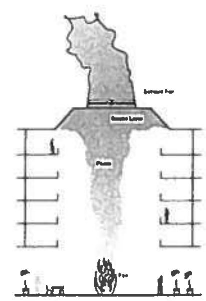
- Large volume to contain smoke; no exhaust

$$\frac{z}{H} = 0.91 \left[\frac{t}{t_g^{2/3} H^{4/5} \left(\frac{A}{H^2} \right)^{3/5}} \right]^{-1.45}$$

Appropriate for a constant cross sectional A, for A/H² from 1 to 23 and for z values ≥ to 20% of H

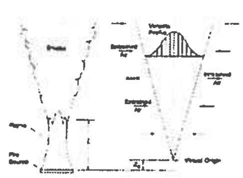
z = height of the first indication of smoke above the fire surface (m)
H = ceiling height above the fire (m)
A = area of atrium (m^2)
t = time (s)
t_g = growth time (s)

Mechanical Exhaust



- Most common form of atrium smoke management in North America
- Maintain smoke layer above design height for design time
- Axisymmetric plume

Axisymmetric plume



- Assume point source
- Virtual origin, z_o.

$$z_o = 0.083 Q^{2/5} - 1.02 D_f$$

- Q = heat release rate (kW).
- D_f = diameter of fire (m).
- High spaces such as atria
  - Height smoke layer large compared to diameter of fire.
  - Base of fire at floor level.

Mass flow rate – Steady fire

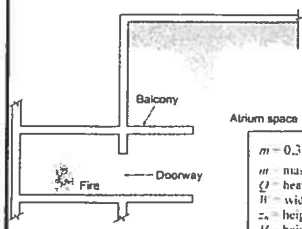
$\dot{m} = 0.071 \dot{Q}_c^{1/3} z^{5/3} + 0.0018 \dot{Q}_c$, for $z \geq$ to z_L

z = height of smoke layer interface above base of fuel (m)
z_L = mean flame height (m)
$\dot{Q}_c$ = convective heat release rate (kW)
where $\dot{Q}_c = \chi \dot{Q}$

$\dot{m} = 0.032 \dot{Q}_c^{3/5} z$, for $z < z_L$,

$z_L = 0.166 \dot{Q}_c^{2/5}$

Balcony Spill Plumes



- Balcony spill plumes
  - Fire in adjacent compartment
  - Plume spills into atrium under balcony

$$m = 0.36(QW^2)^{1/3}(z_b + 0.25H)$$

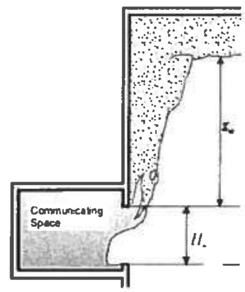
m = mass flow rate in plume (kg/sec)
Q = heat release rate of the fire (kW)
W = width of the plume as it spills under the balcony (m)
z_b = height above the underside of the balcony (m)
H = height of balcony above fuel (m)

If no draft curtains

$$W = w + b$$

W = the width of the plume (m)
w = the width of the opening from the area of origin (m)
b = the distance from the opening to the balcony edge (m)

Window Plumes



- Window plumes
  - Fully developed fire in compartment in communicating space

$$m = [0.68(A_w H_w^{1/2})^{1/3}(z_w + a)^{5/3}] + 1.59 A_w H_w^{1/2}$$

where:
m = mass flow rate plume at height z_w (kg/sec)
a = $[2.40 A_w^{2/5} H_w^{1/5}] - 2.1 H_w$ (m)
A_w = area of ventilation opening (m^2)
H_w = height of ventilation opening (m)
z_w = height above the top of the window (m)

Temperature of Smoke Layer

$$T_s = T_o + \frac{Q_c(1-\eta)}{\dot{m}C_p}$$

C_p specific heat of plume gases (kJ/Kg °C)

η wall and ceiling heat transfer fraction

For an adiabatic atrium $\eta = 0$. This is a conservative assumption

Normal values in the range from 0.3 to 0.7

Volumetric Flow Rate

$$\rho_s = \rho_r \frac{T_r}{T_s}$$

T_r, ρ_r reference temperature and density

T_s, ρ_s smoke temperature and density

- Air density at 294 K is 1.2 kg/m^3
- Volumetric flow rate of exhaust gases is:

$$\dot{V} = \frac{\dot{m}}{\rho_s}$$

$\dot{V}$ = volumetric flow rate (m^3/s)

ρ_s = density of exhaust gases (kg/m^3)

Make-up Air

- For steady flow, mass exhaust equals mass entering below the smoke layer
- Supplied naturally or by a fan (usually 85 –95% of exhaust)
- Velocity of make up air maintained below 1 m/s at perimeter of atrium
  - Minimize deflection of plume
  - Minimize effects on smoke interface

Plume Diameter

- $d_p = K_d z$

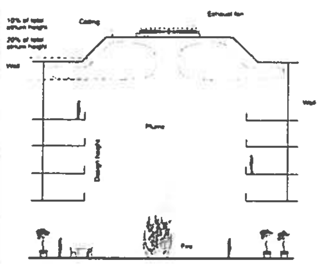
  where

  d_p = plume diameter (m);

  K_d = diameter constant;

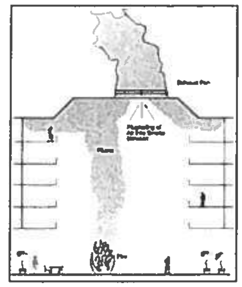
  z = distance above base of the fire (m).
- K_d = 0.5 for plume contact with wall.
- K_d = 0.25 for beam detection of plume.

Minimum Depth of Smoke Layer



- Ceiling jet
  - Smoke flow under ceiling extending radially from point of plume impingement
  - Recirculation flow from walls
  - Total depth typically 10-20% of atrium height
  - Assume 20% unless demonstrate less using modeling

Plugholing



- Plugholing
  - Air from below smoke layer exhausted along with smoke
  - Decrease system effectiveness

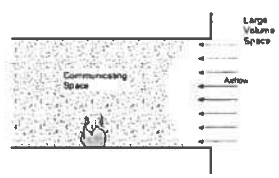
Plugholing

$$V_{max} = 4.16\gamma d^{5/2}\left(\frac{T_s - T_o}{T_o}\right)^{1/2}$$

V_{max} = maximum volumetric flow rate without plugholing at T_s (m^3/s)
T_s = absolute temperature in the smoke layer (K)
T_o = absolute ambient temperature (K)
d = depth of smoke layer below lowest point of the exhaust inlet (m)
γ = exhaust location factor (dimensionless)

- Number of inlets chosen so that maximum flow rate for each inlet not exceeded
- Suggested values for γ
  - Inlet in ceiling distance ≥ 2d from wall: $\gamma = 1$
  - Inlet in ceiling < 2d from wall: $\gamma = 0.5$
  - Inlet in wall: $\gamma = 0.5$

Opposed Air Flow

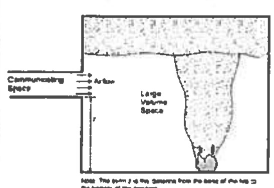


- Prevent smoke from communicating space propagating into atrium

$$v_e = 38[g\,H(T_f - T_o)/T_f]^{1/2}$$

v_e = limiting average air velocity (m/sec)
g = acceleration of gravity (9.8 m/sec²)
H = height of the opening (m)
T_f = temperature of heated smoke (°K)
T_o = temperature of ambient air (°K)

Opposed Air Flow

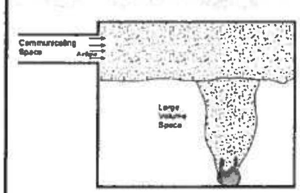


- Prevent smoke from atrium propagating into communicating space
- Plume in contact with walls
- Limiting velocity <1 m/s
- Should not be used if z < 3 m

$$v_e = 17[Q/z]^{1/3}$$

v_e = limiting average air velocity (m/s)
Q = heat release rate of the fire (kW)
z = distance above the base of the fire to the bottom of the opening (m)

Opposed Air Flow



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Summary

- Overview of algebraic equations that can be used for the design of atrium smoke management systems.
- Good estimates when used within limits.
- Assume simple atrium designs.
- For complex geometries or if outside limits of equations, detailed engineering analysis using zone or CFD models required.