Introduction to Fire Dynamics for Structural Engineers

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Training School for Young Researchers
COST TU0904, Malta, April 2012
Textbooks

Introduction to fire Dynamics


Principles of Fire Behavior
by James G. Quintiere
Fire Safety: protect Lives, Property and Business

from Physical Parameters Affecting Fire Growth, Torero and Rein, CRCpress
Boundary at 256s

Heat release rate (kW) vs. Time

ARUP

bre
Discipline Boundaries

![Diagram showing the overlap between Fire, Structures, and Fire & Structures with Heat Transfer in the overlap area.](image)
Lame Substitution of 1\textsuperscript{st} kind

Failure of structures at 550+X °C
Lame Substitution of 2\textsuperscript{nd} kind

![Diagram showing the relationship between Fire & Structures]

- Burning Time [hr]
- Fire
- Structures
- Fire & Structures
Lame Substitution of 3\textsuperscript{rd} kind

Fire & Structures

Failure of structures at 550+X °C
Ignition – fuel exposed to heat

- Material start to decompose giving off gasses: pyrolysis

- Ignition takes place when a flammable mixture of fuel vapours is formed over the fuel surface

Before ignition  After 5 minutes  After 15 minutes
Pyrolysis video

Iris Chang and Frances Radford, 2011 MEng project
Time to ignition

Experimental data for PMMA (polymer) from the literature. Thick samples

\[ t_{ig} = \frac{\pi k \rho c}{4 \left( T_{ig} - T_o \right)^2} \left( \frac{T_{ig} - T_o}{q''_e} \right) \]
### Flammability

#### Ignition Data from ASTM E-1321 per Quintiere

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_{ig}$ [$^\circ$C]</th>
<th>$kpC$ [(kW/m$^2$ K)$^2$ s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood fiber board</td>
<td>355</td>
<td>0.46</td>
</tr>
<tr>
<td>Wood hardboard</td>
<td>365</td>
<td>0.88</td>
</tr>
<tr>
<td>Plywood</td>
<td>390</td>
<td>0.54</td>
</tr>
<tr>
<td>PMMA</td>
<td>380</td>
<td>1.00</td>
</tr>
<tr>
<td>Flexible foam plastic</td>
<td>390</td>
<td>0.32</td>
</tr>
<tr>
<td>Rigid foam plastic</td>
<td>435</td>
<td>0.03</td>
</tr>
<tr>
<td>Acrylic carpet</td>
<td>300</td>
<td>0.42</td>
</tr>
<tr>
<td>Wallpaper on plasterboard</td>
<td>412</td>
<td>0.57</td>
</tr>
<tr>
<td>Asphalt shingle</td>
<td>378</td>
<td>0.70</td>
</tr>
<tr>
<td>Glass-reinforced plastic</td>
<td>390</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Video from WPI (USA)

Effect of heat Release Rate on Flame height

http://www.youtube.com/watch?v=7B9-kZCCUxU&feature=player_embedded
Burning rate (per unit area)

![Image of burning material]

Table 9.3 Asymptotic burning rates (from various sources)

<table>
<thead>
<tr>
<th>Material</th>
<th>g/m² s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyvinyl chloride (granular)</td>
<td>16</td>
</tr>
<tr>
<td>Methanol</td>
<td>21</td>
</tr>
<tr>
<td>Flexible polyurethane (foams)</td>
<td>21–27</td>
</tr>
<tr>
<td>Polymethylmethacrylate</td>
<td>28</td>
</tr>
<tr>
<td>Polystyrene (granular)</td>
<td>38</td>
</tr>
<tr>
<td>Acetone</td>
<td>40</td>
</tr>
<tr>
<td>Gasolene</td>
<td>48–62</td>
</tr>
<tr>
<td>JP-4</td>
<td>52–70</td>
</tr>
<tr>
<td>Heptane</td>
<td>66</td>
</tr>
<tr>
<td>Hexane</td>
<td>70–80</td>
</tr>
<tr>
<td>Butane</td>
<td>80</td>
</tr>
<tr>
<td>Benzene</td>
<td>98</td>
</tr>
<tr>
<td>Liquid natural gas</td>
<td></td>
</tr>
<tr>
<td>Liquid propane</td>
<td></td>
</tr>
</tbody>
</table>

\[ \dot{m}'' = \frac{\dot{q}''}{\Delta h_p} \]

*from Quintiere, Principles of Fire Behaviour*
Firepower – Heat Release Rate

Heat release rate (HRR) is the power of the fire (energy release per unit time)

\[
\dot{Q} = \Delta h_c \dot{m} = \Delta h_c \dot{m}'' A
\]

1. \( \dot{Q} \) Heat Release Rate (kW) - evolves with time
2. \( \Delta h_c \) Heat of combustion (kJ/kg-fuel) \( \sim \) constant
3. \( \dot{m} \) Burning rate (kg/s) - evolves with time
4. \( \dot{m}'' \) Burning rate per unit area \( (m^2) \) \( \sim \) constant
5. \( A \) Burning area \( (m^2) \) - evolves with time

Note: the heat of reaction is negative for exothermic reaction, but in combustion this is always the case, so we will drop the sign from the heat of combustion for the sake of simplicity.
Heat of Combustion

Table 1.13 Heats of combustion of selected fuels at 25°C (298 K)

<table>
<thead>
<tr>
<th>Fuel Description</th>
<th>ΔH_f (kJ/mol)</th>
<th>ΔH_f (kJ/g)</th>
<th>ΔH_f,air (kJ/g(air))</th>
<th>ΔH_f,act (kJ/g(O_2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon monoxide</td>
<td>283</td>
<td>10.10</td>
<td>4.10</td>
<td>17.69</td>
</tr>
<tr>
<td>Methane</td>
<td>800</td>
<td>50.00</td>
<td>2.91</td>
<td>12.54</td>
</tr>
<tr>
<td>Ethane</td>
<td>C_2H_6</td>
<td>1423</td>
<td>47.45</td>
<td>2.96</td>
</tr>
<tr>
<td>Ethene</td>
<td>C_2H_4</td>
<td>1411</td>
<td>50.35</td>
<td>3.42</td>
</tr>
<tr>
<td>Ethyne</td>
<td>C_2H_2</td>
<td>1253</td>
<td>48.20</td>
<td>3.65</td>
</tr>
<tr>
<td>Propane</td>
<td>C_3H_8</td>
<td>2044</td>
<td>46.45</td>
<td>2.97</td>
</tr>
<tr>
<td>n-Butane</td>
<td>n-C_4H_10</td>
<td>2650</td>
<td>45.69</td>
<td>2.97</td>
</tr>
<tr>
<td>n-Pentane</td>
<td>n-C_5H_12</td>
<td>3259</td>
<td>45.27</td>
<td>2.97</td>
</tr>
<tr>
<td>n-Octane</td>
<td>n-C_6H_14</td>
<td>5104</td>
<td>44.77</td>
<td>2.97</td>
</tr>
<tr>
<td>c-Hexane</td>
<td>c-C_6H_12</td>
<td>3680</td>
<td>43.81</td>
<td>2.97</td>
</tr>
<tr>
<td>Benzene</td>
<td>C_6H_6</td>
<td>3120</td>
<td>40.00</td>
<td>3.03</td>
</tr>
<tr>
<td>Methanol</td>
<td>CH_3OH</td>
<td>635</td>
<td>19.83</td>
<td>3.07</td>
</tr>
<tr>
<td>Ethanol</td>
<td>C_2H_5OH</td>
<td>1232</td>
<td>26.78</td>
<td>2.99</td>
</tr>
<tr>
<td>Acetone</td>
<td>(CH_3)_2CO</td>
<td>1786</td>
<td>30.79</td>
<td>3.25</td>
</tr>
<tr>
<td>D-Glucose</td>
<td>C_6H_12O_6</td>
<td>2772</td>
<td>15.4</td>
<td>3.08</td>
</tr>
<tr>
<td>Cellulose</td>
<td>—</td>
<td>16.09</td>
<td>3.15</td>
<td>13.59</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>—</td>
<td>43.28</td>
<td>2.93</td>
<td>12.65</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>—</td>
<td>43.31</td>
<td>2.94</td>
<td>12.66</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>—</td>
<td>39.85</td>
<td>3.01</td>
<td>12.97</td>
</tr>
<tr>
<td>Polyvinylchloride</td>
<td>—</td>
<td>16.43</td>
<td>2.98</td>
<td>12.84</td>
</tr>
<tr>
<td>Polymethylmethacrylate</td>
<td>—</td>
<td>24.89</td>
<td>3.01</td>
<td>12.98</td>
</tr>
<tr>
<td>Polycrylonitrile</td>
<td>—</td>
<td>30.80</td>
<td>3.16</td>
<td>13.61</td>
</tr>
<tr>
<td>Polyoxymethylene</td>
<td>—</td>
<td>15.46</td>
<td>3.36</td>
<td>14.50</td>
</tr>
<tr>
<td>Polylethleneterephthalate</td>
<td>—</td>
<td>22.00</td>
<td>3.06</td>
<td>13.21</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>—</td>
<td>29.72</td>
<td>3.04</td>
<td>13.12</td>
</tr>
<tr>
<td>Nylon 6,6</td>
<td>—</td>
<td>29.58</td>
<td>2.94</td>
<td>12.67</td>
</tr>
</tbody>
</table>

* The initial states of the fuels correspond to their natural states at normal temperature and pressure (298°C and 1 atm pressure). All products are taken to be in their gaseous state—thus these are the net heats of combustion.
Burning area

area of the fire \( A \) increasing with time

\[
\dot{Q} = \Delta h_c \dot{m}'' A
\]
Burn-out and travelling flames

a) near burn-out, location *running out of fuel*

b) Recently ignited by flame
Flame Spread vs. Angle

Rate of flame spread over strips of thin samples of balsa wood at different angles of 15, 90, -15 and 0°.
Test conducted by Aled Beswick BEng 2009
http://www.youtube.com/watch?v=V8gcFX9jLGc
Flame spread

- On a uniform layer of fuel ignited, spread is circular

\[ \frac{dR}{dt} = S = \text{flame spread rate} \]

if \( S = \text{constant} \Rightarrow R = St \)

\[ A = \pi R^2 = \pi (St)^2 \]

\[ \dot{Q} = \Delta h_c \dot{m}' A = \pi \Delta h_c \dot{m}' S^2 t^2 \]

\[ \dot{Q} = \pi \Delta h_c \dot{m}' S^2 t^2 = \alpha t^2 \]

if flame spread is \( \sim \text{constant} \), the fire grows as \( t^2 \)
t-square growth fires

- Tabulated fire-growths of different fire types

\[ \dot{Q} = \alpha t^2 \]

<table>
<thead>
<tr>
<th>Description</th>
<th>Typical scenario</th>
<th>( \alpha ) kW/s^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow</td>
<td>Densely packed paper products(^a)</td>
<td>0.00293</td>
</tr>
<tr>
<td>Medium</td>
<td>Traditional mattress/boxspring(^a)</td>
<td>0.01172</td>
</tr>
<tr>
<td></td>
<td>Traditional armchair</td>
<td></td>
</tr>
<tr>
<td>Fast</td>
<td>PU mattress (horizontal)(^a)</td>
<td>0.0469</td>
</tr>
<tr>
<td></td>
<td>PE pallets, stacked 1 m high</td>
<td></td>
</tr>
<tr>
<td>Ultrafast</td>
<td>High-rack storage</td>
<td>0.1876</td>
</tr>
<tr>
<td></td>
<td>PE rigid foam stacked 5 m high</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) National Fire Protection Association (1993a).
Sofa fire

Peak HRR = 3 MW
Average HRR ~1 MW

Residual burning + smouldering

from NIST http://fire.nist.gov/fire/fires
Fire Test at BRE commissioned by Arup 2009
4x4x2.4m – small premise in shopping mall
190s
285s
316s
Fire Test at BRE commissioned by Arup 2009
4x4x2.4m – small premise in shopping mall

Suppression with water
Free burning vs. Confined burning

\[ \dot{m}'' = \frac{\dot{q}''}{\Delta h_p} \]

Experimental data from slab of PMMA (0.76m x 0.76m) at unconfined and confined conditions

Smoke and walls radiate downwards to fuel items in the compartments
Sudden and generalized ignition (flashover)

What is flashover?

Sudden period of very rapid growth caused by generalized ignition of fuel items in the room.

Some indicators:

- Average smoke temperature of ~500-600 °C
- Heat flux ~20 kW/m² at floor level
- Flames out of openings (ventilation controlled)

NOTE: These three are not definitions but indicators only
Flashover

Mechanism for flashover:

Fire produces a plume of **hot smoke**

Hot smoke layer **accumulates** under the ceiling

Hot smoke and heated surfaces **radiate downwards**

**Flame spread** rate and rate of secondary ignition **increases**

**Rate of burning** **increases**

Firepower larger and smoke hotter
Compartment fires

Fire development in a compartment - rate of heat release as a function of time

\[ \dot{Q}_{\text{max}} \]

\[ \dot{Q}_{\text{fo}} \]

- **(a) growth period**
- **(b) fully developed fire**
- **(c) decay period**
Discipline Boundaries

Fire

Structures

Heat Transfer

Fire & Structures
GI $\Rightarrow$ GO

- If the input is incomplete/flawed, the subsequent analysis is flawed and cannot be trusted for design.

- Fire is the input (boundary condition) to subsequent structures analysis.
Design Fires

“The Titanic complied with all codes.

Lawyers can make any device legal, 
only engineers can make them safe”

Prof VM Brannigan
University of Maryland
Traditional Design Fires

- Standard Fire ~1917
- Swedish Curves ~1972
- Eurocode Parametric Curve ~1995
Traditional Methods

- Traditional methods are based on experiments conducted in \textit{small compartment} experiments ($\sim 3 \text{ m}^3$)

1. Traditional methods assume \textit{uniform fires} that lead to uniform fire temperatures (?)

2. Traditional methods have been said to be \textit{conservative} (?)
Limitations

For example, limitations according Eurocode:

- Near rectangular enclosures
- Floor areas < 500 m²
- Heights < 4 m
- No ceilings openings
- Only medium thermal-inertia lining
< 500 m² floor?
< 4 m high?

Rectangular?

Excel, London

Proposed WTC Transit Hub
Insulating lining?

No ceiling opening?

Shard

Arup Campus
Edinburgh Survey 3,080 compartments

- 1850-1990 buildings: **66%** of volume within limitations
- 2008 building: **8%**

Modern architecture increasingly produces buildings out of range

Jonsdottir et al
Fire Risk Management 2009
Traditional Methods

- Traditional methods are based on experiments conducted in **small compartment** experiments (~3 m³)

1. Traditional methods assume **uniform fires** that lead to uniform fire temperatures (?)

2. Traditional methods have been said to be **conservative** (?)

Stern-Gottfried et al, Fire Risk Management 2009
Fuel Load

- Mixed livingroom/ office space
- Fuel load is ~ 32 kg/ m²
- Set-up Design for robustness and high repeatability
Compartment Temperature

Fig. 6. Comparisons of the measured temperature distributions against the associated normal distributions at 4 min intervals after flashover for Dalmarnock Test One.

Cardington Results
Temperature Distributions

<table>
<thead>
<tr>
<th>Test</th>
<th>Min $\sigma$ (°C)</th>
<th>Mean $\sigma$ (°C)</th>
<th>Max $\sigma$ (°C)</th>
<th>Max $T_{\text{avg}}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalmarnock Test One</td>
<td>105</td>
<td>132</td>
<td>233</td>
<td>733</td>
</tr>
<tr>
<td>Cardington 1</td>
<td>38</td>
<td>84</td>
<td>136</td>
<td>857</td>
</tr>
<tr>
<td>Cardington 2</td>
<td>31</td>
<td>83</td>
<td>153</td>
<td>1075</td>
</tr>
<tr>
<td>Cardington 3</td>
<td>31</td>
<td>100</td>
<td>208</td>
<td>1103</td>
</tr>
<tr>
<td>Cardington 4</td>
<td>31</td>
<td>52</td>
<td>93</td>
<td>1199</td>
</tr>
<tr>
<td>Cardington 5</td>
<td>18</td>
<td>56</td>
<td>135</td>
<td>1147</td>
</tr>
<tr>
<td>Cardington 6</td>
<td>25</td>
<td>44</td>
<td>129</td>
<td>1218</td>
</tr>
<tr>
<td>Cardington 7</td>
<td>20</td>
<td>51</td>
<td>159</td>
<td>1200</td>
</tr>
<tr>
<td>Cardington 8</td>
<td>32</td>
<td>83</td>
<td>213</td>
<td>1107</td>
</tr>
<tr>
<td>Standard Fire Tests</td>
<td>8</td>
<td>12</td>
<td>39</td>
<td>N/A</td>
</tr>
</tbody>
</table>

- Peak local temperatures range from 23% to 75% above compartment average, with a mean of 38%.
- Local minimum temperatures range from 29% to 99% below compartment average, with a mean of 49%.
Travelling Fires

- **Real fires have been observed to travel**
  - WTC Towers 2001
  - Torre Windsor 2005
  - Delft Faculty 2008

- **Experimental data indicate fires travel in large compartments**

- **In larger compartments, the fire does not burn uniformly but burns locally and spreads**
Design Fires

“Problems cannot be solved by the level of awareness that created them”

Attributed to A Einstein
Travelling Fires

Fire environment split into two:

**Near-field** ≈ **1000-1200 °C**

**Far-field** ≈ **200-1200 °C**

(Alper's correlation)

Total burning duration is a function of the area of the fire
Travelling Fires

- Each structural element sees a combination of Near Field and Far Field temperatures as the fire travels.
Example – 25% Floor Area fire in a 1000 m²

- Near field temperature 1200°C for 19 min
- Far field temperature ~ 800°C for 76 min
Structural Results – Rebar Temperature

Graph showing the rebar temperature over time for different percentages of load. The x-axis represents time in hours, and the y-axis represents rebar temperature in °C.
Case Study: Generic Multi-Storey Concrete Structure

Stern-Gottfried et al, SPFE PBD, 2010, Lund
Law et al, Engineering Structures 2011
Rebar Temperature

- Using a 3D Finite Element Model
Rebar Temperature

- 50% burn area
- 100% burn area

Temperature vs. Time

- 400°C
- 0°C

- 600 minutes
- 1200 minutes
Rebar Temperature

Temperature vs. Time for 25%, 50%, and 100% burn area.
Rebar Temperature

- 10% burn area
- 25% burn area
- 50% burn area
- 100% burn area
Rebar Temperature

- 5% burn area
- 10% burn area
- 25% burn area
- 50% burn area
- 100% burn area

Temperature vs. Time

- 400°C
- 0°C

Time:
- 600 minutes
- 1200 minutes
Rebar Temperature

Legend:
- Blue: 2.5% burn area
- Gray: 5% burn area
- Dotted: 10% burn area
- Blue dashed: 25% burn area
- Dotted gray: 50% burn area
- Red: 100% burn area

Law et al, Engineering Structures 2011
Max Rebar Temperatures vs. Fire Size

1h 18 min

Law et al., Engineering Structures 2011
Max Deflection vs. Fire Size

Deflection (m) vs. Burning Area

Law et al, Engineering Structures 2011
Conclusions

- In large compartments, a post flashover fire is not likely to occur, but a travelling fire is.
- Provides a range of possible fire dynamics.
- Novel framework complementing traditional methods.
- Travelling fires give more onerous conditions for the structure.
- Strengthens collaboration between fire and structural fire engineers.
Thanks

Collaborators:

J Stern-Gottfried
A Law
A Jonsdottir
M Gillie
J Torero

Sponsors:

ARUP

The Leverhulme Trust

The Royal Academy of Engineering

Law et al, Engineering Structures 2011
Jonsdottir et al, Interflam 2010, Nottingham
Stern-Gottfried et al, SPFE PBD, 2010, Lund
Stern-Gottfried et al, Fire Risk Management 2009
Jonsdottir et al, Fire Risk Management 2009
Rein et al, Interflam 2007, London
Strengthening the bridges
Temperature of the plume

Figure 4.22  Variation of centreline temperature rise with height in a buoyant methane diffusion flame. Scales as $z/Q_c^{2/5}$ (Table 4.2) (McCaffrey (1979)), by permission). A similar correlation has been demonstrated for a range of hydrocarbon pool fires by Kung and Stavrianides (1982)
Conservation of Mass – burning time

Burning at average heat release per unit area

\[ t_b = \frac{m'' \Delta h_c}{Q''} \]

- 50 MW fire on 200 m² burns for 30 min
- 50 MW fire on 1000 m² burns for 15 min

where \( t_b \) is the burning time, \( m'' \) is the fuel load density (kg/m²), \( \Delta h_c \) is the effective heat of combustion and \( Q'' \) is the heat release rate per unit area (MW/m²)

Rein et al, Interflam 2007, London
Aftermath
Average Compartment Temperature

- Flashover: 5 min
- Window breakage: 13 min
- External flaming: 18 min
- Firefighters: 19 min
Three different beams used

- Unprotected steel I-beam
- Protected steel I-beam to 60 min (12mm high density perlite)

(Not to scale)
Example: Cardington
Results for Insulated Steel: Parametric vs. Travelling fires

Jonsdottir et al, Interflam 2010, Nottingham

- Compared to parametric fire, 110% higher temperatures for a protected steel with 39 mm-gypsum
Structural Behaviour

- Normalized stress
- Rebar temperature
- Standard Fire
- Parametric - Short hot
- Parametric - Long cool

- Normalized strain
- Sagging strain
- Standard Fire
- Parametric - Short hot
- Parametric - Long cool

- Normalized strain
- Hoggling strain
- Standard Fire
- Parametric - Short hot
- Parametric - Long cool

- Normalized deflection
- Deflection
- Standard Fire
- Parametric - Short hot
- Parametric - Long cool
Fire Progression

Sudden

Gradual
1st burn region  2nd burn region  3rd burn region  4th burn region

Base case  Corner  Ring - inwards  Ring - outwards
Fire Shape/Path

- Core
- Linear
- Corners
- Core
- Ring - Inwards
- Core
- Ring - Outwards
Far Field Temperature Discretization

![Graph showing temperature variations with distance from end in a far field. The graph includes three different cases: One Far Field, Two Far Fields, and Monotonic Far Field. Each case is represented by a line with distinct markers at different temperature levels and distance points.](image-url)
- Unprotected steel – up to 10% higher steel temperature (independent of fire size)

- Protected steel – from 65%-95% higher steel temperature
  - Maximum over prediction (110%) at fire areas of 5-10%
  - Maximum under prediction (20%) at fire areas over 85%
The above methodology was applied to a real building, The Informatics Forum Building of the University of Edinburgh.
Results

$T_{\text{max}}$-method / $T_{\text{max}}$-parametric curve - for unprotected steel:

- HE-A 600
- HE-A 300
- HE-A 200
Heron Tower

- 46 Storey Office Building in City of London
- 3-storey atriums forming ‘villages’
- First ever project to consider the robustness of a structure in a multi-storey fire.
Heron Tower
Sudden and generalized ignition (flashover)

When feedback heat flux is ~20 kW/m² (above the critical ignition for most known fuels) enhanced flame spread and fast secondary ignition take places in the compartment → onset of flashover

$q'' \sim \sigma T^4$
NOTE: Immediate fatalities as a proxy to overall damage. Disaster defined as >10 fatalities, >100 people affected, state of emergency or call for international assistance.
Technological Disasters 1900-2000
Fire and Explosions

EM-DAT International Disaster Database, Université catholique de Louvain, Belgium. www.emdat.be
Jocelyn Hofman, Fire Safety Engineering in Coal Mines MSc Dissertation, University of Edinburgh, 2010
Buoyancy

Candle burning on Earth (1g) and in microgravity inside the ISS (~0g)
Family of possible fires

Stern-Gottfried et al, SPFE PBD, 2010, Lund
Far Field Temperature

- Maximum temperature at ceiling jet. Average calculated over the correlation with the distance from the fire (Alpert’s correlation)

\[
T_{ff}^4 = \frac{\int_{r_{nf}}^{r_{ff}} T_{max}^4 \, dr}{r_{ff} - r_{nf}}
\]

\[
T_{max} - T_{\infty} = \frac{5.38 (Q/r)^{2/3}}{H}
\]
Products of Combustion

Mass flow of combustion products at the flame:

(Atmospheric air is 21% Oxygen, $MW_{air}=29 \text{ g/mol}$)

$$m_{pc} = m + m_{st,air} = m \left(1 + \frac{MW_{air}}{MW_{fuel}} \cdot \frac{x + y/4}{0.21}\right) \approx m(1+16)$$

Flow of products of combustion

- Fuel flow rate by pyrolysis
- Flow of stoichiometric air

$\dot{m}_{ent} >> \dot{m}_{pc} \implies \dot{m}_{smoke} = \dot{m}_{pc} + \dot{m}_{ent} \approx \dot{m}_{ent}$

- Smoke is mostly made of entrained air
- Most of the smoke is $N_2$!
Ventilation flows

Flows in and out of the compartment are controlled by buoyancy which scales with the density differences and the size of the opening.

\[ \rho v^2 = \Delta \rho g H_o \]

for buoyant flows

\[ \dot{m} = vA_0 \Rightarrow \dot{m} \propto A_0 \sqrt{H_0} \]

\[ \dot{m}_{a,max} = 0.5 A_0 \sqrt{H_0} \]

ventilation factor

\[ \dot{m}_{a,max} \geq \dot{m}_a \]

\( \dot{m}_a \) Mass flow of air into compartment (kg/s)

\( A_o \) Opening area (m²)

\( H_o \) Height of opening (m)

• The flow through openings has a maximum possible limit.

• At steady state, flow of smoke out is approximately equal to the flow of air in.
When a solid material heats up, it eventually reaches a temperature threshold where it begins to chemically break down. This process is called pyrolysis and is similar to gasification but with one key difference – pyrolysis is the simultaneous change of chemical composition (eg, long hydrocarbon chains to shorter chains) and physical phase (ie, solid or liquid to vapour) and is irreversible. When a solid is burning with a flame, it is actually the pyrolysis vapours (aka *pyrolyzate*) directly above it that is burning, not the solid itself.
Flame Spread – rate of area growth

Flame spread is inversely proportional to the time to ignition

\[ S \propto \frac{\delta_s}{t_{ig}} \]

\[ t_{ig} = \frac{\pi}{4} k \rho c \left( \frac{T_{ig} - T_o}{\dot{q}''_e} \right)^2 \]
Ignition – fuel exposed to heat

- Material start to decompose giving off gasses: pyrolysis

- Ignition takes place when a flammable mixture of fuel vapours is formed over the fuel surface
Flame Spread vs. Angle

A graph to show the rate of flame spread over balsa at angles between -90 and 90 degrees.

Upward spread up to 20 times faster than downward spread
Examples of HRR

workstation  mattress  wood crib
Under Ventilated fires and External flaming

Polypropylene: burning inside a small compartment (0.4m cube)
Ceiling Jet

Figure 2-2.1. Ceiling jet flow beneath an unconfined ceiling.

\[ T - T_\infty = 5.38 \frac{\dot{Q}^{2/3}}{H^{5/3}} \left( \frac{r}{H} \right)^{2/3} \]
Size Matters

Surface Area to Volume Ratio vs Floor Area for a 3m High Square Compartment

Fire Tests

Real Buildings

Stern-Gottfried et al, Fire Risk Management 2009
Encouraging initial reactions to this work

- Abstract submitted in 2007 to Structures in Fire (SiF)
- Title: “ON THE STRUCTURAL DESIGN FIRES FOR VERY LARGE ENCLOSURES”
  - Reviewer #1: This abstract does not fit with [conference] theme.
  - Reviewer #2: This paper is outside the scope of the conference
  - Reviewer #3: The authors are encouraged to submit their paper somewhere else

- Abstract submitted in 2011 to Structures in Fire (SiF)
- Title: “TRAVELLING FIRES IN LARGE COMPARTMENTS: MOST SEVERE POSSIBLE SCENARIOS FOR STRUCTURAL DESIGN”
  - Reviewer 1: Several works has been done and published
  - Reviewer 2: No significant input
  - Reviewer 3: Authors must provide examples for typical case studies
Thanks