Using FDS Modelling to Establish Performance Criteria for Water Mist Systems on Very Large Fires in Tunnels

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Authors & acknowledgement

- J. R. Mawhinney - full-scale fire testing
  - 1990 to present

- Javier Trelles, Ph.D. - CFD modelling
  - Modelling fire suppression in tunnels (NIST – FDS)

- Marioff Corporation
  - Water Mist spray characteristics
  - Access to fire test data
Water Mist Systems in Tunnels

- **Authorities require full-scale fire testing**
  - HGV fires 5 to 10 times larger than most testing experience
  - Large fires = dynamic, high variability

- **Need performance criteria – appropriate for scale and complexity of the fire**

Fire tests (unsuppressed fires):
- 203 MW
- 158 MW
- 125 MW
- 70 MW
Performance Criteria for control …

- Single-point measurements based on experience with smaller fires, e.g.
  - Within 2 min, Temp at end of zone < 50°C
  - Within 5 min, Temp 5-m from truck < 250°C
  - Temperature at ceiling above fire: < 500°C

- The apparent precision is out of scale with the chaotic variability of large fires

- We can never measure enough to communicate all dimensions of the performance …
Computational Fluid Dynamics Modelling of Tunnel Fires

- CFD is a powerful tool to examine more than is measured
- NIST Fire Dynamics Simulator (FDS) version 4
- Use fire test data to evaluate model
- Use the model to extend the understanding of the fire/mist interaction
Marioff Water Mist System Tests
San Pedro de Anes – TST Test Facility, Spain

Fire Test Zone
0+350 to 0+430

Ceiling Jet Fans
Longitudinal
Ventilation

Oxygen Analyzer
Velocity Probes
0+610

Section modeled
140-m

0+320
0+460

600-m
Tunnel curvature …

Tunnel centerline + “stations” at 10-m intervals

Four thermocouple trees

Ceiling TC’s on centerline at 5-m spacing

Nozzles on three parallel lines

A composite fuel load

Figure 2.
## FDS4 Input Parameters

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFD Domain</td>
<td>Facility</td>
<td>San Pedro de Anes Research Tunnel</td>
</tr>
<tr>
<td></td>
<td>Simulation dimensions</td>
<td>140 m × 23 m × 5.17 m</td>
</tr>
<tr>
<td>Numerical</td>
<td>Grid dimensions</td>
<td>560 × 100 × 24 cells</td>
</tr>
<tr>
<td></td>
<td>Cell size</td>
<td>25.0 cm × 23.0 cm × 21.5 cm</td>
</tr>
<tr>
<td></td>
<td>Total # of cells</td>
<td>1,344,000</td>
</tr>
<tr>
<td></td>
<td>Wall boundary conditions</td>
<td>Concrete</td>
</tr>
<tr>
<td></td>
<td>Floor boundary conditions</td>
<td>Concrete</td>
</tr>
<tr>
<td></td>
<td>Ceiling boundary conditions</td>
<td>Concrete/Promat Promatect-H</td>
</tr>
<tr>
<td></td>
<td>Gravity vector (-1%)</td>
<td>(0.0981, 0.0, -9.8095) m/s²</td>
</tr>
<tr>
<td>Spray Nozzle</td>
<td>Type</td>
<td>Marioff 4S1MD6MD(1000,10RE) water mist</td>
</tr>
<tr>
<td></td>
<td>Configuration</td>
<td>4 m × 3.3 m grid</td>
</tr>
<tr>
<td></td>
<td>Activation criteria</td>
<td>Times as determined from test data</td>
</tr>
</tbody>
</table>
Water Mist Spray Characterization

Drop size distribution

\[ F(d) = \begin{cases} 
\frac{1}{2} \left[ 1 + \text{erf} \left( \frac{\ln(d / d_m)}{\sqrt{2}\sigma} \right) \right] & \text{if } d \leq d_m \quad \text{(Log - Normal)} \\
1 - e^{-\ln(\frac{d}{d_m})^\gamma} & \text{if } d > d_m \quad \text{(Rosin - Rammler)}
\end{cases} \tag{1} \]

Discharge Volume
Radius = 200 mm
Water mist spray characterization

- Using measured values of $D_{v10}$, $D_{v50}$ and $D_{v90}$

- $D_{v50} = d_m = \text{volumetric median drop diameter}$

- $D_{v90} = 171 \, \mu m$, $D_{v50} = 89 \, \mu m$, $D_{v10} = 35 \, \mu m$

- Obtain $\sigma = 0.728; \, \gamma = 1.84$

\[
F(d) = \begin{cases} 
\frac{1}{2} \left[ 1 + \text{erf} \left( \frac{\ln \left( \frac{d}{d_m} \right)}{\sqrt{2} \sigma} \right) \right] & \text{if } d \leq d_m \quad \text{(Log-Normal)} \\
1 - e^{-\ln 2 \left( \frac{d}{d_m} \right)^\gamma} & \text{if } d > d_m \quad \text{(Rosin-Rammler)}
\end{cases}
\]
## Spray inputs: velocity, mass flow/orifice

<table>
<thead>
<tr>
<th>Test Identifier</th>
<th>Run Pressure (bar)</th>
<th>$T_{H_2O}$ (°C)</th>
<th>4S 1MD 6MD 1000</th>
<th>2N 1MD 6MD 10RE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$u$ (m/s)</td>
<td>$\dot{m}_c$ (a) (kg/s/m²)</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>50</td>
<td>123.5</td>
<td>51.2</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>50</td>
<td>110.5</td>
<td>45.8</td>
</tr>
<tr>
<td>3</td>
<td>78</td>
<td>80</td>
<td>———</td>
<td>———</td>
</tr>
<tr>
<td>10</td>
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<td>80</td>
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</tr>
<tr>
<td>13</td>
<td>80</td>
<td>50</td>
<td>110.5</td>
<td>45.8</td>
</tr>
</tbody>
</table>

a.) The subscript “c” stands for center orifice; subscript “r” for ring orifices.
Lagrangian droplet tracking ...

Fire peak: 56 MW in 14 minutes
Ventilation velocity: 3.5 m/s
Spray activation time determined by test data

Time start $t = 0.0$; time ignition $t_{ig} = 60\ s$; time water mist $t_{wm} = 450\ s$
Modelling the fire

- “For FDS, all you need is the HRR curve …!”

- Need to capture other important phenomena
  - Flame spread rate through wood pallets
  - Air flow through the porous array
  - Flame volume, angle, length
  - Collapse of consumed sections changing ventilation
Heat Release Rate – suppressed fire

Test 02-02-2006

Water mist on
Relating appearance to HRR

Ignition at 1:00 min

Water mist on full

Time, minutes

HRR, kW

I + 1:08 min

I + 2:00 min

I + 3:00 min

I + 4:20 min
Heat Release Rate – not suppressed

From T 10: Representative
Modelling the fire

Wood pallet stacks

Porous fuel package

Air movement through support platform
Input Heat Release Rates

- Heat release rate per unit area
- Open cells burn as horizontal bed
- Cells with X not yet contributing
Half-height, top cell method
FDS4 – computed HRR based on model

- Oxygen depletion algorithm turned off
FDS Simulation of HRR - unsuppressed
Flames.wmv: Suppressed & Unsuppressed

Even suppressed, there is a region where flames touch ceiling
Temperature Control

- Temperature profile along tunnel

Tunnel Position (m)

Temperature, Deg C

02-02-2006 Test 1
TC Profile @ Ceiling

Test Data

Temperature Control

Temperature profile along tunnel

Test Data
Temperature Profiles at 1020 Seconds

Position along Tunnel, m

Ceiling Temperature, deg C

Model
Test 1
Modelling an unsuppressed fire

- Simulations agreed with test data
- Utilized model to simulate an un-suppressed fire (not tested)
- Examine the contrast between “with” and “without” an active suppression system
Animations

- Flames.wmv
- ISO.wmv
- Flux.avi
Temperature iso-surfaces near ceiling

Back layering both cases

Envelopes: >100°C, > 350°C, and > 500°C at 7 min 22 s
Temperature envelopes near ceiling

Back layering gone

Envelopes: $>100^\circ C$, $>350^\circ C$, and $>500^\circ C$ at 8 min 22 s

1 min after mist

Unsuppressed
Heat flux on floor of tunnel before mist

Heat flux > 5 kW/m²: Time = 7 min:22s
Heat flux on floor of tunnel: 1 min after mist

Heat flux > 5 kW/m²: Time = 8 min:22s

Suppressed

Unsuppressed
Heat flux on floor of tunnel, 16 minutes +

Heat flux > 5 kW/m²: Time = 16 min:05s

Without suppression, propagation in both directions assured
Global performance benefit of water mist

- Stop back layering
- Reduced area of direct flame impingement on ceiling
- Life-safety **and** Property Protection benefits evident
Conclusions

- Very large fires in tunnels are complex, chaotic, highly variable events

- Single-point measurements do not reveal the global benefits of the suppression system

- CFD modelling, validated by test data, reveals global performance benefits beyond what can be measured
Acknowledgements

Marioff Corporation Oy