Modelling water spray – From laboratory scale up to fire safety application –

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1 Context and Objectives

2 Practical problems: tunnel configuration

3 More fundamental problems

4 Conclusion and future works
1 Context and Objectives

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3 More fundamental problems

4 Conclusion and future works
**Context and Objectives**

**Practical problems : tunnel configuration**

Description of the test campaign

Studied tests

Test 27: 6 nozzles

Review

**More fundamental problems**

Droplet evaporation

Radiative attenuation

**Conclusion and future works**

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### Context

<table>
<thead>
<tr>
<th>Year</th>
<th>Tunnel</th>
<th>Duration</th>
<th>Consequences for people</th>
<th>Consequences for structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>Mont Blanc tunnel (France/Italy)</td>
<td>53 h</td>
<td>39 deads</td>
<td>closed for three years</td>
</tr>
<tr>
<td>1999</td>
<td>Tauern tunnel (Austria)</td>
<td>13 h</td>
<td>12 deads</td>
<td>closed for three months</td>
</tr>
<tr>
<td>2001</td>
<td>St. Gotthard (Switzerland)</td>
<td>2 days</td>
<td>11 deads</td>
<td>closed for two months</td>
</tr>
<tr>
<td>2005</td>
<td>Fréjus (France/Italy)</td>
<td>-</td>
<td>2 deads, 21 injured</td>
<td>10 km of equipment to be repaired</td>
</tr>
</tbody>
</table>

[Lönnermark, 2005]

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**Characteristics of tunnel fires:**

- Geometry, confined configuration
- Tunnel ventilation
- Potential Heat Release Rate

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Requirements for road tunnels have significantly evolved

 Authorities and operators are still looking for new ways/systems for ensuring a higher safety level
Context and Objectives

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More fundamental problems
Droplet evaporation
Radiative attenuation

Conclusion and future works

Water mist (NFPA 750, XP CEN/TS 14972)

Fine water sprays in which 99 % of the volume of the spray is in drops with diameters less than 1000 µm

Involved phenomena:
- Gas and surface cooling
- Radiative attenuation
- Oxygen dilution
- Interaction with smoke

Design must be assessed on the only basis of real scale tests

→ Very useful by involving real fire load and fluid flow

→ BUT expensive, difficult to conduct and difficult to analyze
Objectives:

- Improve our understanding and quantify the involved phenomena
- Evaluate the capability of computational tools
- Determine their potential contribution to assessment

The study makes an **extensive use of the code FDS**:

- It is free and open source
- It is widely used by scientists in the field of fire science
- A water spray model was already included

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**FDS Technical reference guide**

FDS has been aimed at solving **practical fire problems in fire protection engineering**, while at the same time providing a tool to study fundamental fire dynamics and combustion.
1 Context and Objectives

2 Practical problems : tunnel configuration
   - Description of the test campaign
   - Studied tests
   - Test 27 : 6 nozzles
   - Review

3 More fundamental problems

4 Conclusion and future works
Model tunnel (1/3)
Length : 43 m
Cross section : 4 m²
Measurements :
- HRR : O₂ and MLR
gas temperature
gas velocity
radiative heat flux

Water mist system :
- Operating pressure : 90 bars
- Five-orifice spray nozzle
- Mist discharge rate : 5.5 l/min/nozzle
- Size distribution : hybrid law, \(d_m=40 \, \mu m\) & \(\delta=2.85\)
### Studied tests and approach

#### Tests without water mist

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#### Tests with water mist

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**Diagram:**

- **Ventilation regime:**
  - Sub-critical
  - Supercritical
- **Nozzle locations:**
  - 3 nozzles upstream and 3 nozzles downstream
  - 3 nozzles upstream

**Diagram Details:**

- **Fire section:** 17.5 m
- **Heptane pool:**
- **Air flow direction:**
  - T-9
  - T-3
  - T+4
  - T+8
  - T+12
  - T+24
- **Ventilation system:**
  - FM-7
  - FM+7
  - V-5
  - V+18
  - Compo+22
### Tested tests and approach

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**Model tests**
- Repeatability evaluation

**Estimation of the measurement uncertainty**

**Validation**
- Sensitivity analysis

**Extensive use of the code**
- Quantification of the phenomena

**PhD study** R. Meyrand (PPRIME/CSTB) 2005-2009

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**Experimental stage** | **Computational stage**
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Experimental stage

Computational stage

PhD study R. Meyrand (PPRIME/CSTB) 2005-2009
Simulations of the tests with water mist

Input data:
- dimensions of the test tunnel, wall thermal characteristics
- exhaust gas volume flow at the downstream side
- operating conditions of the water mist system
- heptane combustion reaction, HRR versus time
Test 27: 3 upstream and 3 downstream

Validation

Context and Objectives

Practical problems: tunnel configuration

Description of the test campaign

Studied tests

Test 27: 6 nozzles

Review

More fundamental problems

Droplet evaporation

Radiative attenuation

Conclusion and future works

FDS 5.4.0
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Time (s) Temperature (°C)

0 60 120 180 240 300 360 420 480 540 600

0 100 200 300 400

1.7 m - Experiment - Simulation
1.5 m - Experiment - Simulation
1.0 m - Experiment - Simulation
0.3 m - Experiment - Simulation

FDS 5.4.0
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Heat flux (kW/m²) vs Time (s)

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**Estimation of the measurement uncertainty**

**Validation**
- Sensitivity analysis

**Extensive use of the code**
- Quantification of the phenomena

**PhD study R. Meyrand**
- (PPRIME/CSTB) 2005-2009

**Experimental stage**

**Computational stage**
Test 27 : 3 upstream and 3 downstream
Extensive use : Stratification?

At the HRR peak

Temperature (°C)

Height (m)

0 50 100 150 200
0
0.5
1
1.5
2
At 540 s - 8 m downstream
- 12 m downstream
Test 27 : 3 upstream and 3 downstream
Extensive use : Stratification?

At the HRR peak

At 540 s - 8 m downstream
- 12 m downstream

Oxygen concentration

Temperature (°C)

Height (m)

Oxygen volume fraction

Carbon monoxide concentration

Temperature (°C)

Height (m)

Carbon monoxide volume fraction

After 420 s, the environment is thermally stratified whereas $[O_2]$, $[CO_2]$ and $[CO]$ are almost constant along the vertical axis.
Test 27: 3 upstream and 3 downstream

Extensive use: Heat contribution of water mist

Roughly the half fire heat is absorbed by droplets

22 % of decrease of heat loss to surface induced by mist
Heat is absorbed by the liquid phase by:

- Gas cooling : 73%
- Radiative attenuation : 18%
- Surface cooling : 9%
Heat is absorbed by the liquid phase by:

- Gas cooling: 73%
- Radiative attenuation: 18%
- Surface cooling: 9%

By convection

By radiation
FDS Technical reference guide

FDS has been aimed at solving **practical fire problems** in fire protection engineering, while at the same time providing a tool to study fundamental fire dynamics and combustion.

- Comparison shows a good capability of the code to reproduce the tunnel fire environment with and without water mist.
- Gas cooling appears to be the main mechanism, followed by radiative attenuation.
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- Comparison shows a good capability of the code to reproduce the tunnel fire environment with and without water mist.
- Gas cooling appears to be the main mechanism, followed by radiative attenuation.

Is it capable to solve fundamental problems? In particular droplet evaporation and radiative attenuation.
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2 Practical problems: tunnel configuration

3 More fundamental problems
   - Droplet evaporation
   - Radiative attenuation

4 Conclusion and future works
FDS - Version 5
Eulerian/Lagrangian approach
monodisperse/polydisperse spray

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Evaporation
Model of heat and mass transfer

Context and Objectives

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Description of the test campaign
Studied tests
Test 27: 6 nozzles
Review

More fundamental problems
Droplet evaporation
Radiative attenuation

Conclusion and future works

Current model:

\[
\frac{dm_p}{dt} = -Ah_m \rho \left( Y_p - Y_g \right)
\]

\[
m_p cp \frac{dT_p}{dt} = Ah \left( T_g - T_p \right) + \frac{dm_p}{dt} h_v + \dot{q}_r
\]

Model of Abramzon and Sirignano:

\[
\frac{dm_p}{dt} = -4\pi \rho D \cdot \frac{r_p Sh^*}{2} \cdot \ln \left( \frac{Y_v,g - 1}{Y_p - 1} \right)
\]

\[
m_p cp \frac{dT_p}{dt} = -m_p \overline{C_v} \cdot \frac{(T_g - T_p)}{B_T} + \frac{dm_p}{dt} h_v + \dot{q}_r
\]

Model of Taylor and Krishna:

\[
\frac{dm_p}{dt} = Ap p_0 \frac{W_p}{RT_f} \cdot \frac{ShD}{2 r_p} \ln \left( \frac{1 - Y_g W/W_p}{1 - X_p} \right)
\]

\[
m_p cp \frac{dT_p}{dt} = \frac{dm_p}{dt} h_v + Ap h^*_{p,g} (T_g - T_p) + \dot{q}_r
\]
Rate of evaporation of one single water droplet

[Ranz and Marshall, 1952] :
Droplet size : 1050 $\mu$m
Droplet temperature : 9.11 °C
Air temperature : 24.9 °C
Air velocity : 0 m/s
Relative humidity : 0 %

[Kincaid, 1989] :
Droplet size : [200, 1600 $\mu$m]
Droplet temperature : 12 °C
Air temperature : 22 °C
Air velocity : 0 m/s
Relative humidity : 31 %
Evaporation

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Loss rate = \(- \frac{m_p(t_0) - m_p(t_0 + \Delta t)}{m_p(t_0) \cdot \Delta t}\)
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Discrepancy with measurements:
- FDS: 22.7 %
- AS: 1.4 %
- TK: 20.0 %

FDS: 17.6 %
AS: 19.6 %
TK: 21.4 %
Radiative attenuation through a water spray:

\[
A_t = 1 - T_r = 1 - \frac{\text{Transmission with the spray on}}{\text{Transmission with the spray off}}
\]

Operating pressure: 4 bars

One-single-orifice spray nozzle

Solid elliptic spray patterns

Mist discharge rate: 0.32 l/min/nozzle

\[d_{32}(20 \text{ cm}) = 100 \ \mu \text{m}\]
Radiative attenuation through a water spray:

\[ A_t = 1 - T_r = 1 - \frac{\text{Transmission with the spray on}}{\text{Transmission with the spray off}} \]

Operating pressure: 4 bars
One-single-orifice spray nozzle
Solid elliptic spray patterns
Mist discharge rate: 0.32 l/min/nozzle
d_{32}(20 \text{ cm})=100 \ \mu \text{m}

FDS version 5 underestimates the radiative attenuation
Discrepancy with measurements: 31 %
Discrepancy with BERGAMOTE: 42 %
Radiative attenuation through a water spray:

\[ A_t = 1 - T_r = 1 - \frac{\text{Transmission with the spray on}}{\text{Transmission with the spray off}} \]

Operating pressure: 4 bars
One-single-orifice spray nozzle
Solid elliptic spray patterns
Mist discharge rate: 0.32 l/min/nozzle
\( d_{32}(20 \text{ cm}) = 100 \ \mu\text{m} \)

**Theory**

\[
\kappa_\lambda(s) = \frac{1}{\delta x \delta y \delta z} \int \int_{r=0}^{\infty} f(r, s) C_a(r, \lambda) dr d\lambda
\]

**FDS 5**

\[
\kappa_\lambda(s) = \frac{1}{\delta x \delta y \delta z} \int \int_{r=0}^{\infty} f(r, d_m(s)) C_a(r, \lambda) dr d\lambda
\]

**Proposed modification**

\[
\kappa_\lambda(s) = \frac{1}{\delta x \delta y \delta z} \int C_a(r_{32}, \lambda) d\lambda
\]
Radiative attenuation through a water spray:

\[ A_t = 1 - T_r = 1 - \frac{\text{Transmission with the spray on}}{\text{Transmission with the spray off}} \]

Operating pressure: 4 bars
One-single-orifice spray nozzle
Solid elliptic spray patterns
Mist discharge rate: 0.32 l/min/nozzle
d\(_{32}\)(20 cm) = 100 \(\mu\)m

The modification leads to an improvement in predictions
Discrepancy with measurements: 11 %
Discrepancy with BERGAMOTE: 7 %
Context and Objectives

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- Description of the test campaign
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- Test 27: 6 nozzles
- Review

More fundamental problems
- Droplet evaporation
- Radiative attenuation

Conclusion and future works
Conclusion

Study on tunnel fire tests

- Good capability of the code for predicting the thermal environment (temperature and heat flux) and the gas flow
- Some discrepancies in critical conditions
- Strong duality between thermal and toxic environment
- Heat absorbed by mist represents around 1/2 of HRR
- Heat is mainly absorbed by mist from gaseous phase
- The use of computational tools appears as an interesting complement to experimentation

Study on more fundamental problems

Current version 5

- Evaporation of one single droplet with a mean discrepancy of 18.0 %
- Attenuations through water curtain with a discrepancy close to 30 %

Some modifications have been proposed

- One in the radiative model has been accepted and integrated in the next version 6
- Others in the heat and mass transfer model are still under study
Future works

- Modify the structure of the heat and mass transfer
- Pursue the assessment of evaporation model
- Assess the model of heat transfer to surface

- Study the visibility both with and without water mist

- Study the influence of water mist on fire activity and combustion reaction