Fire Seat

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

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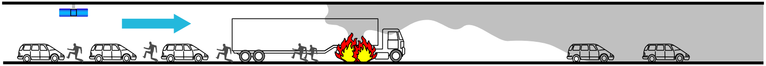
Summary

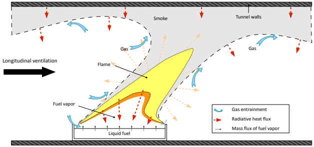


Year	Tunnel	Duration	Consequences for people	Consequences for structure
1999	Mont Blanc tunnel (France/Italy)	53 h	39 deads	closed for three years
1999	Tauern tunnel (Austria)	13 h	12 deads	closed for three months
2001	St. Gotthard (Switzerland)	2 days	11 deads	closed for two months
2005	Fréjus (France/Italy)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

[Lönnermark, 2005]

Characteristics of tunnel fires :

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



➡ Requirements for road tunnels have significantly evolved

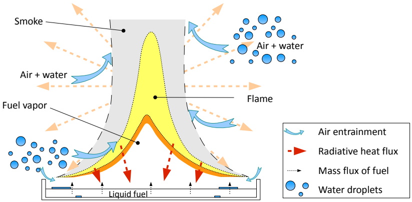
➡ Authorities and operators are still looking for new ways/systems for ensuring a higher safety level

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

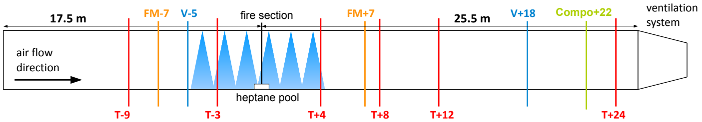
The study makes an **extensive use of the code FDS** :

- 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

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

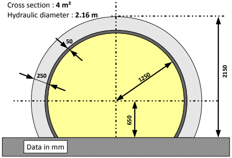
Description of the test campaign



Model tunnel (1/3)
Length : 43 m
Cross section : 4 m^2

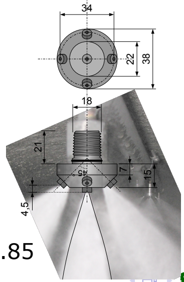
Measurements :

- HRR : O_2 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 μm & δ=2.85



Studied tests and approach

Test	Ventilation regime	Nozzle locations
Tests without water mist		
1	sub-critical	
9	sub-critical	
2	supercritical	
Tests with water mist		
27	supercritical	3 nozzles upstream and 3 nozzles downstream
28	supercritical	3 nozzles upstream

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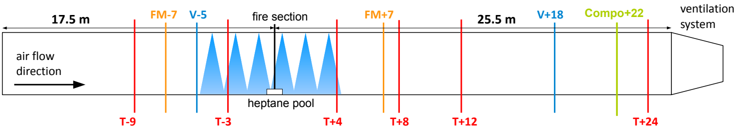

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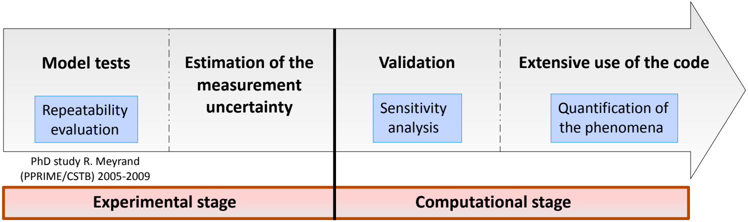

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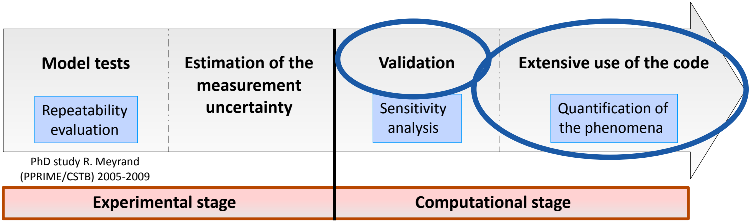
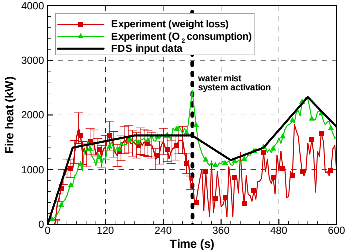


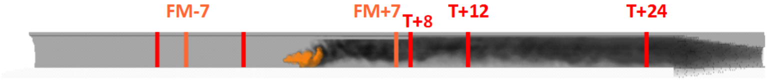
Simulations of the tests with water mist

Input data :

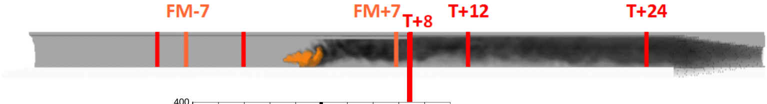
- dimensions of the test tunnel, wall thermal characteristics
- exhaust gas volume flow at the downstream side
- operating conditions of the water mist system
- heptane combustion reaction, HRR versus time



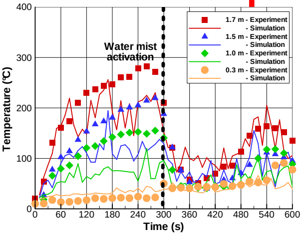
Test 27



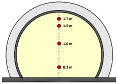
FDS 5.4.0



FM-7
FM+7
T+8
T+12
T+24



Temperature (°C)
Time (s)
Water mist activation
1.7 m - Experiment
- Simulation
1.5 m - Experiment
- Simulation
1.0 m - Experiment
- Simulation
0.3 m - Experiment
- Simulation
0
100
200
300
400
0
60
120
180
240
300
360
420
480
540
600



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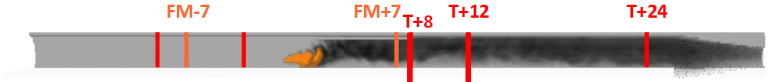
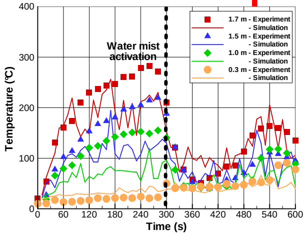
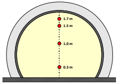
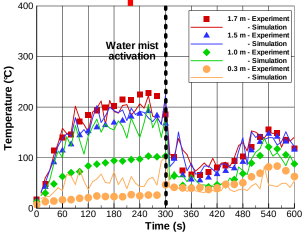
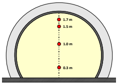
Test 27 : 3 upstream and 3 downstream
Validation











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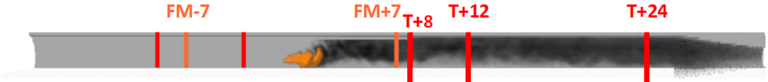

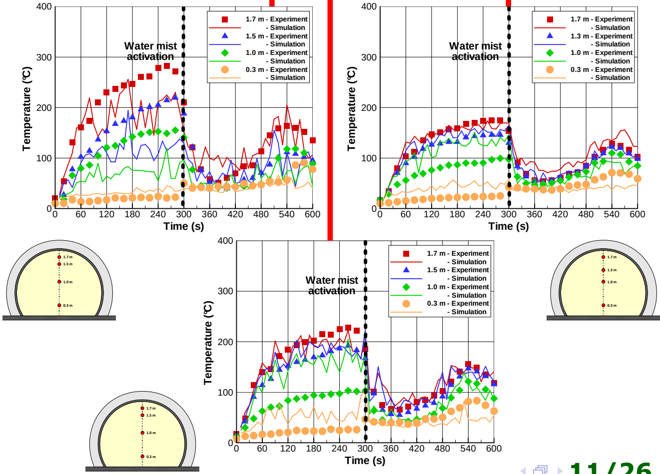

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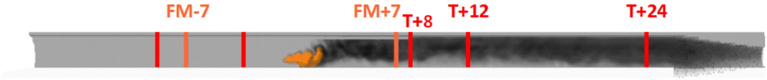

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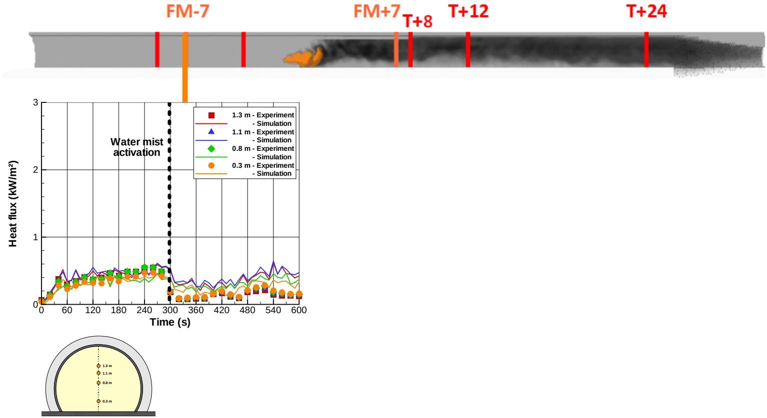
FM-7
FM+7
T+8
T+12
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Water mist activation
1.3 m - Experiment
- Simulation
1.1 m - Experiment
- Simulation
0.8 m - Experiment
- Simulation
0.3 m - Experiment
- Simulation
Heat flux (kW/m²)
Time (s)
0
60
120
180
240
300
360
420
480
540
600
1
2
3

FDS 5.4.0

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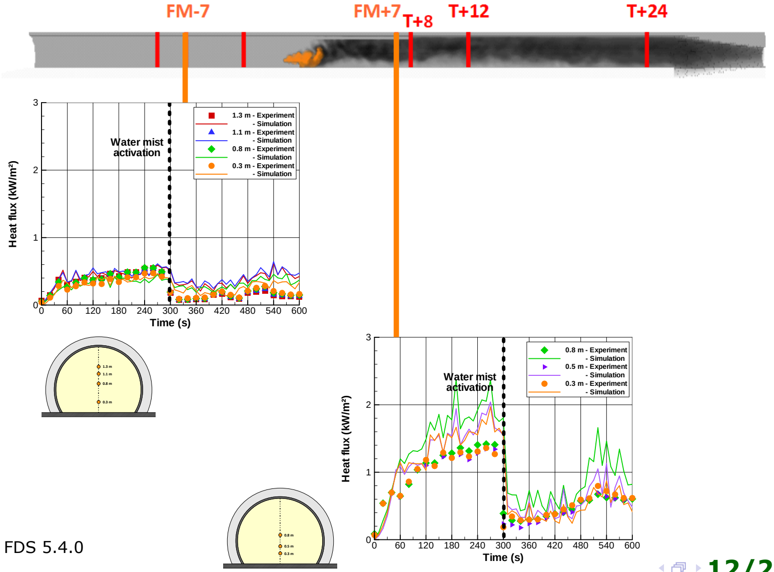

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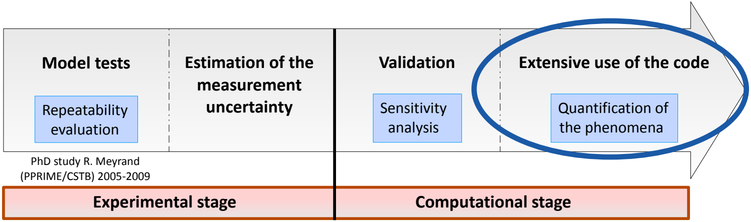
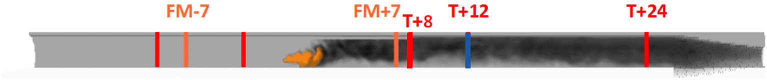
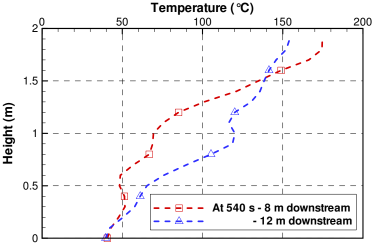


Test 27 : 3 upstream and 3 downstream
Extensive use : Stratification ?



At the HRR peak



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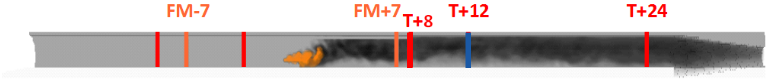
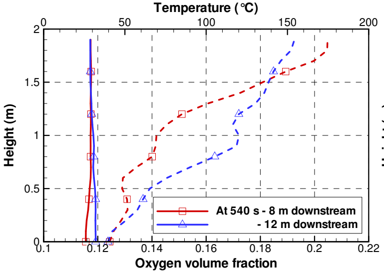
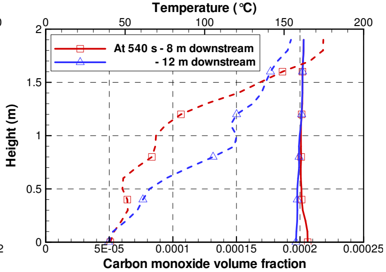


At the HRR peak

Oxygen concentration



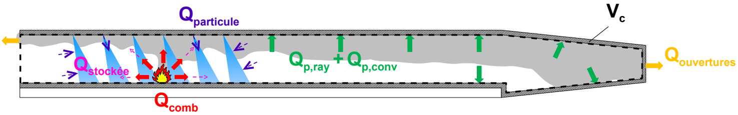
Carbon monoxide concentration

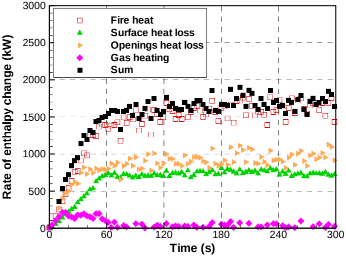


After 420 s, the environment is thermally stratified **whereas** $[O_2]$, $[CO_2]$ and $[CO]$ are almost constant along the vertical axis

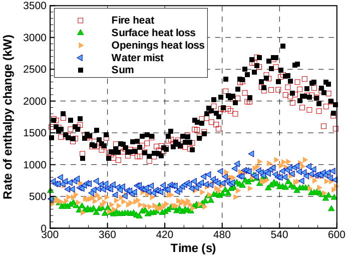
Test 27 : 3 upstream and 3 downstream

Extensive use : Heat contribution of water mist





Before mist activation

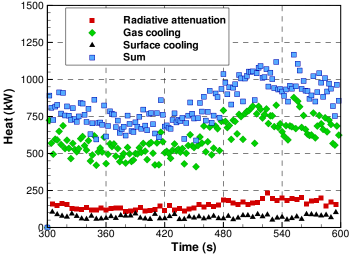


After mist activation

- 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 %



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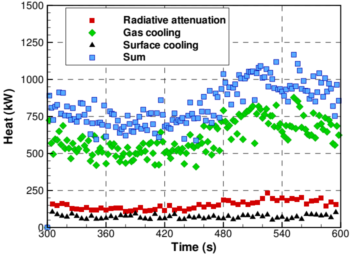
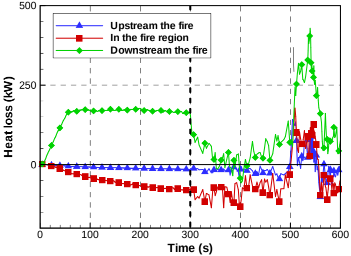
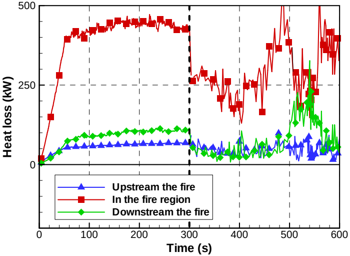




By convection



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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- Gas cooling appears to be the main mechanism, followed by radiative attenuation

Is it capable to solve fundamental problems ?

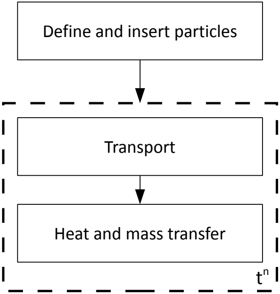
in particular droplet evaporation and radiative attenuation

Validations cases

FDS - Version 5

Eulerian/Lagrangian approach

monodisperse/polydisperse spray



	Submodel	Type	Case
Spray model	transport	verification	free fall of a single droplet
	heat and mass transfer	verification	thermodynamic equilibrium
		validation	evaporation rate of one single water droplet
	radiative model	verification	in a nonparticipating medium
		verification & validation	in a participating medium • downward configuration • upward configuration

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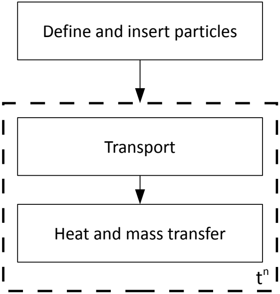

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		verification & validation	2	in a participating medium • downward configuration • upward configuration

Current model :

$$\frac{\mathrm{d}m_p}{\mathrm{d}t} = -A\, h_m\, \rho \left(Y_p - Y_g\right)$$

$$m_p\, c_p\, \frac{\mathrm{d}T_p}{\mathrm{d}t} = A\, h\, (T_g - T_p) + \frac{\mathrm{d}m_p}{\mathrm{d}t}\, h_v + \dot{q}_r$$

Model of Abramzon and Sirignano :

$$\frac{\mathrm{d}m_p}{\mathrm{d}t} = -4\pi\overline{\rho D} \cdot \frac{r_p\, Sh^*}{2} \cdot \ln\left(\frac{Y_{v,g} - 1}{Y_p - 1}\right)$$

$$m_p\, c_p\, \frac{\mathrm{d}T_p}{\mathrm{d}t} = -\dot{m}_p\, \overline{C_v} \cdot \frac{\left(T_g - T_p\right)}{B_T} + \frac{\mathrm{d}m_p}{\mathrm{d}t}\, h_v + \dot{q}_r$$

Model of Taylor and Krishna :

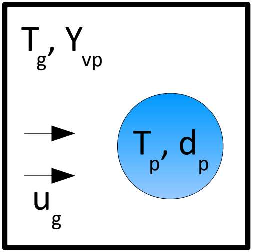
$$\frac{\mathrm{d}m_p}{\mathrm{d}t} = A_p\, \frac{p_0\, W_p}{R T_f} \cdot \frac{\mathrm{Sh}D}{2\, r_p} \ln\left(\frac{1 - Y_g\, \overline{W}/W_p}{1 - X_p}\right)$$

$$m_p\, c_p\, \frac{\mathrm{d}T_p}{\mathrm{d}t} = \frac{\mathrm{d}m_p}{\mathrm{d}t}\, h_v + A_p\, h^{\bullet}_{p,g}\, (T_g - T_p) + \dot{q}_r$$

Rate of evaporation of one single water droplet

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

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



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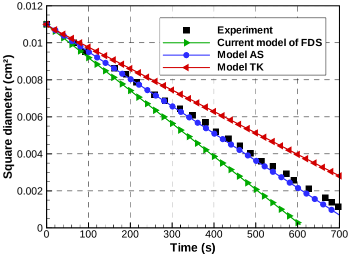

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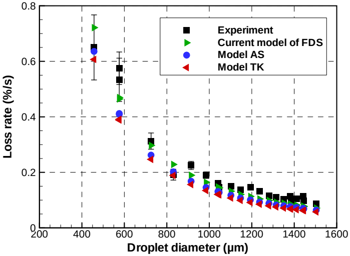

$$\text{Loss rate} = \frac{m_p(t_0) - m_p(t_0 + \Delta t)}{m_p(t_0) \cdot \Delta t}$$

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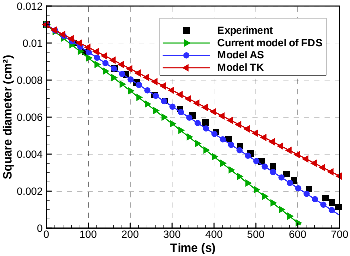

Discrepancy with measurements :

FDS : 22.7 %
AS : 1.4 %
TK : 20.0 %

[Kincaid, 1989] :

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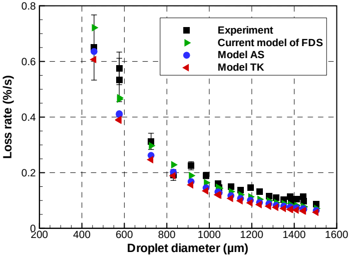
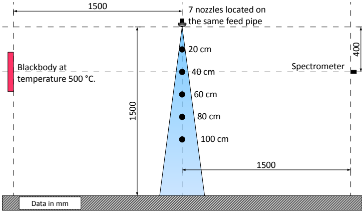


FDS : 17.6 %
AS : 19.6 %
TK : 21.4 %

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 cm)=100 μm



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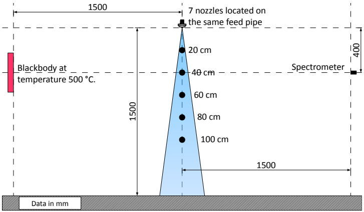
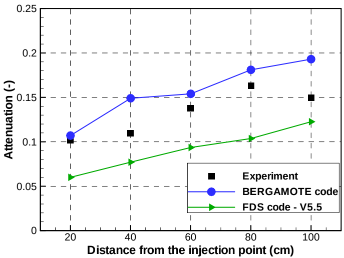
$d_{32}(20\text{ cm})=100\ \mu\text{m}$





FDS version 5 underestimates the radiative attenuation

Discrepancy with measurements : 31 %

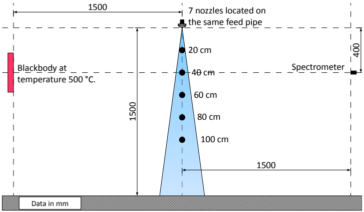
Discrepancy with BERGAMOTE : 42 %

Radiative attenuation
data from [Lechene's PhD thesis, LEMTA, 2010]

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

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

FDS 5

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

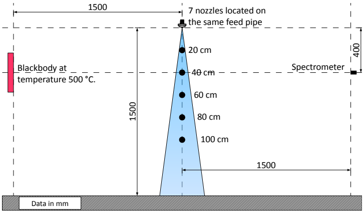
Proposed modification

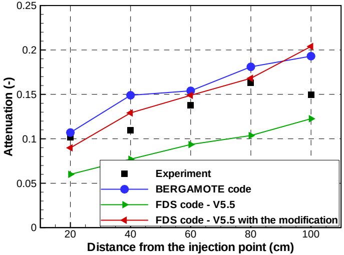
$$\kappa_\lambda(s) = \frac{1}{\delta x \delta y \delta z} \int_\lambda C_a(r_{32},\lambda) \mathrm{d}\lambda$$

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 μm





The modification leads to an improvement in predictions

Discrepancy with measurements : 11 %

Discrepancy with BERGAMOTE : 7 %

Summary

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 %

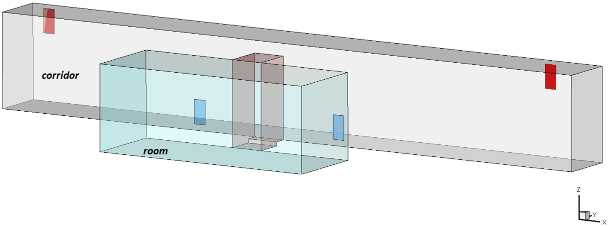
Some modifications have been proposed

- 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