Identification of fire suppression mechanisms by water mist: experimental and numerical analysis

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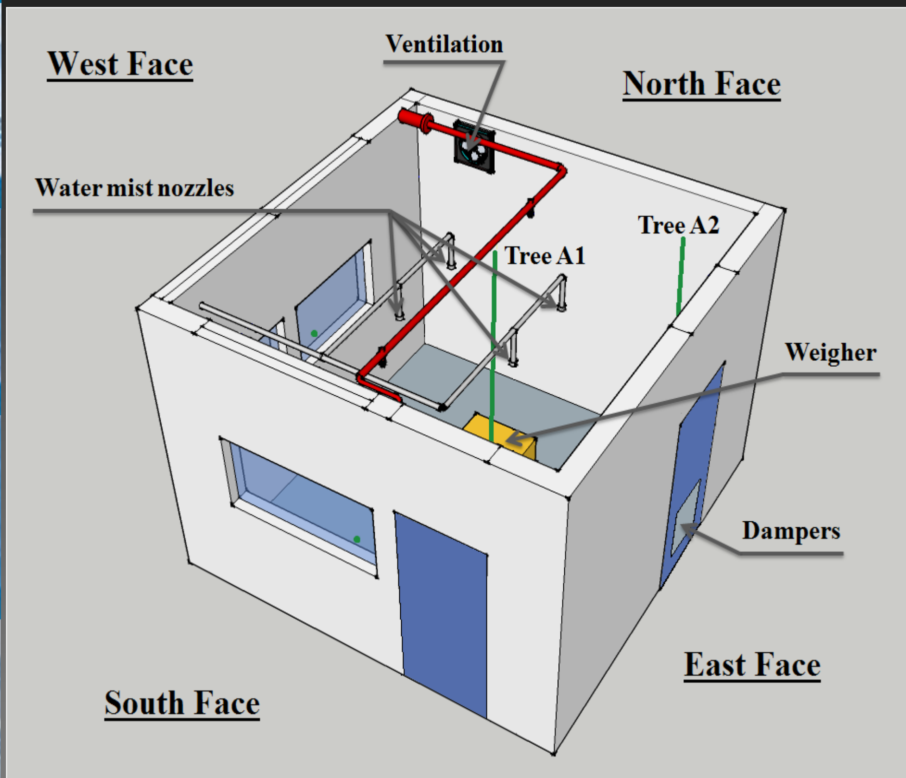
Extinction mechanisms

- **Gas phase cooling;**
- **Oxygen displacement and fuel vapor dilution;**
- **Fuel surface cooling and wetting;**

- **Radiative transfer attenuation;**
- **Kinetic effects.**

Experimental setup



- Pool diameters : 25 and 35 cm
- HRR up to 75 kW

Metrology:

- 18 thermocouples
- Gas analyser for O_2, CO_2 and CO
- Load cell
- Video camera

Water mist characteristics:

- Pressure = 10 bars
- Flow rate = 6.3 l/min/nozzle
- Injection angle = 130°
- D_{32} = 112 µm

Extinction mechanisms observation

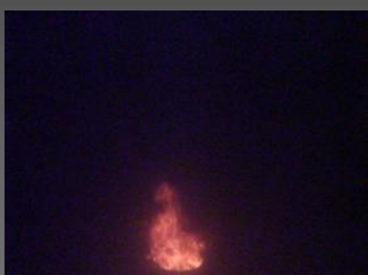
Test 18
t_{app} = 5 min

t_0+10 s

t_0+1 min

t_0+2 min

t_0+3 min



t_{app}-1 s

t_{app}+2 s

t_{app}+5 s

t_{app}+8 s

t_{app}+10 s

- Late application: strong evaporation;
- Dominating mechanism: flame cooling and inerting effects;
- Quick extinction.

Extinction mechanisms observation

Test 14

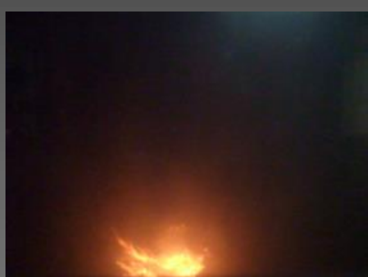
t_{app} = 1 min


t_0+10 s


t_{app}-1 s

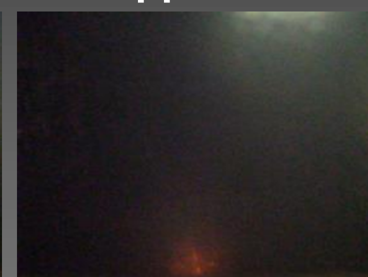

t_{app}+2 s


t_{app}+5 s


t_{app}+10 s


t_{app}+20 s


t_{app}+30 s


t_{app}+60 s


t_{app}+65 s

- Early application: weak evaporation;
- Dominating mechanism: fuel cooling;
- Longer extinction.

Experimental results: fuel oil

N°	D_{pool} [cm]	T_0 [°C]	t_{app} [s]	Q_{app} [kW]	$T_{A2,290,app}$ [°C]	Δt_{vid} [s]	Δt_{gas} [s]	Δt_{pool} [s]	Ext. Mech.
13	35	12	38	8	21	40	35	35	F.C
14	35	11	64	15	32	65	61	65	F.C
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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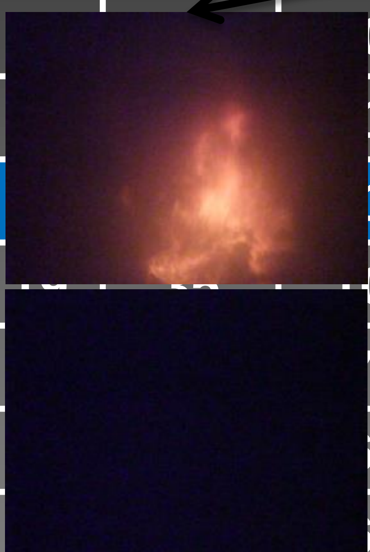
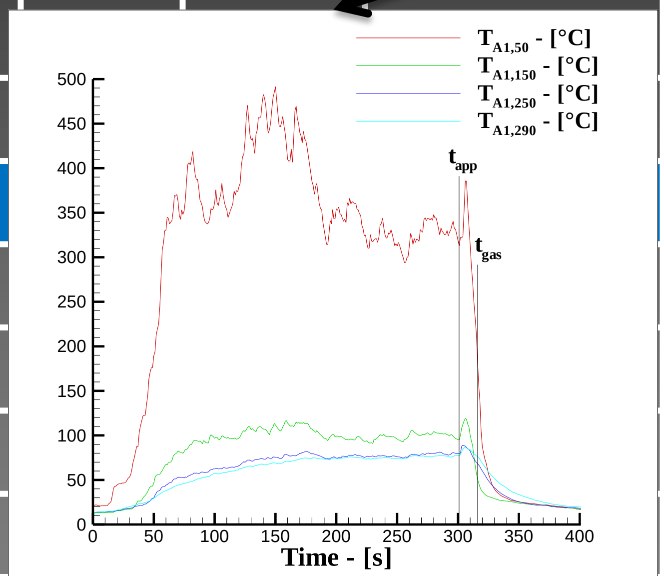
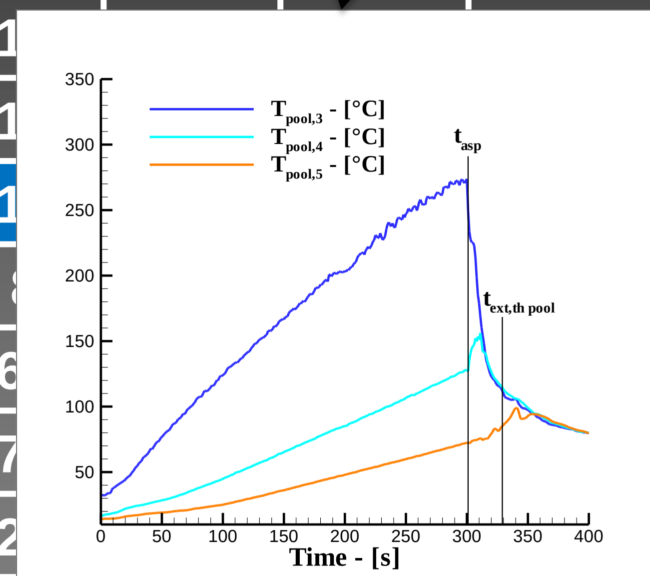






Experimental results: fuel oil

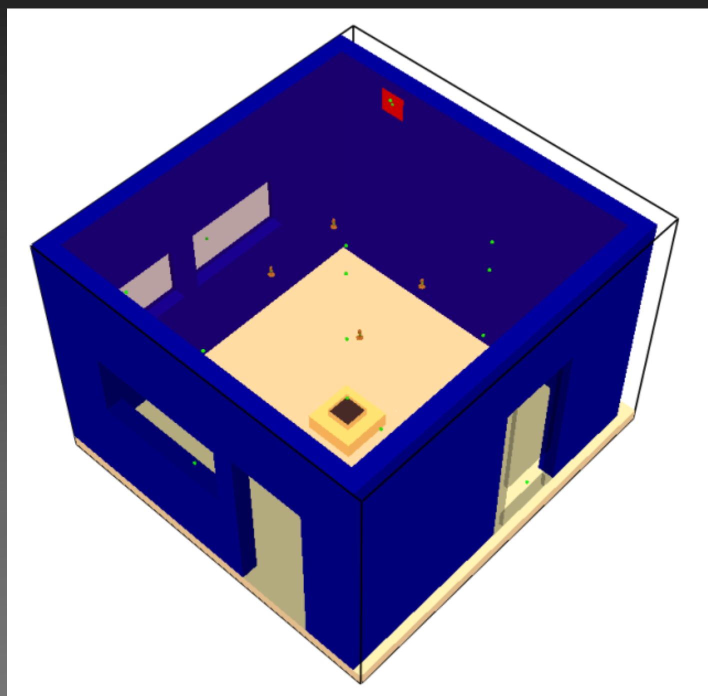
N°	D_{pool} [cm]	T_0 [°C]	t_{app} [s]	Q_{app} [kW]	$T_{A2,290,app}$ [°C]	Δt_{vid} [s]	Δt_{gas} [s]	Δt_{pool} [s]	Ext. Mech.
					21	40	35	35	F.C
					32	65	61	65	F.C
					52	10	8	24	G.C
					61	16	17	61	G.C
					71	10	15	28	G.C
					52	8	10	30	G.C
					42	65	58	78	F.C
					51	70	57	78	F.C
					62	26	26	56	G.C

A hotter environment leads to « gas cooling » extinction and a cooler to « fuel cooling » extinction

For « fuel cooling » tests, $\Delta t_{vid} \approx \Delta t_{pool}$

For « gas cooling » tests, $\Delta t_{vid} << \Delta t_{pool}$

Numerical model



Main parameters:

- Cell size: 5 cm x 5 cm x 5 cm;
- HRR increase defined as a ramp following the actual measured curve until stationary regime;
- After mist activation, HRR guided toward a reduction through extinction model.

Extinction model: $\dot{m}''_{pyro}(t) = \dot{m}''_{pyro,0}\; e^{-\int k(t)dt}$

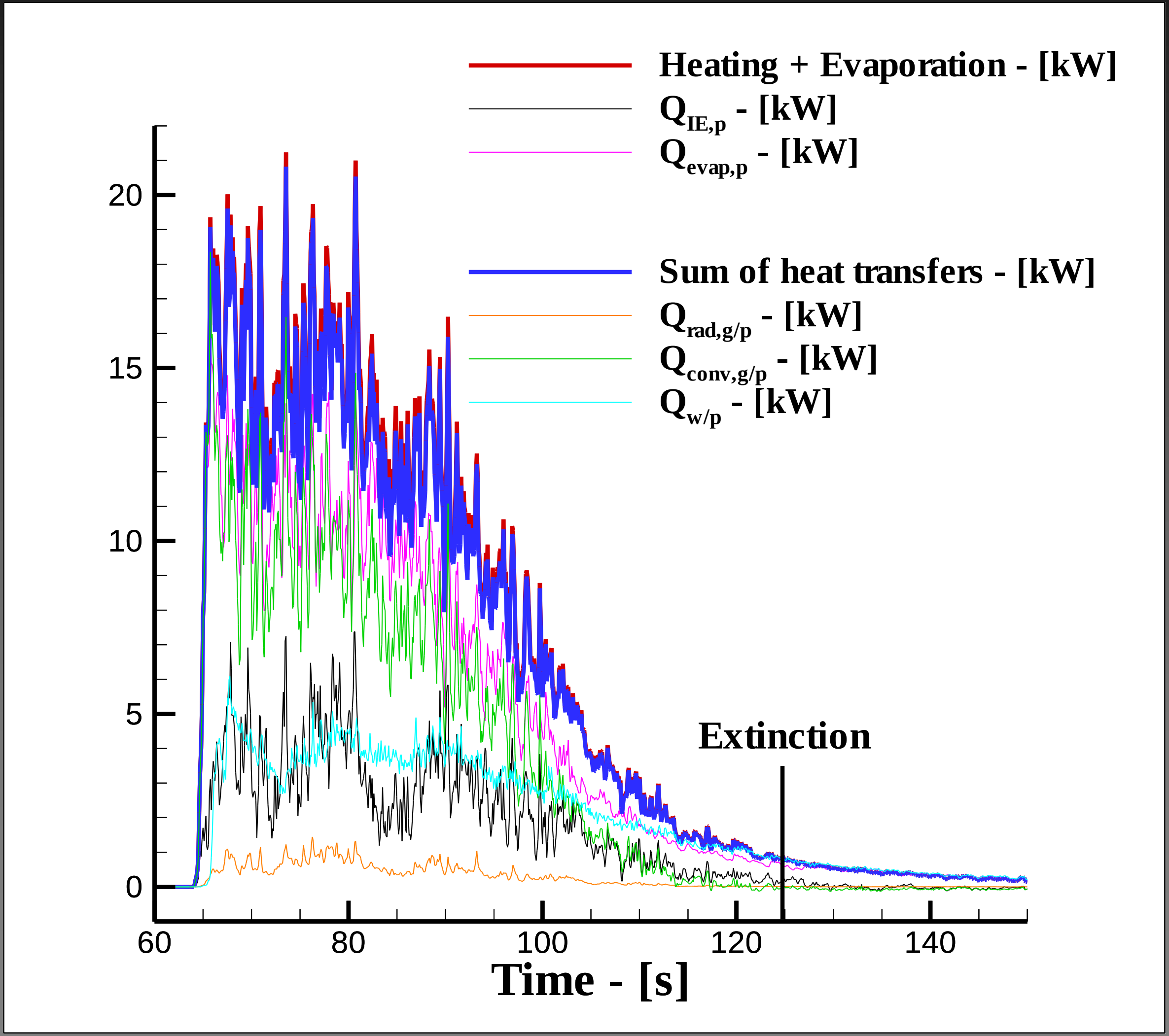
with $k(t) = a\; m''_{w}(t)$

Mass and energy balances

Mass balances	Energy balances
For « flame + gas » $$\dot m_g(t) = \dot m_{pyro}(t) + \dot m_{adv,g}(t) + \dot m_{evap}(t)$$	**For « flame + gas »** $$\dot Q(t) = \dot Q_{conv,g/w}(t) + \dot Q_{rad,g/w}(t) + \dot Q_{adv,g}(t) + \dot Q_{conv,p/g}(t) + \dot Q_{rad,p/g}(t) + \dot Q_{IE,g}(t)$$
For « droplets » $$\dot m_p(t) = \dot m_{inj}(t) + \dot m_{adv,p}(t) - \dot m_{evap}(t)$$	**For « droplets »** $$\dot Q_{evap}(t) + \dot Q_{IE,p}(t) = \dot Q_{conv,g/p}(t) + \dot Q_{rad,g/p}(t) + \dot Q_{w/p}(t)$$

Understanding
Training/Qualifying
Evaluating
Certifying
Advising
Informing

Energy balances results



Fire extinction model

HRR reduction should be linked to fuel temperature during water application

Model:

$$\begin{cases} \dot{m}''_{pyro}(t) = A\sqrt{T_{fuel}(t) - T_{ign}}\,\exp\left(-\dfrac{B}{T_{fuel}(t)}\right) & \text{if } T_{fuel} \geq T_{ign} \\ \dot{m}''_{pyro}(t) = 0 & \text{if } T_{fuel} < T_{ign} \end{cases}$$

A and B are empirical coefficients which can be easily determined, even without experimental tests.

Based on the Arrhenius law: $\dot{m}''_{pyro}(t) = A'\exp\left(-\dfrac{B'}{T_{fuel}(t)}\right)$

Understanding
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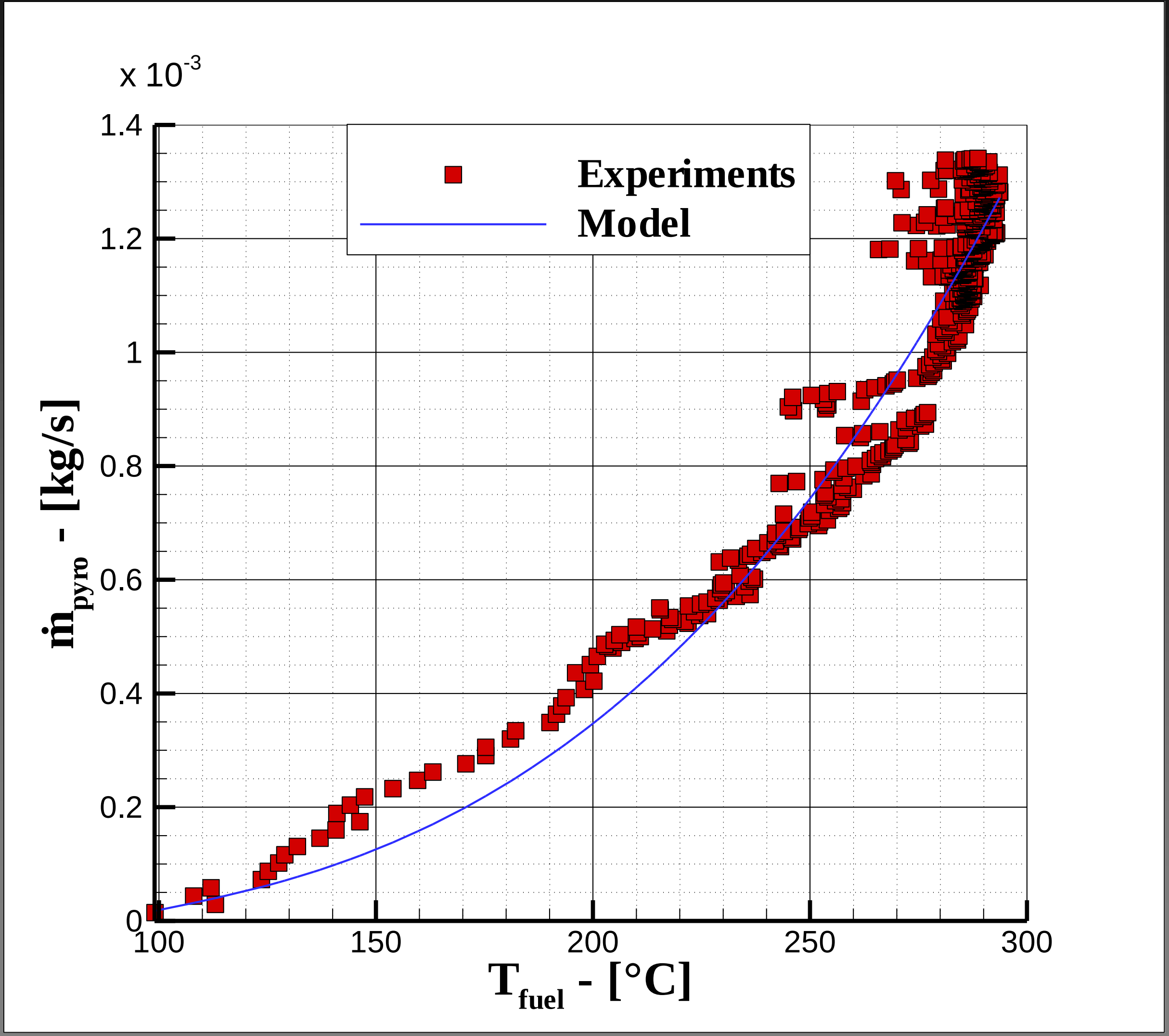
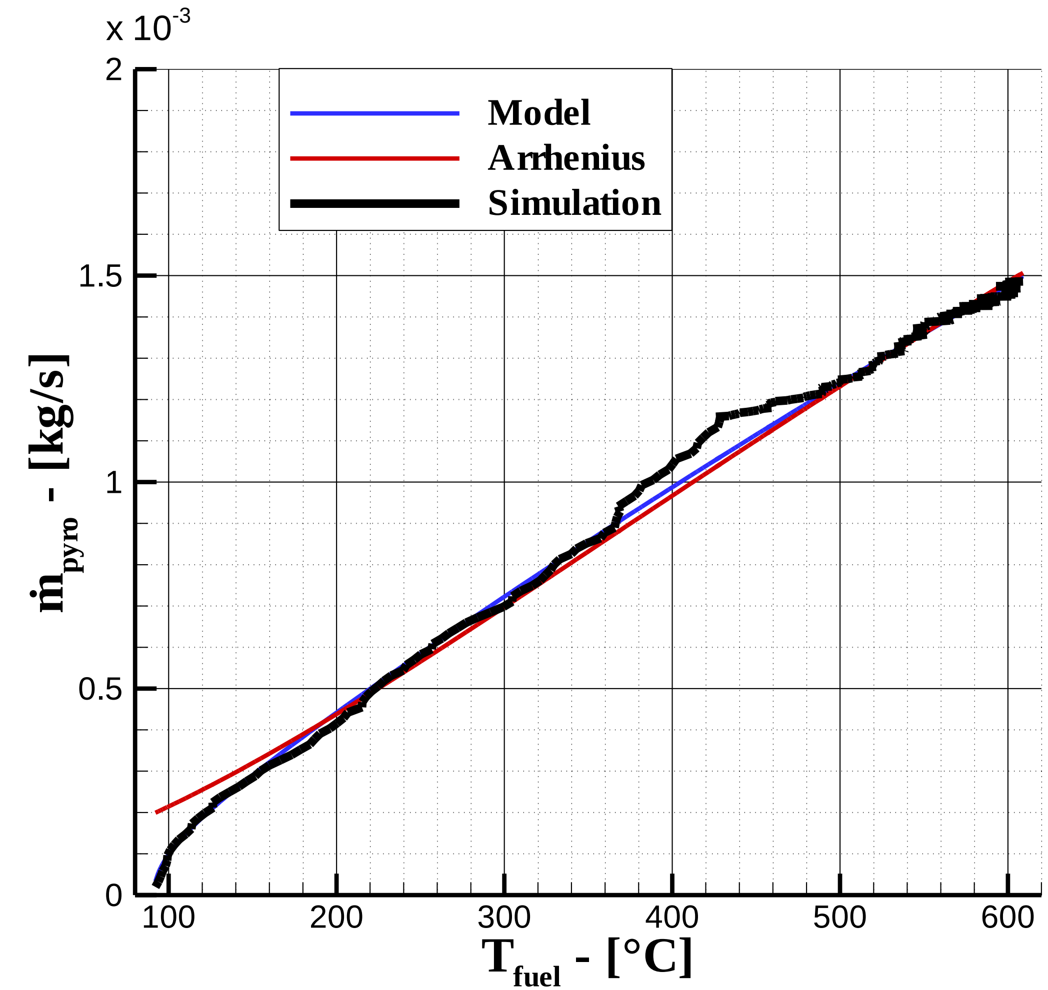
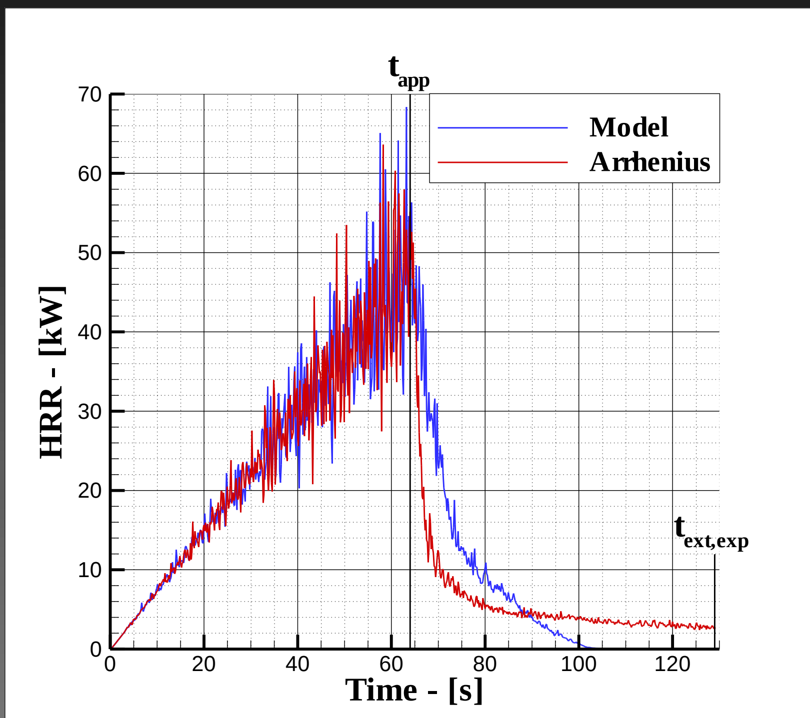
Validation without water mist

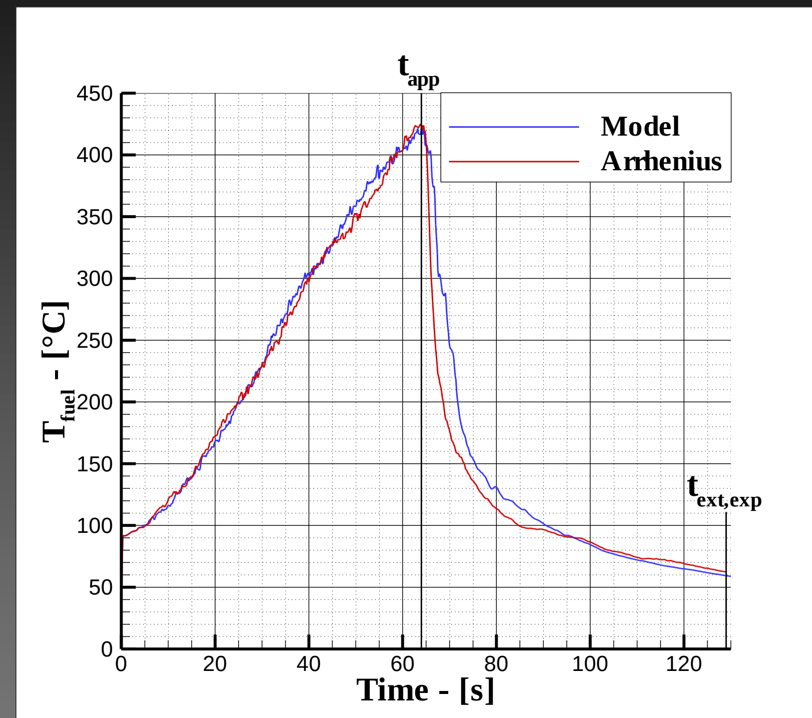


With simulation only



Results on extinction time





- Identical results for T_{fuel} but extinction after 38 s with model.
- $t_{ext,num}$ too short ($t_{ext,exp}$ = 65 s), corresponding to a gap of 42 %.
- First results with a full predictive model.

Results on extinction time

N°	13	14	20	21	31	32	33	34	35	36	37
$t_{ext,exp}$ (s)	40	65	65	70	31	30	69	99	106	105	129
$t_{ext,num}$ (s)	22	38	56	66	9	21	43	58	77	100	134
Gap (s)	18	27	9	4	22	9	26	41	29	5	5
Gap (%)	45	42	14	6	71	30	38	41	27	5	4

- **HRR reduction is always captured;**
- **Gap between 4 and 41 s between experimental and model results;**
- **Model does not predict “wrong” extinction.**

Conclusions

1. Late application => Developed fire and hot environment => Strong evaporation => Quick extinction by gas cooling and inerting effects;
2. Early application => "Cool" environment => Weak evaporation => Longer extinction by fuel cooling for fuel oil fires;
3. For the latter case, a new extinction model has been integrated to FDS;
4. The average gap between experimental and model results is 18 s (or 29 %). The model did not predict "wrong" extinction.

Current work

1. **Improve model results through a modification of particles / fuel exchanges modeling;**
2. **Determine FDS capability to determine extinction by flame cooling and inerting effects in FDS 6.**

Energy balances results

N°	a [m²/kg/s]	$\dot{Q}_{evap} / \dot{Q}_p$	$\dot{Q}_{IE,p} / \dot{Q}_p$	$\dot{Q}_{conv,g/p} / \dot{Q}_p$	$\dot{Q}_{rad,g/p} / \dot{Q}_p$	$\dot{Q}_{w/p} / \dot{Q}_p$	Ext. Mech.
13	0.3	68 %	32 %	58 %	4 %	38 %	F.C
14	0.15	74 %	[illegible]	[illegible]	[illegible]	[illegible]	F.C
16	50	84 %	[illegible]	[illegible]	[illegible]	[illegible]	G.C
17	20	86 %	[illegible]	[illegible]	[illegible]	[illegible]	G.C
18	30	87 %	[illegible]	[illegible]	[illegible]	[illegible]	G.C
19	90	83 %	[illegible]	[illegible]	[illegible]	[illegible]	G.C
20	0.6	75 %	[illegible]	[illegible]	[illegible]	[illegible]	F.C
21	0.2	76 %	[illegible]	[illegible]	[illegible]	[illegible]	F.C
22	3.3	81 %	19 %	71 %	4 %	25 %	G.C

Strong evaporation for « gas cooling » cases. In any case, evaporation is stronger than variation of internal energy.

‘a’ between 0 and 1 m²/kg/s for (suited) « fuel cooling » cases.

Energy balances results

N°	a [m²/kg/s]	$\dot{Q}_{evap} / \dot{Q}_p$	$\dot{Q}_{IE,p} / \dot{Q}_p$	$\dot{Q}_{conv,g/p} / \dot{Q}_p$	$\dot{Q}_{rad,g/p} / \dot{Q}_p$	$\dot{Q}_{w/p} / \dot{Q}_p$	Ext. Mech.
13	0.3	68 %	32 %	58 %	4 %	38 %	F.C
14	0.15	74 %	26 %	62 %	4 %	34 %	F.C
16	50	84 %	16 %	74 %	3 %	23 %	G.C
17	20	86 %	14 %	79 %	4 %	17 %	G.C
18	30	87 %	13 %	73 %	3 %	24 %	G.C
19	90	83 %	17 %	65 %	2 %	33 %	G.C
20	0.6	75 %	25 %	71 %	4 %	24 %	F.C
21	0.2	76 %	24 %	67 %	5 %	28 %	F.C
22	3.3	81 %	19 %	71 %	4 %	25 %	G.C

Energy balances results

N°	a [m²/kg/s]	$\dot{Q}_{evap} / \dot{Q}_p$	$\dot{Q}_{IE,p} / \dot{Q}_p$	$\dot{Q}_{conv,g/p} / \dot{Q}_p$	$\dot{Q}_{rad,g/p} / \dot{Q}_p$	$\dot{Q}_{w/p} / \dot{Q}_p$	Ext. Mech.
31	1	65 %	35 %	57 %	4 %	39 %	F.C
32	1	71 %	29 %	61 %	4 %	35 %	F.C
33	0.24	75 %	25 %	68 %	5 %	27 %	F.C
34	0.26	77 %	23 %	74 %	6 %	20 %	F.C
35	0.42	77 %	23 %	78 %	6 %	15 %	F.C
36	0.74	79 %	21 %	81 %	7 %	12 %	F.C
37	0.24	79 %	21 %	81 %	7 %	13 %	F.C

- **Evaporation part < 80 %;**
- **‘a’ between 0 and 1 $m^2/kg/s$;**
- **Convection > wall / particles exchanges > radiation.**