GDR Incendie – CORIA UME 6614, July 2-3, 2009

HEAT RELEASE RATE

NATURAL VENTILATION-CONTROLLED ROOM FIRES

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The study of thermodynamic aggressions of the equipment and structures of the closed rooms needs data concerning HRR

The fire evolution in a room can be affected by:

- Quantity and arrangement of fuel in the fire room
- Oxygen supply

If the **ventilation is great enough** (sufficiency of oxygen), the fire is said to be **fuel-controlled**

However, if the **ventilation is small**, relative to the size of the fire, there is not enough oxygen to combust all the pyrolysis fuel, the fire is said to be **ventilation-controlled**. The associated **HRR depends** mainly on the **amount of available oxygen** (ventilation condition).

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The four different fire phases, characterized by a HRR, can be distinguished in this figure

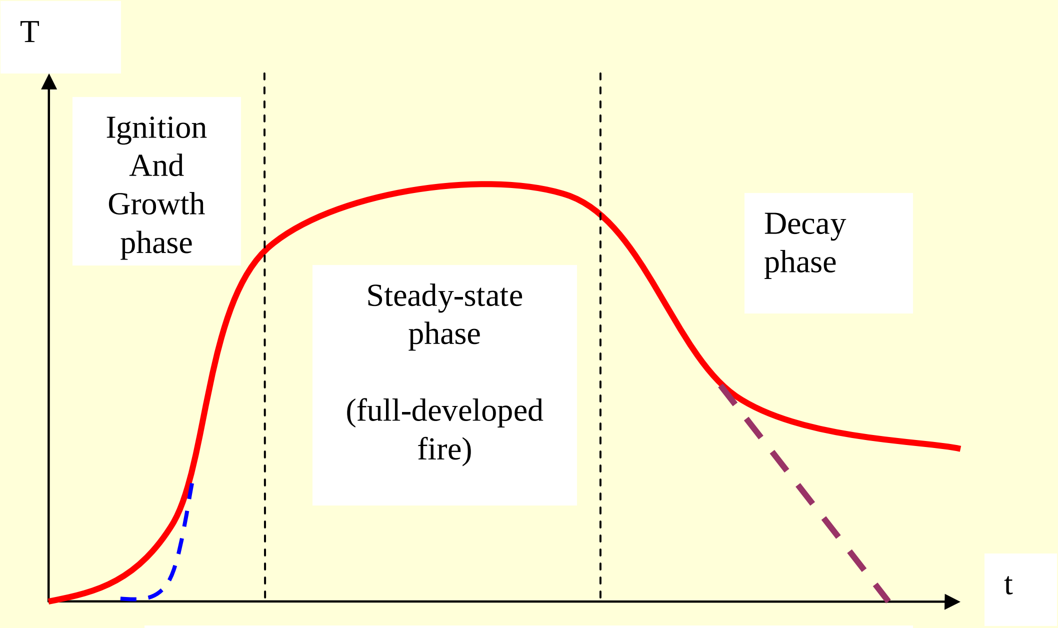

Fig 1: Temperature evolution in a fire room – Fire phases

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1. **Ignition phase**: fire starts with the ignition of burning material (usually in a single location of the room)

2. **Growth phase**: fire starts to propagate within the room. It is characterized by an exponentially increasing HRR that depends on:
   - the type and geometry of fuel,
   - interaction with the surrounding,
   - access to oxygen.

   The development can evolve towards the maximum of HRR

3. **Fully developed phase**: the HRR is relatively unchanging and leading to small variations in temperature.

   The situation can evolve toward one of the following situation:

- Fuel-controlled situation:
  - **Spread of the fire to the whole room** (flashover phenomenon): the gas temperature, became so elevated, can cause the sudden ignition of “every object” and unburnt gas in the room
  - **No spread of the fire to the whole room**: if the propagation is slow, the gas temperature rise is not sufficient to cause flashover, fire can find no combustible material in its closed vicinity. The fire remains localized and, with time, dies out.

The HRR is related to the pyrolysis rate by equation:

$$\dot{Q}(t) = \Delta H_{c,eff}(t).\dot{m}(t) \qquad \text{with} \qquad \Delta H_{c,eff}(t) = \xi(t).\Delta H_{c,net}$$

- Ventilation-controlled situation:

  If:
  - air is not allowed to enter the room: the fire dies out
  - air is not sufficiently allowed to enter the room: the fire development is limited,
  - air is sufficiently allowed to enter the room by creating a new opening: the rapid flame can occur such as a backdraft and smoke explosion.

4. Decay phase

This phase is characterized by a continuous deceleration in HRR. In this period the fire may go to:

- a ventilation-controlled situation
- a fuel-controlled situation

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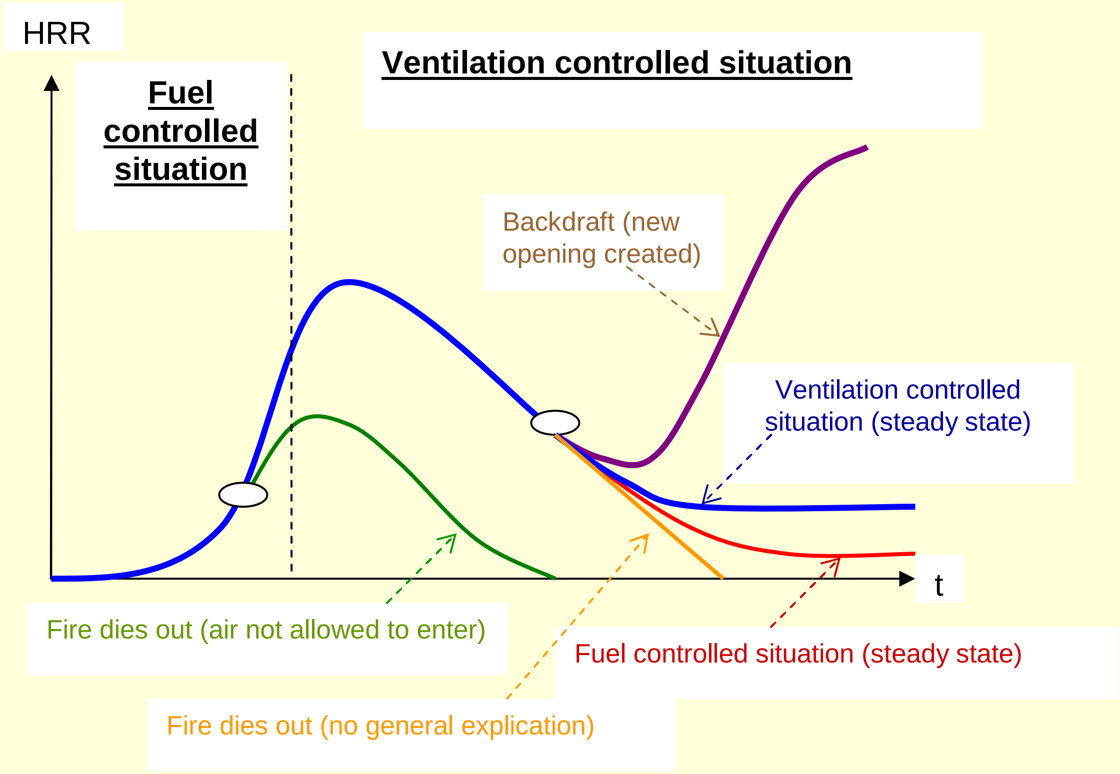
Evolution possible of the HRR (or average temperature)
in a fire room as function of time



Fuel controlled situation

Ventilation controlled situation

Backdraft (new opening created)

Ventilation controlled situation (steady state)

Fire dies out (air not allowed to enter)

Fuel controlled situation (steady state)

Fire dies out (no general explication)

Figure 2: HRR evolution according to the fire situation (fuel or ventilation-controlled)

Thermal mechanisms that take place are:

1. Convection and radiation from the flame to the fuel surface
2. Radiation from the hot smoke
3. Conduction within the fuel

Nota: *radiation between the walls and the fuel is not represented*

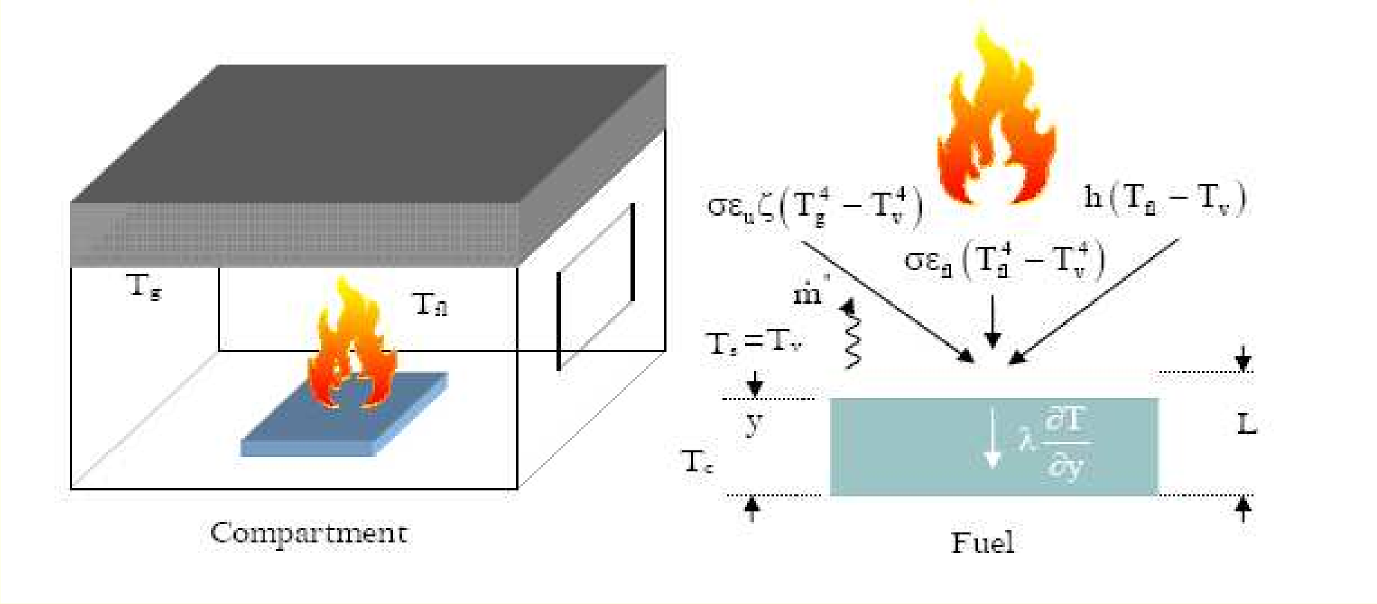


Figure 3: Schematic burning of a non-charring fuel in a room

Experimental results from free burning can’t be used

to estimate the room burning rate

$$\dot{m}_{room} \neq \dot{m}_{free}$$

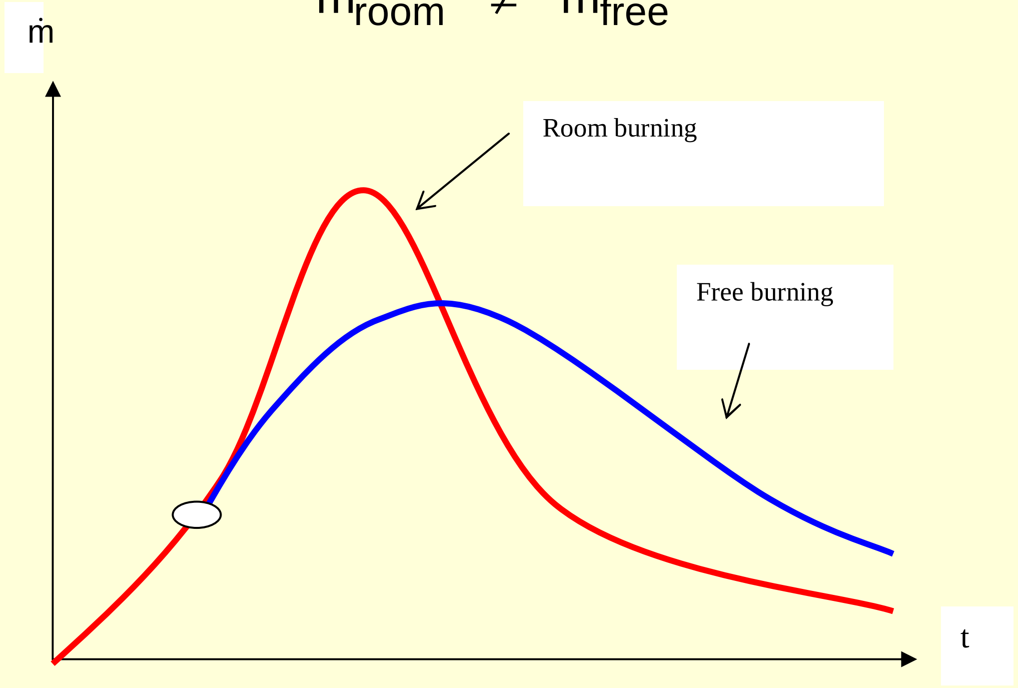


Figure 4: Room effect on mass loss rate

Pyrolyse rate equation

$$\dot{m}_{room} = \dot{m}_{free} + \frac{\sigma.\varepsilon.\zeta.\left[T_g^4(t) - T_v^4\right] + h.\left[T_g(t) - T_v\right] - \lambda.\frac{T_v - T_c(t)}{y(t)}}{L_v}$$

Where

- $\dot{m}_{free}$: pyrolyse rate in free burning (open condition)
- ζ : factor taking into account the transparency and absorptivity of the flame (ranges from 0 to 1)
- T_g : gas temperature
- T_v : vaporisation temperature of fuel
- T_c : fuel temperature
- $y(t)$: fuel thickness
- L_v : heat of vaporisation

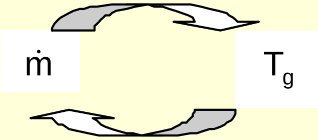
Nota: *radiation from wall and “flame” not represented*

Factors Influencing HRR of fire in a room

1. **Fuel**
   - Size and location of the ignition source
   - Fuel package (type, amount, position …)
2. **Room**
   - Geometry
   - Ventilation condition (openings, forced ventilation …)
   - Material properties of partitions (thermal inertia, diffusivity)

burning rate $\neq$ pyrolyse rate

Vicious circle:



$\dot{m}$ T_g

Conclusion: In **room fire** situation, it is **NOT POSSIBLE** to **derive a general theory to predict exactly the HRR**

A theoretical model to **predict the maximum HRR** is developed

to be used, **in the field of engineering,**

to determine the **thermodynamic aggressions**

reasonably conservative

ASSUMPTIONS

The proposed model is based on the following assumptions

- Natural vents at two levels: lower and upper (ceiling or wall vent)
- Well stirred reactor cabinet: temperature, density and concentration of gases homogeneous
- Incubation phase ignored
- Fire development divided in two characteristic phases: a growth phase (t-squared) and a steady phase (constant).

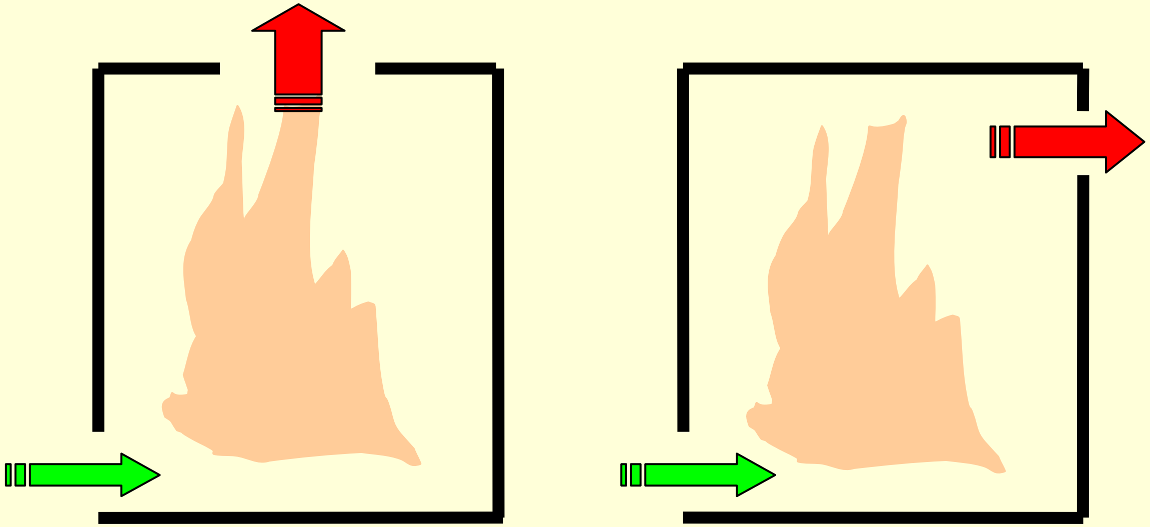


Figure 5 : Ceiling vent and Wall vent

Theoretical model oh HRR

$$\dot{Q}(t) = \begin{cases} \alpha t^2 & \text{if} \quad t \le t_{peak} \\ \dot{Q}_{max} & \text{if} \quad t > t_{peak} \end{cases} \qquad \text{Eq. (1)}$$

The first relation of (1), t-squared approximation, represents the pre-flashover phase and the second, constant, the post-flashover.

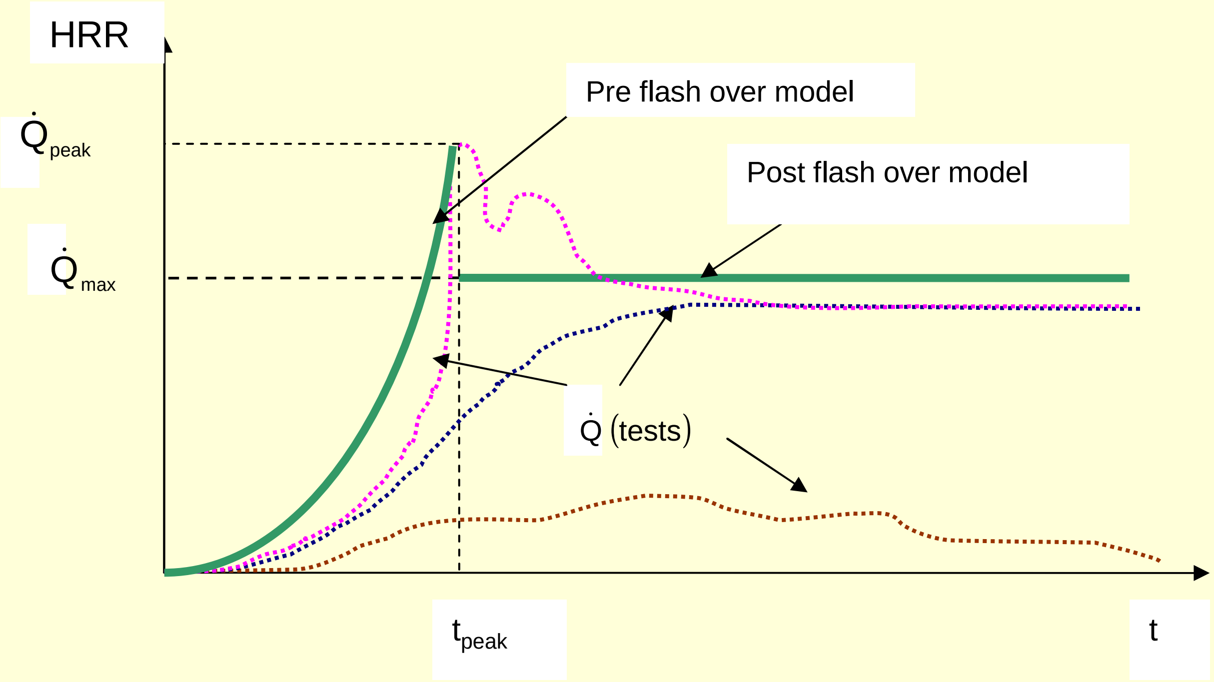


Figure 6: Theoretical and experimental variations of the HRR

DETERMINATION OF MAXIMUM HRR

A. Pre-flashover model (growth phase)

1. Oxygen consumption principle

$$\dot{Q} = \Delta H_{R,O_2} . \frac{X^0_{O_2} - X_{O_2}}{\left(1 - X_{O_2}\right)} . \dot{m}_i . \frac{M_{O_2}}{M_{air}} . \left(1 - X^0_{H_2O} - X^0_{CO_2}\right) \qquad \text{Eq. (2)}$$

2. Oxygen concentration

$$\frac{dX_{O_2}}{dt} = \frac{1}{\rho_0 V} . \dot{Q} \frac{\left(1 - X_{O_2}\right)}{k.\Delta H_{R,O_2}} . \frac{M_{air}}{M_{O_2}} . \frac{1}{\left(1 - X^0_{H_2O} - X^0_{CO_2}\right)} . - \frac{\dot{Q}}{\rho_0 V k \Delta H_{R,O_2}} \qquad \text{Eq. (3)}$$

Where: k : entrainment coefficient (=2 for ceiling outlet flow, =1 for wall outlet flow)

$\Delta H_{R,O_2}$: heat release per O_2 consumed (= 13,100 kJ/kg)

$M_{air} = M_{dry\ air}$: molecular weight of air (= 29 kg/kmol),

M_{O_2} : molecular weight of O_2 (= 32 kg/kmol)

ρ_0 : density of the incoming air (= 1.18 kg/ m^3)

V : volume of the room (m^3)

X_{O_2} : mole fraction of O_2 inside the room at time t,

Note: X_{O_2} *decreases from* $X^0_{O_2} = 23\ \%$ *to* $X_{O_2,0} = 1.1 LOI$ (extinction limit)

The analytical solution of differential equation (3) is

$$X_{O_2} = \frac{a+b}{a} + \left(X^0_{O_2} - \frac{a+b}{a} \right).\exp\left(-\frac{a}{3}.t^3 \right) \qquad \text{Eq. (4)}$$

At the peak, these equations give the **time to reach the HRR** (maximum of fire growth phase), function of the minimum and maximum oxygen concentration.

$$t_{peak} = \left[-\frac{3}{a} \ln\left(\frac{X_{O_2,0} - \dfrac{a+b}{a}}{X^0_{O_2} - \dfrac{a+b}{a}} \right) \right]^{1/3} \text{and} \quad \dot{Q}_{peak} = \alpha t^2_{peak} \qquad \text{Eq. (5)}$$

where

$$a = \frac{\alpha}{\rho_0 V} \cdot \frac{1}{k \Delta H_{R,O_2}} \cdot \frac{M_{air}}{M_{O_2}} \cdot \frac{1}{\left(1 - X^0_{H_2O} - X^0_{CO_2}\right)}$$

$$b = -\frac{\alpha}{\rho_0 V k \Delta H_{R,O_2}}$$ (dimensionless parameters)

Remarks

If we take $\Delta H_{R,O_2} =$ 13,100 kJ/kg, $M_{air} = M_{dryair}$ = 29 kg/kmol,

M_{O_2} = 32 kg/kmol and $\rho_0 =$ 1.18 kg/ m^3,

the time to reach the HRR peak becomes

$$t_{peak} = 37.\left[-\frac{k.V}{\alpha} \ln(3{,}2.LOI + 0{,}3) \right]^{1/3}$$

Eq. (6)

This time remains “independent” of LOI under 4%. Therefore, if we take LOI = 0%, Eq. (6) becomes

$$t_{peak} = 39.4 \left(\frac{k.V}{\alpha} \right)^{1/3}$$

Eq. (7)

It should be noted that the growth factor α is not unique and rarely reproducible in fire tests. However the SFPE Handbook, suggests these values

- α = 0,00293 kW/s2 (slow)
- α = 0,01172 kW/s2 (medium)
- α = 0,0469 kW/s2 (fast)
- α = 0,1876 kW/s2 (ultra-fast)

B. Post-flashover model (steady phase)

After the peak, the HRR decreases. It is assumed to tend towards an asymptotic direction corresponding to a fire which is controlled by natural ventilation.

By taking $\frac{dX_{O_2}}{dt} = 0$ Eq. (2) becomes

$$\dot{Q}_{max} = \dot{m}_i . Z_{LOI} \left(X^0_{O_2} . \Delta H_{R,O_2} \right) \qquad \text{Eq. (8)}$$

where

$$Z_{LOI} = \frac{X^0_{O_2} - X_{O_2,0}}{X^0_{O_2}} = \frac{23 - \frac{32}{29}.LOI}{23} \cong \frac{21 - LOI}{21} \qquad \text{Eq. (9)}$$

The expression of the pressure differences, ΔP_e in vents at lower level and ΔP_i upper level, using the Bernoulli equation, can be expressed as

$$\Delta P_e = -\Delta P_i + \rho_0 \left(1 - \frac{T_0}{T}\right) gH \qquad \text{Eq. (10)}$$

where H is the difference in height between the air inlet and outlet (m)

We neglected the combustion mass inside the cabinet to obtain a simple mass balance relating the incoming and exhausting mass flows in a steady phase.

$$\dot{m}_i = \dot{m}_e = A_e C_e \rho_0 \sqrt{2gH} \sqrt{\frac{\tau - 1}{\mu\tau + 1}} \qquad \text{Eq. (11)}$$

where $$\tau = \frac{T}{T_0} = \frac{T}{293}$$

$$\mu = \left(\frac{kA_i C_i}{A_e C_e} \right)^2$$

A_i : area of the room air inlet (m^2),
A_e : area of the room air outlet (m^2)
C_i : vent inlet coefficient determined by specific test (flow resistant) (no unit)
C_e : vent exhaust coefficient determined by specific test (no unit)

The dimensionless parameter τ increases from T / 293 to reach the maximum value

$$\tau_{max} = 1 + \sqrt{1 + \left(\frac{A_e C_e}{kA_i C_i}\right)^2}$$

Eq. (12)

The asymptotic HRR becomes

$$\dot{Q}_{max} = Z_{LOI}.\left(Y_{O_2,\infty}.\Delta H_{R,O_2}\right).\rho_0.\sqrt{2.g.H}.A_e.C_e.\frac{1}{\left(1+\sqrt{1+\frac{1}{\mu}}\right)}$$

Eq. (13)

If we take g = 9.81 m/s^2 ; $X^0_{O_2}.\Delta H_{R,O_2} = 0.23x13100 \cong 3{,}000\ kJ/kg$ and

$\rho_0 = 1.18$ kg/m^3, Eq. (13) becomes simply

$$\boxed{\dot{Q}_{max} = 747.(21-LOI).\frac{A_e C_e \sqrt{H}}{1+\sqrt{1+\left(\frac{A_e C_e}{kA_i C_i}\right)^2}}}$$

Eq. (14)

The following expression can be used for most of fuels (polymers, etc.)

$$LOI = -0.01 \times T + 15 = -3.\left(1 + \sqrt{1 + \left(\frac{A_e C_e}{k A_i C_i}\right)^2}\right) + 15$$

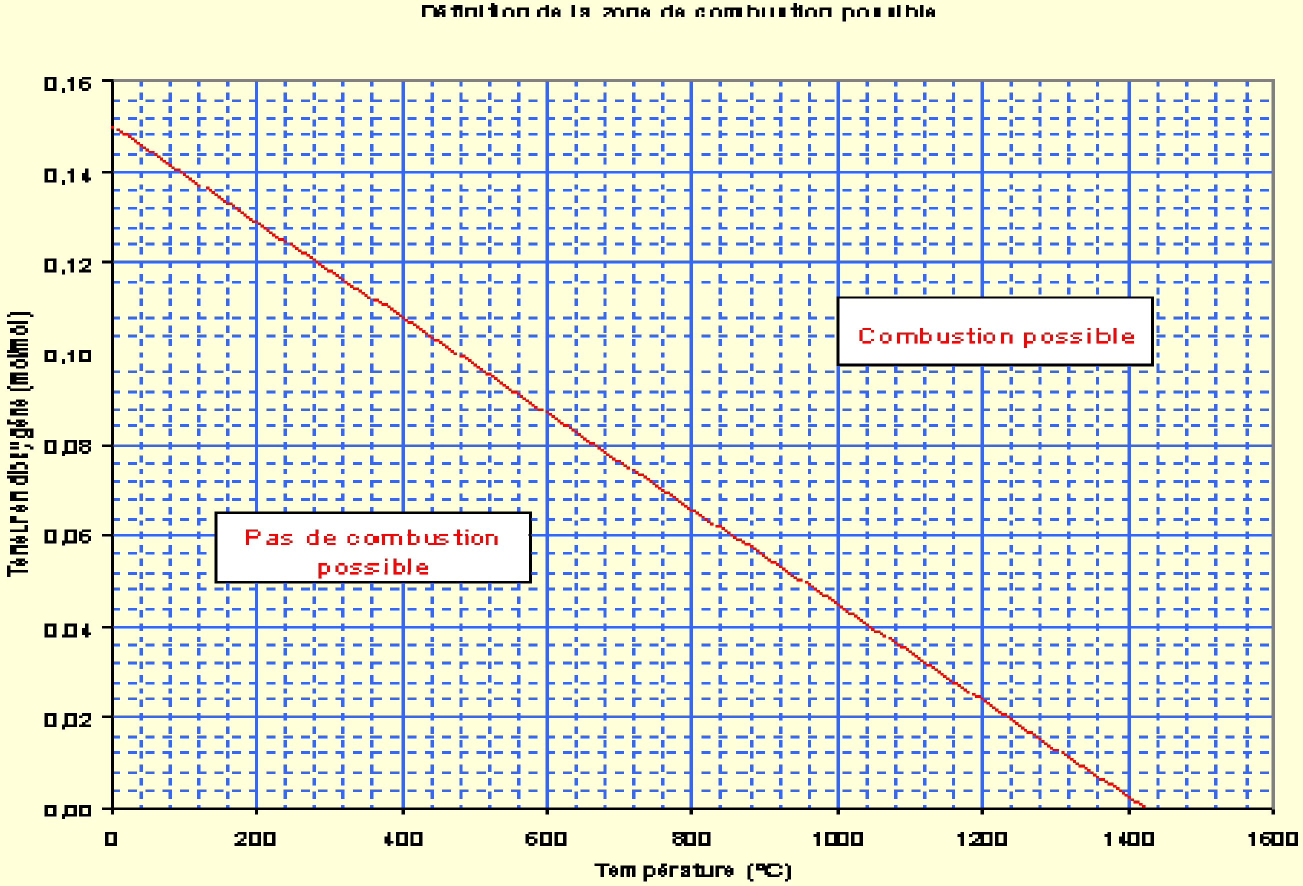


Figure 3: Laboratoire National d'Essais (LNE) test results: Evolution of LOI as a function of temperature (used by permission)

Remarks

The flow coefficients C_i and C_e can be determined by means of specific tests.
As most materials found in nuclear facilities are “polymers”, the LOI can be expressed as a function of temperature

$$LOI = -0.01\,T + 15 \qquad \text{Eq. (15)}$$

$$LOI_{minimum} = -3.\left(1+\sqrt{1+\left(\frac{A_eC_e}{kA_iC_i}\right)^2}\right)+15$$

Finally, we obtain the asymptotic HRR to represent the post-flashover phase

$$\boxed{\dot{Q}_{max} = 2240\left[3+\sqrt{1+\left(\frac{A_eC_e}{kA_iC_i}\right)^2}\right].\frac{A_eC_e\sqrt{H}}{1+\sqrt{1+\left(\frac{A_eC_e}{kA_iC_i}\right)^2}}} \qquad \text{Eq. (16)}$$

VERIFICATION & VALIDATION OF THE PROPOSED MODEL

Comparison between tests and calculations

Objective: blind calculation of time to reach the peak and asymptotic HRR and comparison with test results

Tests selected: 10 IRSN tests in a closed steel box 1m(wide) X 0.6m (deep) X 2m (height), naturally vented, are used

Initial objective of tests: evolution of mass moss rate considering influence of

- Inlet vent area: tests 1-2-3-4
- Outlet area: tests 3-5 and 7-8
- Nature of fuels and configuration: tests 7-9-10

The measured mass loss rate is used to estimate the experimental HRR

IRSN test configurations

Test number	**Vent area (m^2)**		**Fuel**	
	Inlet A_i	Outlet A_e	Nature	Dimensions
1	0.1	0.1 (top)	PMMA	Plate of 1.05 m^2
2	0.05	0.1 (top)	PMMA	Plate of 1.05 m^2
3	0.025	0.1 (top)	PMMA	Plate of 1.05 m^2
4	0.0175	0.1 (top)	PMMA	Plate of 1.05 m^2
5	0.025	0.05 (top)	PMMA	Plate of 1.05 m^2
6	0.0175	0.05 (top)	PMMA	Plate of 1.05 m^2
7	0.025	0.1 (upper rear)	PMMA	105 squared of 0.01 m^2 each one
8	0.025	0.05 (upper rear)	PMMA	105 squared of 0.01 m^2 each one
9	0.025	0.1 (upper rear)	50%PMMA + 50%PVC	105 squared of 0.01 m^2 each one
10	0.025	0.1 (upper rear)	37%PMMA + 31.5%PVC + 31.5 PE	105 squared of 0.01 m^2 each one

Table 1: Experimental configurations

The fire is ignited with a linear 0.7m propane gas burner and is positioned at the bottom of the fuel

No experimental data is used .The zero of the calculation time axis is set at the end of the incubation phase (ignition reference time ignored).

Experiment	α (kW / s^2)	k	H (m)
1	0.0469 (fast) and 0.1876 (ultrafast)	2 (top outlet vent)	1.9
2	0.0469 (fast)	2	1.9
3	0.01172 (medium)	2	1.9
4	0.01172 (medium)	2	1.9
5	0.00293 (slow) and 0.01172 (medium)	2	1.9
7	0.01172 (medium)	1 (wall outlet vent)	1.8
8	0.00293 and 0.01172	1	1.8
9	0.01172 (medium)	1	1.8
10	0.01172 (medium)	1	1.8

Table 2: Standard growth parameter, entrainment coefficient and difference in height between the air inlet and outlet

Formula and data used for the comparison

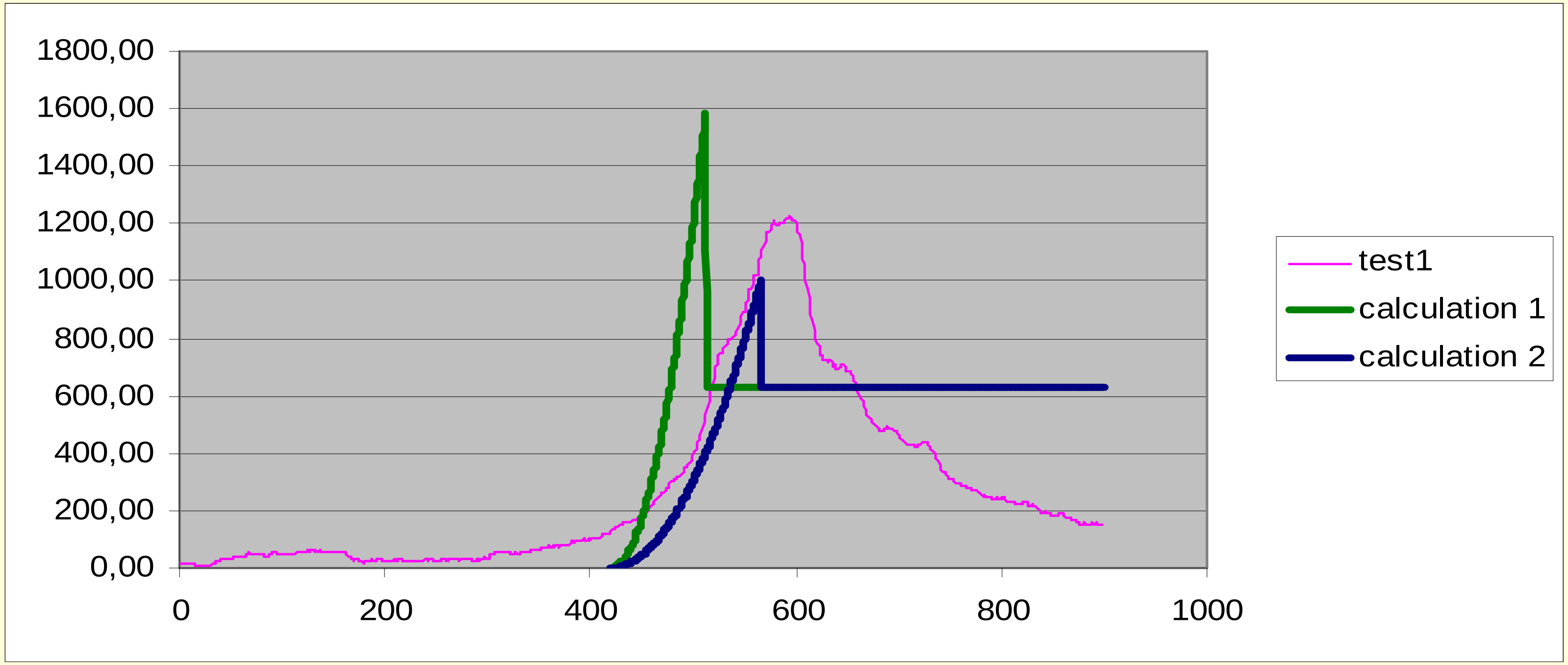
LOI = 8% and $C_e = C_i = 1$ (default values) are used to calculate

- $t_{peak} = 39.4x\left(\frac{k.V}{\alpha}\right)^{1/3}$
- $\dot{Q}_{peak} = \alpha(t_{peak})^2$
- $\dot{Q}_{max} = 9700.\frac{A_e\sqrt{H}}{1+\sqrt{1+\left(\frac{A_e}{kA_i}\right)^2}}$

The results of the comparison can be presented as follows

Influence of fire growth parameter

Data: $\alpha = 0.1876$ (ultra-fast) and $\alpha = 0.0469$ (fast) : $k = 2$ and $H = 1.90$ m: (top outlet vent)



Test 1

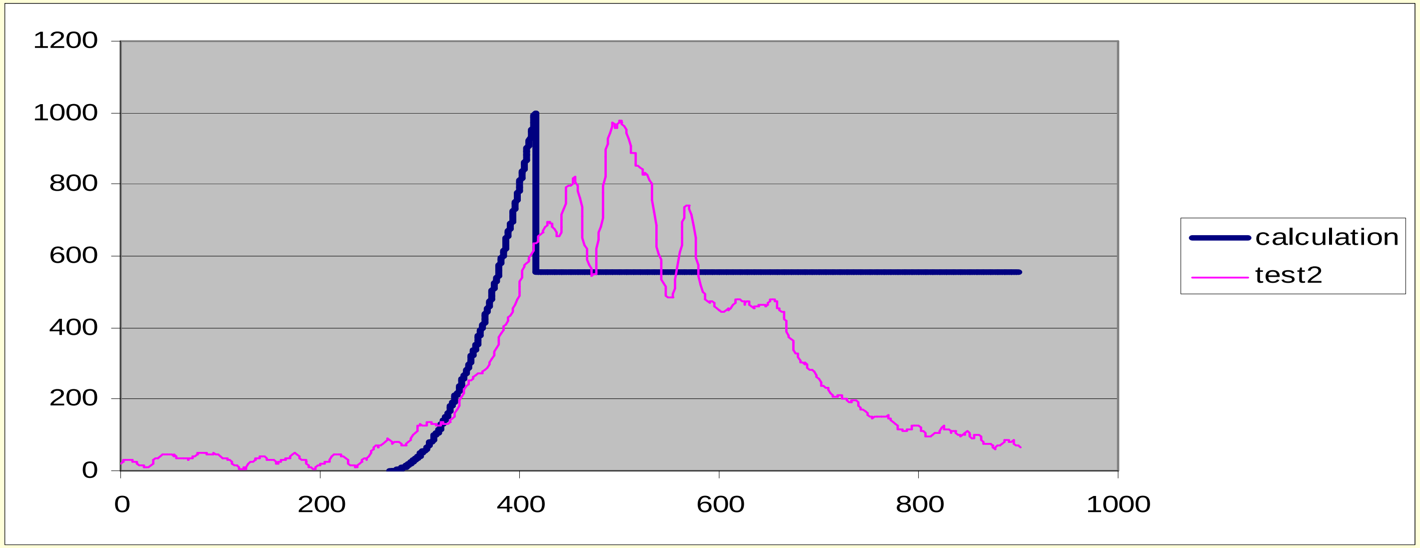
Remarks

- The early extinction has been observed after reaching the maximum HRR
- The influence of fire growth coefficient appears:

$$\alpha \uparrow \quad \Rightarrow \quad \dot{Q}_{peak} \uparrow \;, \quad t_{peak} \downarrow$$

Peak and steady state

Data: α = 0.0469 (fast) : k = 2 and H = 1.90 m: (top outlet vent)



Test 2

Remarks

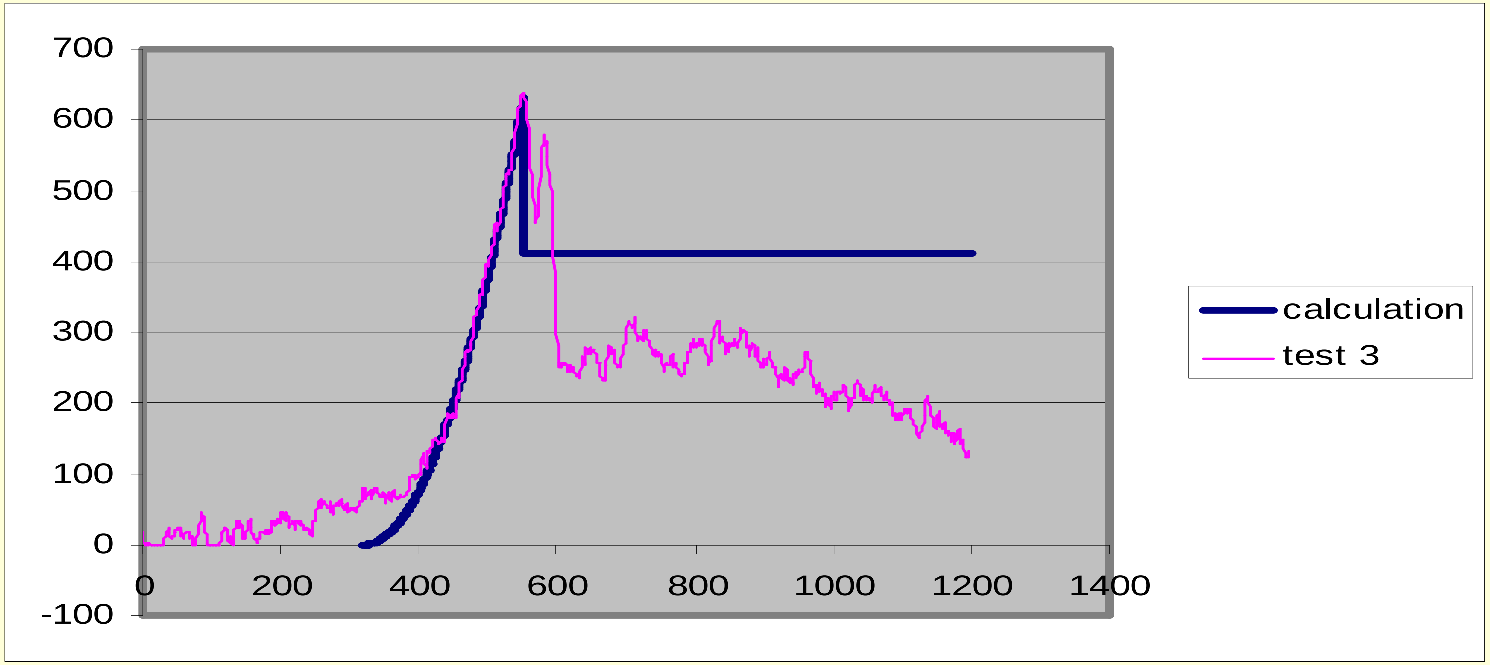
The peak of HRR is correctly estimated

The theoretical result is not conservative during the fire extinction phase for two main reasons:

- influence of fire growth factor
- “2^{nd} steady state” (?) and/or decay phase ignored in the model (junction between peak and steady state)

Maximum HRR

Data: α = 0.01172 (medium) : k = 2 and H = 1.90 m: (top outlet vent)



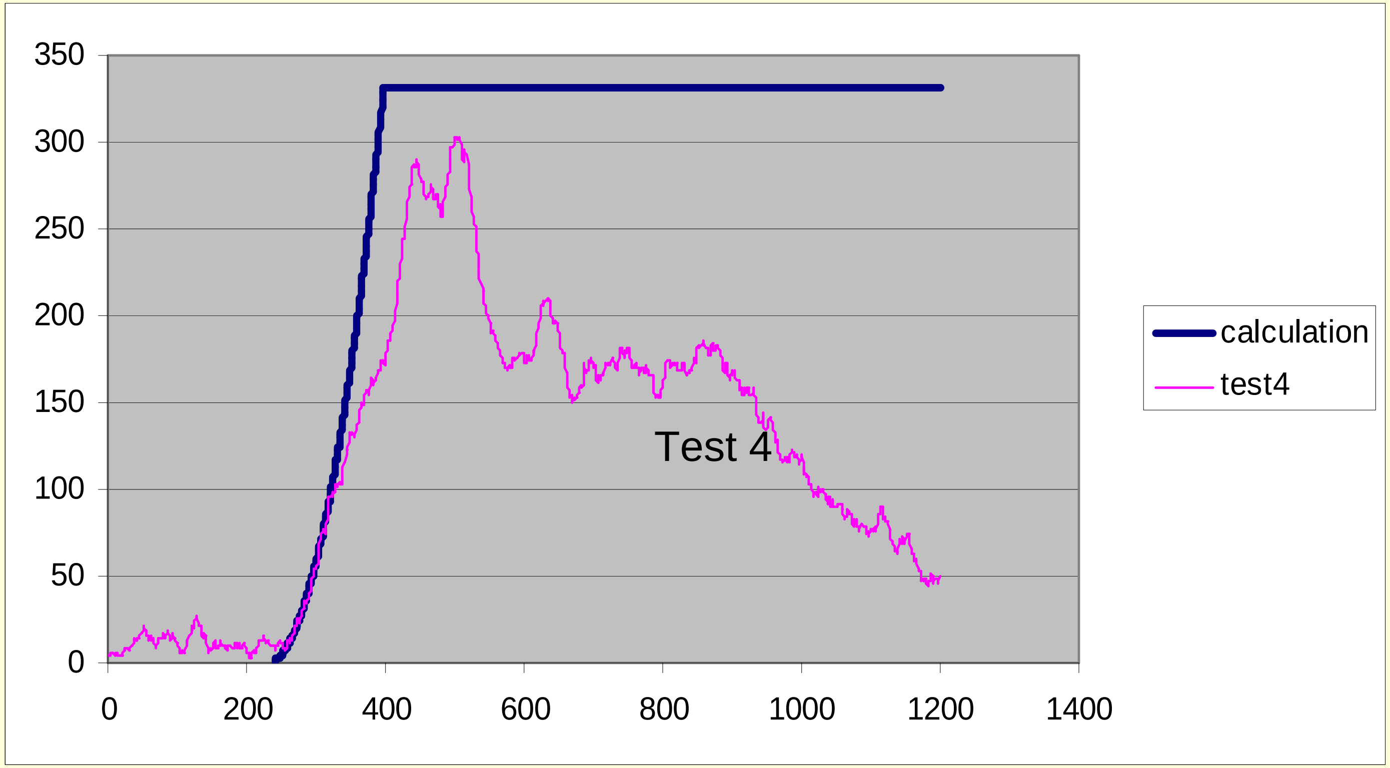
Test 3

Remarks

- Peak of HRR is correctly estimated
- Steady state HRR is overestimated: after reaching the peak, the fire doesn’t become necessary controlled by the ventilation

Steady state phase

Data: α = 0.01172 (medium); k = 2 and H = 1.90 m (top outlet vent)



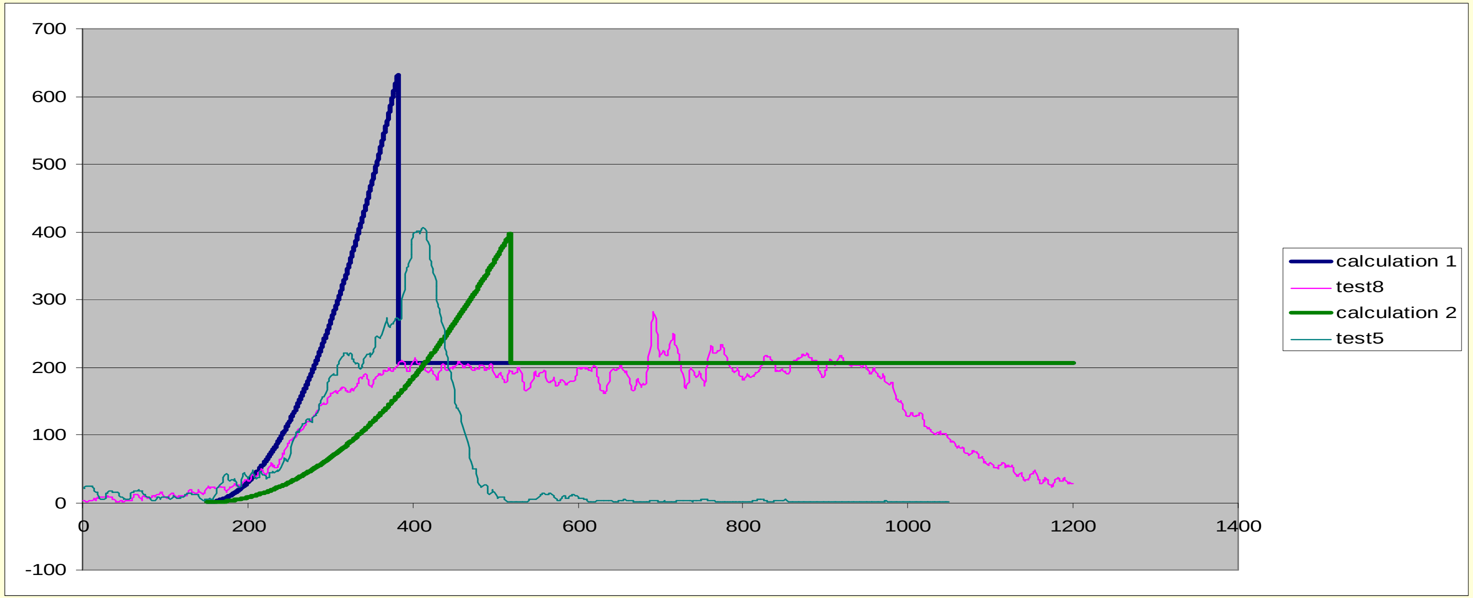
Test 4

Remarks

- Fire controlled by fuel (peak is not reached)
- Steady state HRR is overestimated (fire controlled by fuel and not by ventilation)

Influence of outlet vent location

Data test 8: α = 0.01172 (medium) and 0.00293 (slow); k = 1 and H = 1.80 m (wall outlet vent)



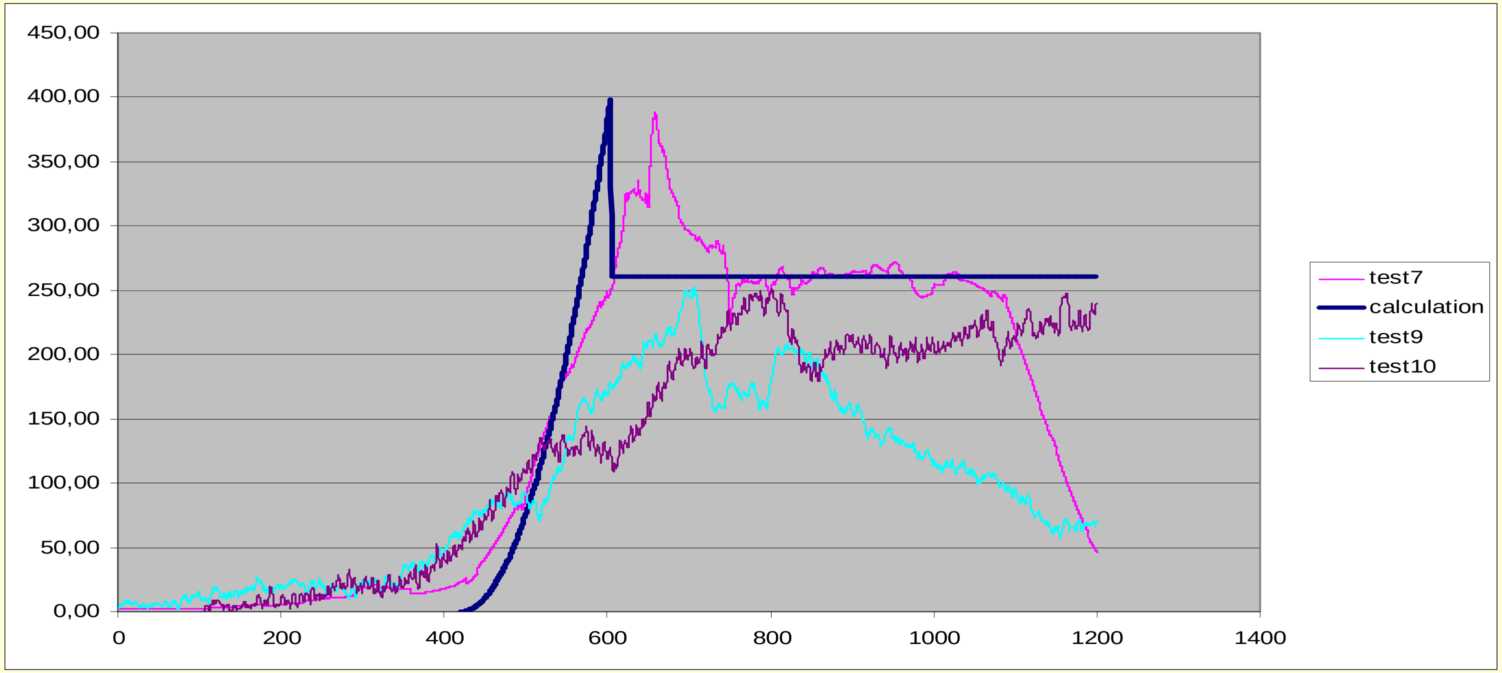
Tests 5 and 8

Remarks

- Experiment 5 (top vent area) : early extinction has been observed (plotted as an indication).
- Experiment 8 (wall vent area) : no peak has been observed
- Maximum of HRR : correctly estimated

Influence of nature of fuels and configuration

Data: α = 0.01172 (medium); k = 2 and H = 1.80 m (wall outlet vent)



Tests 7, 9 and 10

Remarks

- Great influence of nature of fuels and configurations on combustion phenomena
- HRR during the stationary phase is better predicted than that of the growth phase

CONCLUSION

A comparison of the IRSN test with the calculated data gives encouraging results.

It should be noted that calculations results are strongly conditioned by the fire growth parameter (function of all parameters such as vent flow areas, nature and configuration of fuels)

It will be necessary to complete the comparison in order to determine the weaknesses or strengths of the formula, especially in rooms of large volume.

The following formula can be recommended to be used for engineering computation

$$t_{peak} = 50.\left(\frac{V}{\alpha}\right)^{1/3} \quad ; \quad \dot{Q}_{max} = 20000.\frac{A_e\sqrt{H}}{1+\sqrt{1+\left(\frac{A_e}{2.A_i}\right)^2}}$$

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Thank you for your attention