LOCAFI+

Temperature assessment of a vertical member subjected to LOCAlised FIre
Dissemination

Grant Agreement n° 754072

4. Analytical method and validation

4. Analytical method and validation

4.1. Concept of Virtual Solid Flame

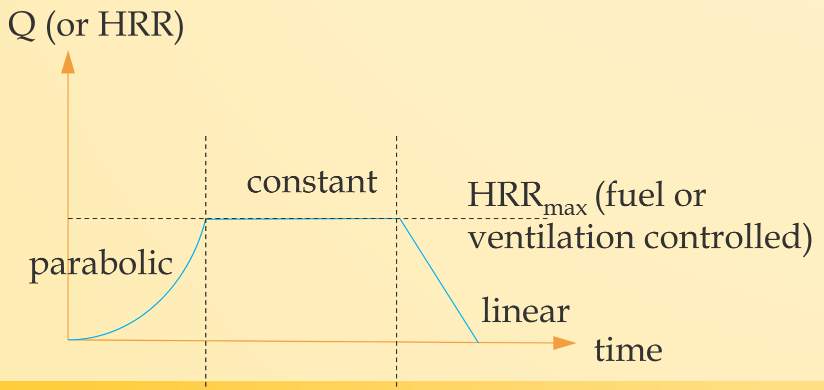
Modelling of the flame

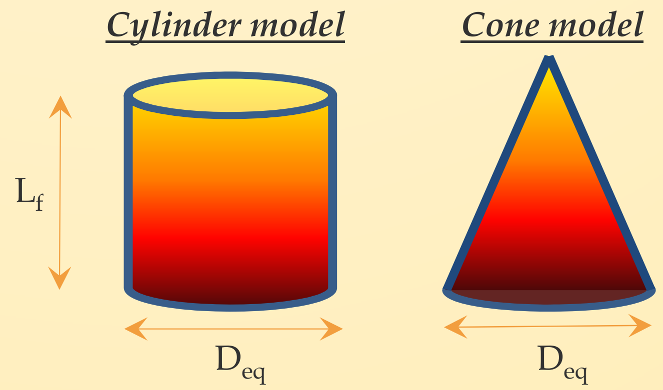
Step 1: The surface of the fire is transformed into an equivalent discus $D_{fire} = \sqrt{\frac{4.S}{\pi}}$

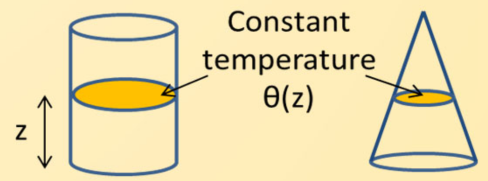
Step 2: The evolution of Heat Release Rate is calculated according to EN 1991-1-2 Annex E (growing phase, plateau, decaying phase)

Step 3: The flame length L_f is calculated by application of EN 1991-1-2 Annex C $L_f(t) = -1.02\, D_{fire} + 0.0148\, Q(t)^{0.4}$

Step 4: The action of the fire is represented by a virtual solid flame, conic or cylindric, defined by D_{eq} and L_f





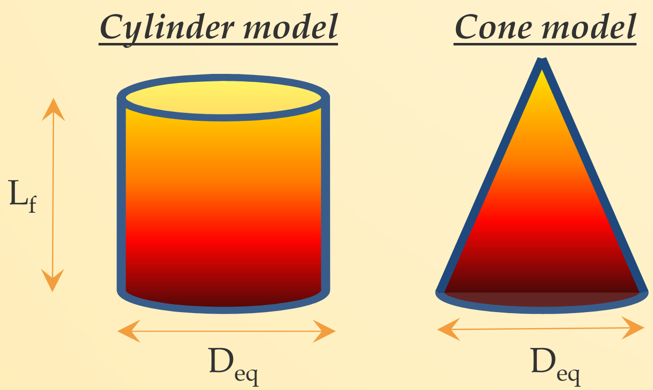


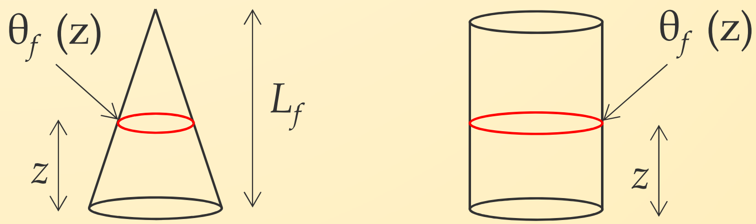
4. Analytical method and validation

4.1. Concept of Virtual Solid Flame

Modelling of the flame

If the flame does not impact the ceiling ($L_f < H_{ceiling}$ or no ceiling)





$$\theta_f(z) = \min\left(900; 20 + 0.25\big(0.8Q(t)\big)^{2/3}(z - z_0)^{-5/3}\right)$$

$$z_0 = -1.02D_{fire} + 0.00524\, Q(t)^{0.4}$$

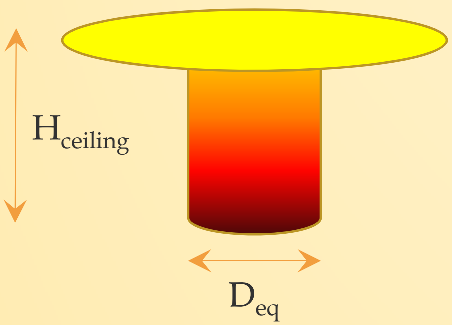
4. Analytical method and validation

4.1. Concept of Virtual Solid Flame

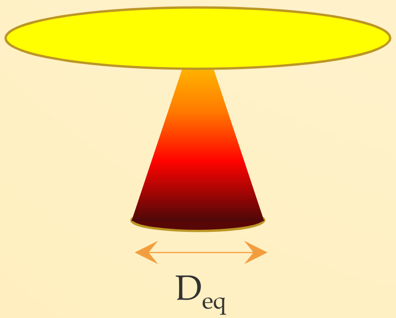
Modelling of the flame

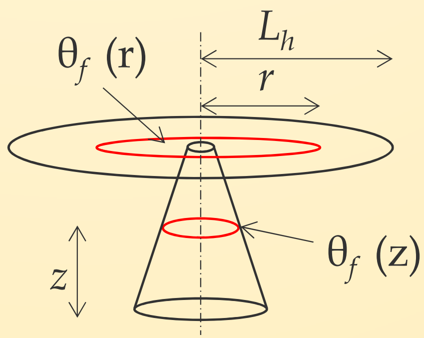
If the flame does impact the ceiling ($L_f > H_{ceiling}$)

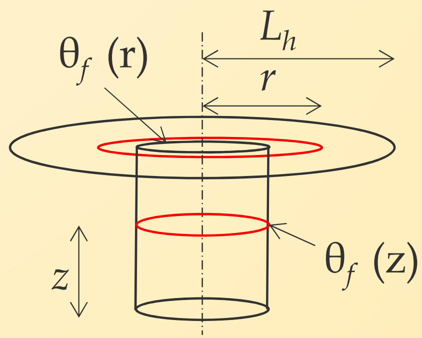
Cylinder model



Cone model







$$\theta_f(z) = \min\left(900; 20 + 0.25\left(0.8Q(t)\right)^{2/3}(z - z_0)^{-5/3}\right)$$

$$z_0 = -1.02D_{fire} + 0.00524\, Q(t)^{0.4}$$

$$L_h(t) = H\left(2.9Q(t)_H^{0.33} - 1\right)$$

$\dot{h}(r)$ *calculated from Hasemi*

$\theta_f(r)$ *satisfies to* $\dot{h}(r) = \sigma\left(\left(\theta_f(r) + 273\right)^4 - 293^4\right) + 35\left(\theta_f(r) - 20\right)$

Note : the contribution of the ring is really low, except if the member is situated in the ring → considered only for elements at the ceiling level

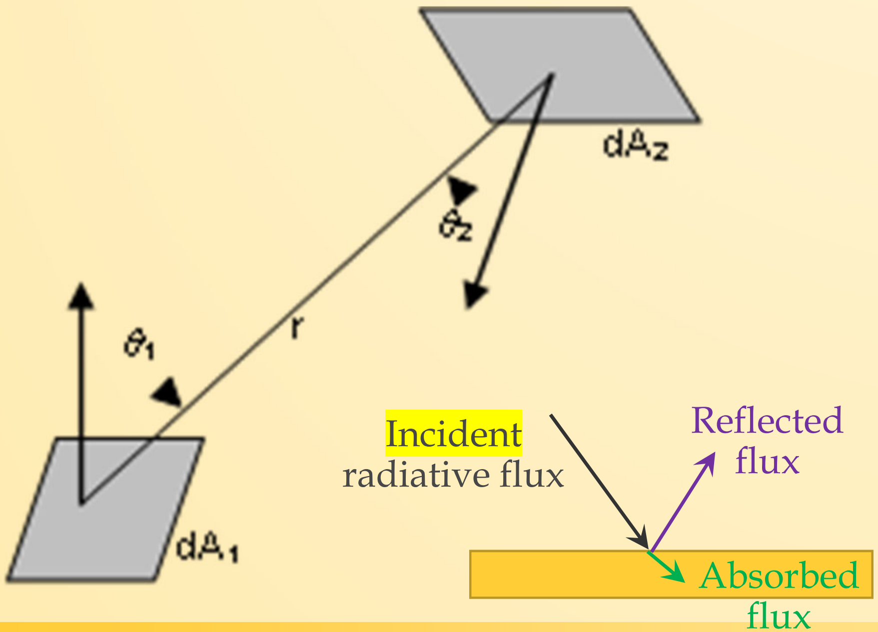
4. Analytical method and validation

4.2. Geometrical method for exchanged heat fluxes

Assessment of radiative heat fluxes

The radiative heat flux leaving a given radiating surface dA_1 and received by a surface dA_2 is :

$$\emptyset_{dA_1 \rightarrow dA_2} = \alpha_2 \varepsilon_1 \sigma . T^4 \frac{cos(\theta_1)cos(\theta_2)dA_1 dA_2}{\pi r^2}$$



- the emissivity ε_1 (of the emitting surface) is assumed equal to 1 for flames
- the absorptivity α_2 depends on the receiving surface properties
- Kirchoff Law : absorptivity (α) = emissivity (ε)
- For steel, $\varepsilon = \alpha = 0.7$

4. Analytical method and validation

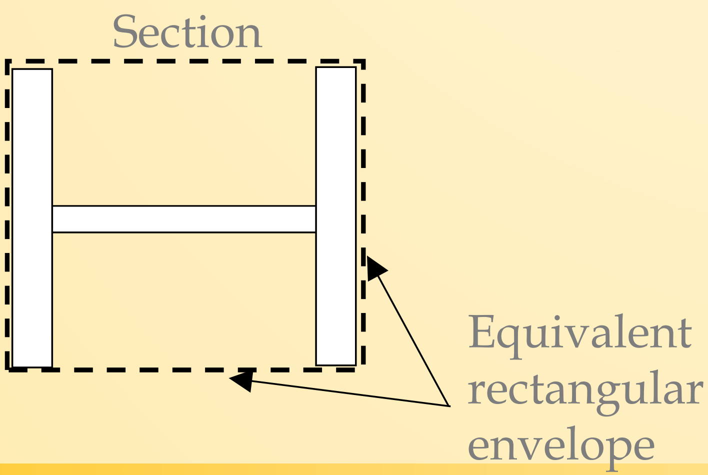
4.2. Geometrical method for exchanged heat fluxes

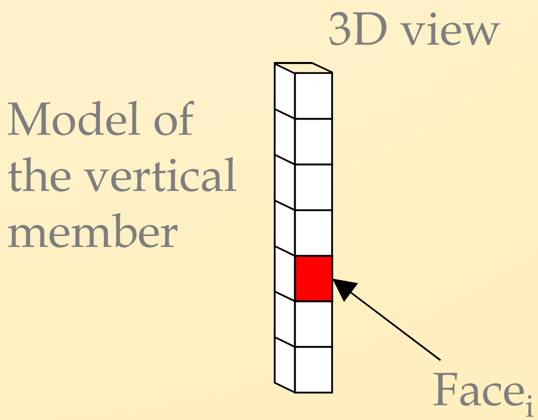
Modelling of the vertical member

Concave sections imply **shadow effect** → As a simplification, heat fluxes are calculated on a convex perimeter

For I- or H-sections, the structural member is transformed into a rectangular-shape tubular section (in line with EN 1991-1-2 Annex G)

Then, the perimeter surface is sub-divided into faces

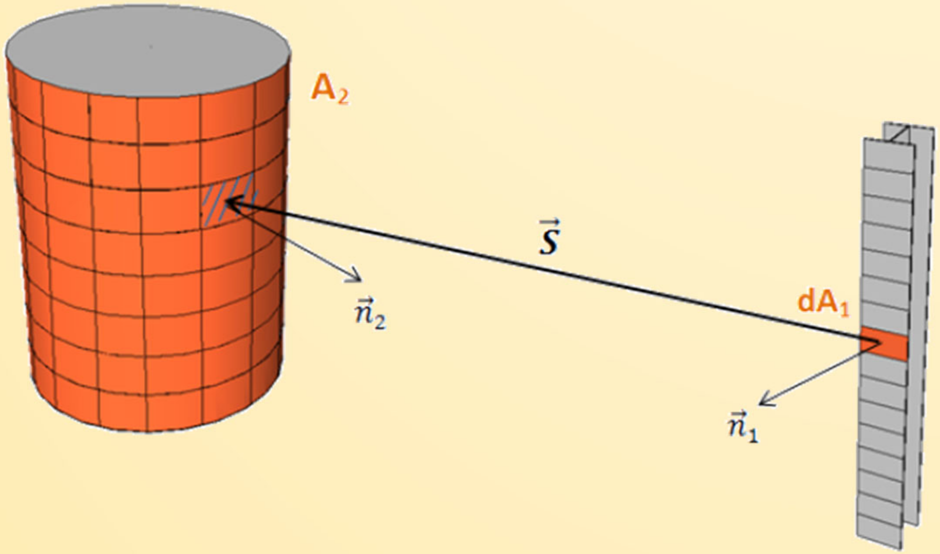




4. Analytical method and validation

4.2. Geometrical method for exchanged heat fluxes

Numerical integration



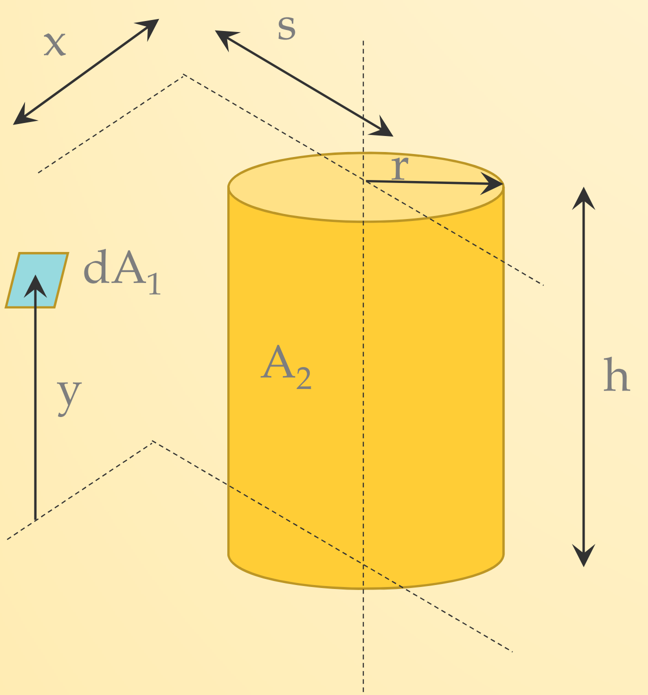
$$F_{d1-2} \simeq \frac{-1}{\pi} \sum_i \frac{(\vec{S}.\vec{n_1})(\vec{S}.\vec{n_2})}{S^4} \Delta A_i$$

- Each "individual" radiative exchange is calculated (at each time step).
- Requires a program for real applications.
- Allows applying non-uniform conditions (radiative fluxes) on the section perimeter.

4. Analytical method and validation

4.3. Simplified model

Factor view between an infinitesimal surface and a cylinder



$$F_{dA_1 \to A_2} = \frac{S}{B} - \frac{S}{2B\pi}\left\{ \begin{array}{l} cos^{-1}\left(\frac{Y^2 - B + 1}{A - 1}\right) + cos^{-1}\left(\frac{C - B + 1}{C + B - 1}\right) \\ -Y\left[\frac{A + 1}{\sqrt{(A-1)^2 + 4Y^2}} cos^{-1}\left(\frac{Y^2 - B + 1}{\sqrt{B}(A - 1)}\right)\right] \\ -\sqrt{C}\frac{C + B + 1}{\sqrt{(C + B - 1)^2 + 4C}} cos^{-1}\left(\frac{C - B + 1}{\sqrt{B}(C + B - 1)}\right) \\ +H cos^{-1}\left(\frac{1}{\sqrt{B}}\right) \end{array} \right\}$$

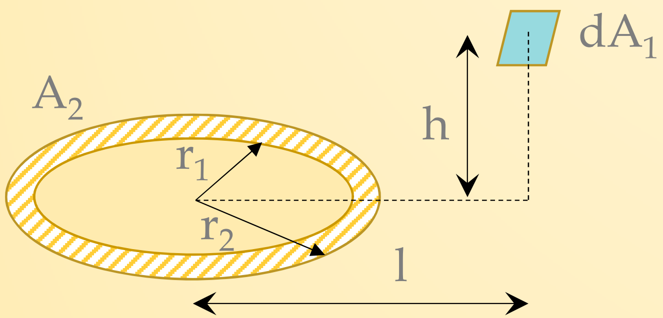
$$S = s/r$$
$$X = x/r$$
$$H = h/r$$
$$A = X^2 + Y^2 + S^2$$
$$B = S^2 + X^2$$
$$C = (H - Y)^2$$

Valid only if the plane defined by dA_1 does not intersect the cylinder !

4. Analytical method and validation

4.3. Simplified model

Factor view between an infinitesimal surface and a ring



$$F_{dA_1 \to A_2} = \frac{H}{2}\left(\frac{H^2 + R_2^2 + 1}{\sqrt{(H^2 + R_2^2 + 1)^2 - 4R_2^2}} - \frac{H^2 + R_1^2 + 1}{\sqrt{(H^2 + R_1^2 + 1)^2 - 4R_1^2}}\right)$$

$H = h/l$
$R = r/l$

Valid only if $l > r_2$!

4. Analytical method and validation

4.3. Simplified model

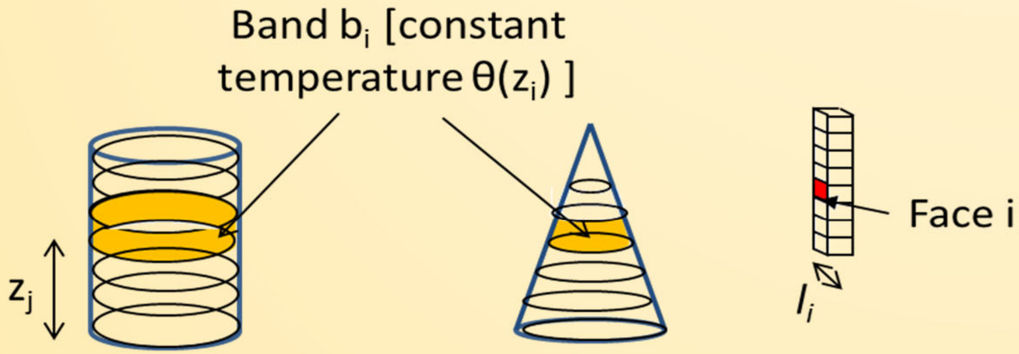
Sub-division of the flame into cylinders and rings

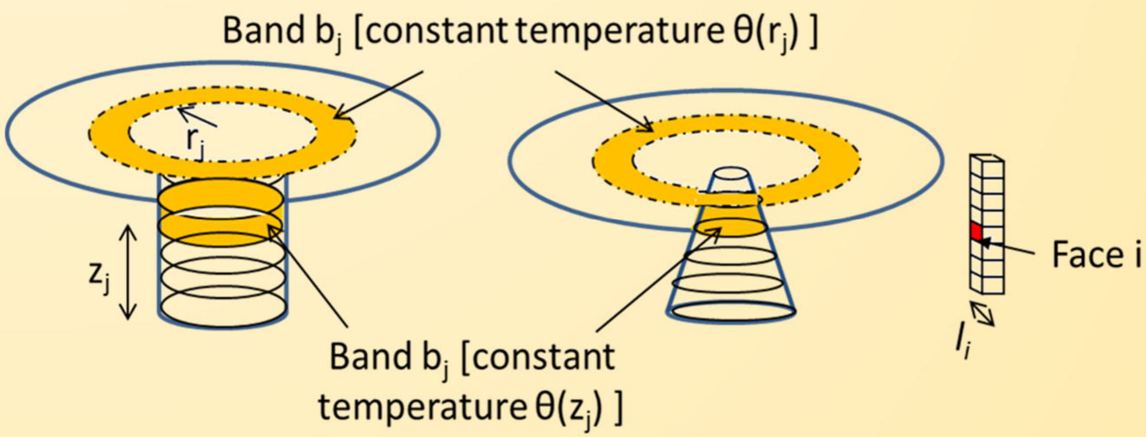
If the flame does not impact the ceiling

($L_f < H_{ceiling}$ or no ceiling)

If the flame does impact the ceiling

($L_f > H_{ceiling}$)



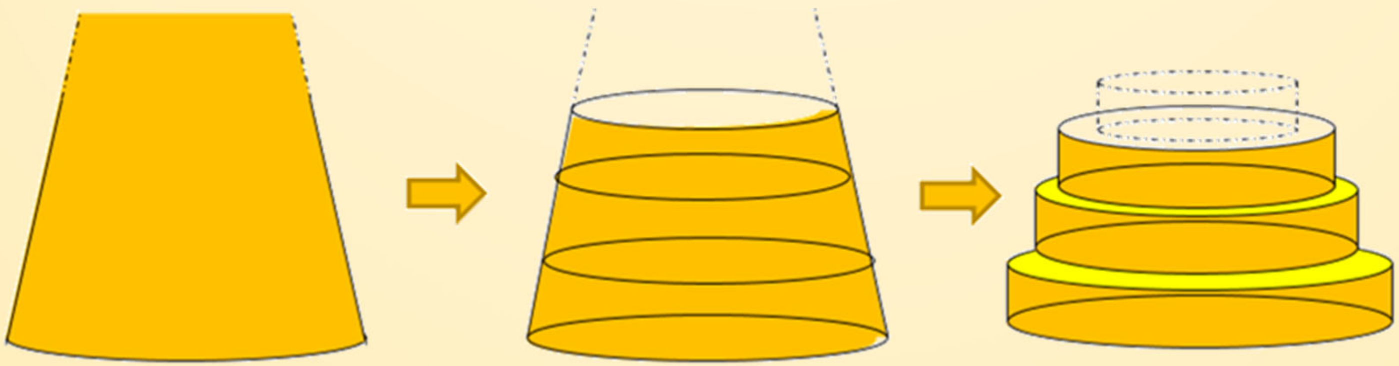


Note : the contribution of the ring is really low, except if the member is situated in the ring → considered only for elements at the ceiling level

4. Analytical method and validation

4.3. Simplified model

Sub-division of the flame into cylinders and rings (Adaptation 1)



Conical solid flame | Truncated cones | Cylinders and rings

! By neglecting the contribution of rings, we underestimate the incident flux and could even obtain a incident flux equal to 0 above the fire !

4. Analytical method and validation

4.3. Simplified model

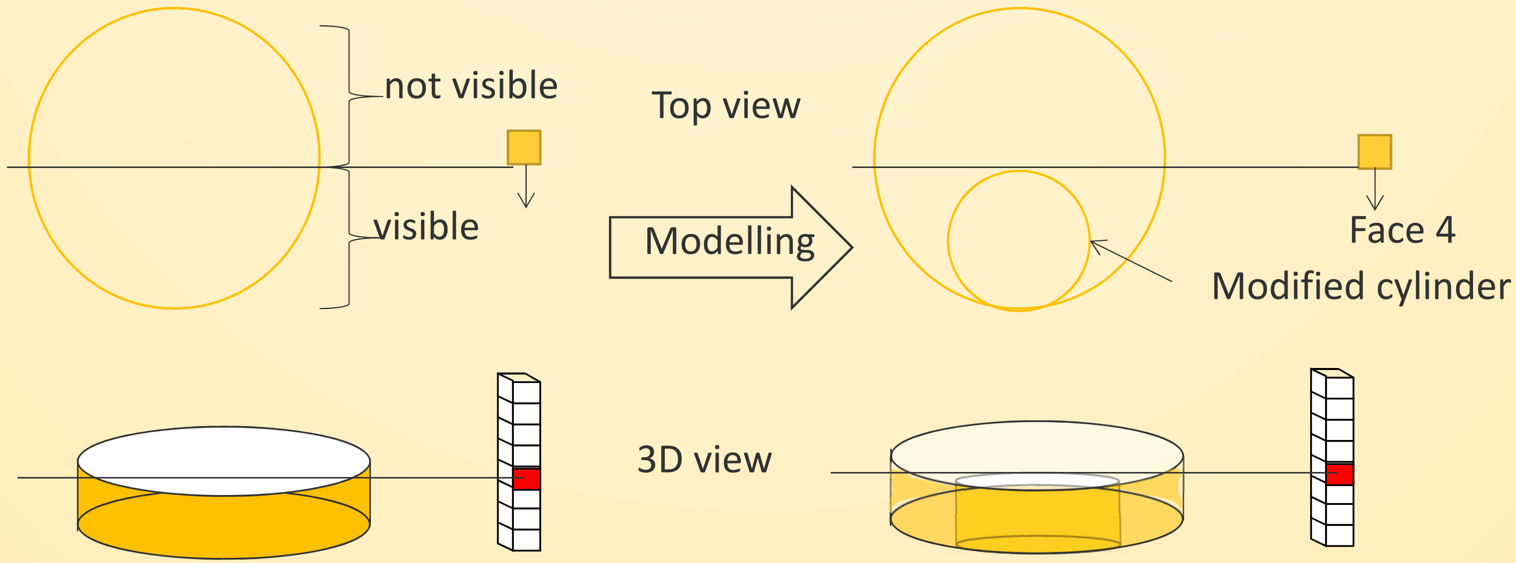
Sub-division of the flame into cylinders and rings (Adaptation 2)

! The formula for cylinder is not valid if the receiving surface intersect the cylinder !

4. Analytical method and validation

4.3. Simplified model

Sub-division of the flame into cylinders and rings (Adaptation 2)

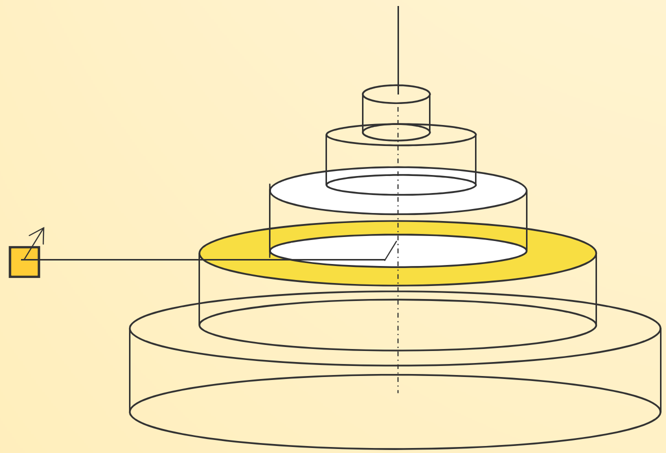


In this case, initial cylinder transformed into a modified cylinder in the visible zone

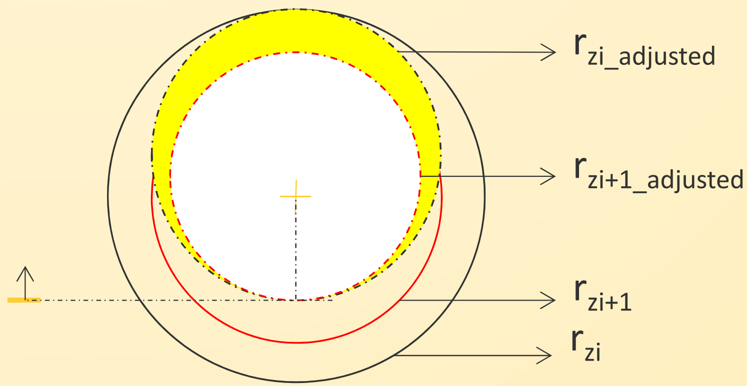
4. Analytical method and validation

4.3. Simplified model

Sub-division of the flame into cylinders and rings (Adaptation 3)



3D view



Top view

A portion of rings is « hidden » by the cylinder situated above → A reduced zone should be considered (safe-sided to ignore this reduction…)

4. Analytical method and validation

4.3. Simplified model

Additional remarks

- Recommended width of cylinder is 50 cm
- For elements situated below the ceiling, convection should be added → Hasemi
- For several fires, the fluxes received from each fire must be added. The total incident flux is limited to 100 kW/m² $\dot{h}_{tot} = min(\dot{h}_{rad\_section} + \dot{h}_{conv}; 100000)$ [W.m^{-2}]
- The member temperature is calculated by stating the thermal balance of the member

$$\rho_a c_a(T)\frac{dT}{dt} = \frac{A_m}{V}\left[\varepsilon * \dot{h}_{tot} + \alpha_c(20-\theta) + \varepsilon\left(\sigma(293^4 - (\theta+273)^4)\right)\right] \qquad [\mathrm{W.m^{-2}}]$$

ρ_a, c_a, and A_m/V are density [kg.m^{-3}], specific heat [J.kg^{-1}.K^{-1}] and massivity [m^{-1}] of the member

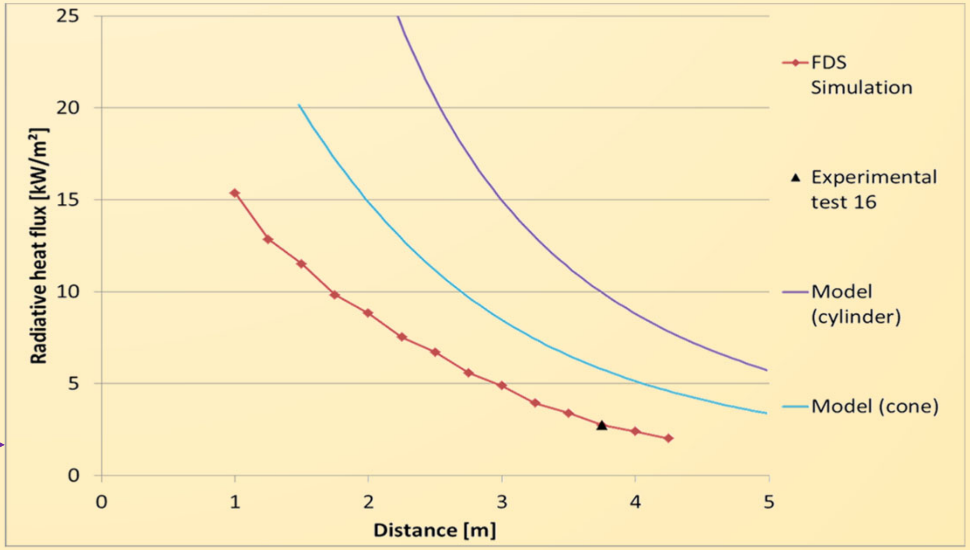
4. Analytical method and validation

4.3. Simplified model

Model validation based on Liège tests (and FDS modelling)

- Gauge situated at 3.75 m from the fire source (height : 1.75 m)
- Orientation of the gauge : perpendicular to the fire-gauge axis

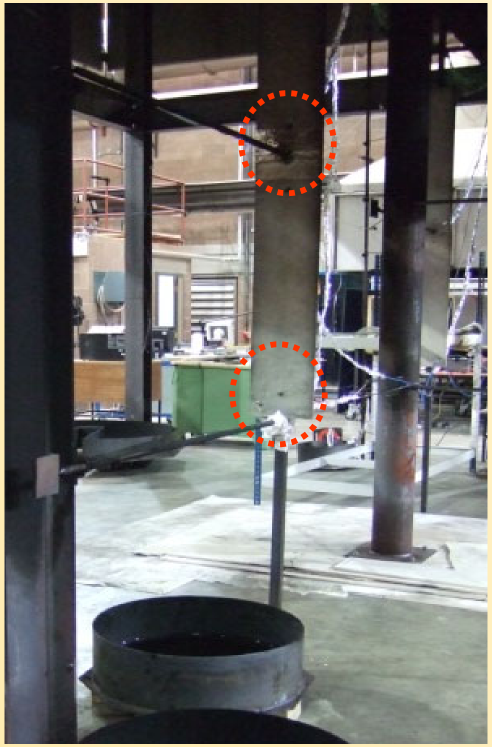
Diam.	Experiment mean value	Tests no	Cylinder flame	Conic flame
[m]	[kW/m²]	[-]	[kW/m²]	[kW/m²]
0.60	0.31	1 to 4	1.20	0.74
1.00	0.73	5 to 8	3.23	1.95
1.40	1.36	9 to 14	6.19	3.67
1.80	2.12	15 to 18	9.95	5.78
2.20	3.39	19 to 22	14.55	8.30

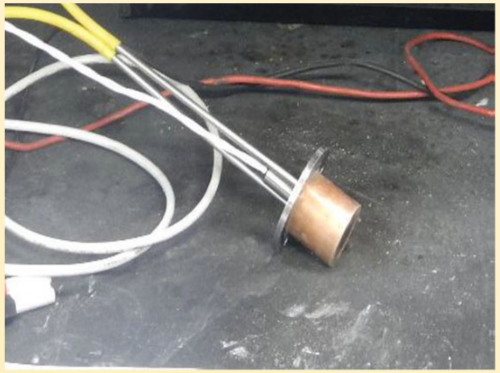


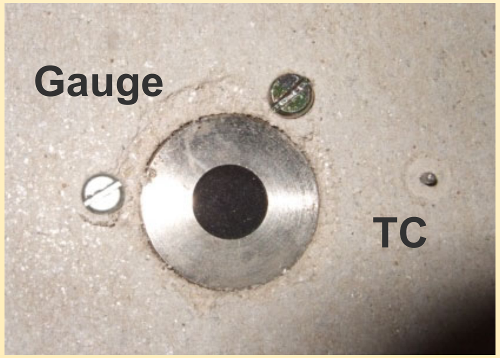
4. Analytical method and validation

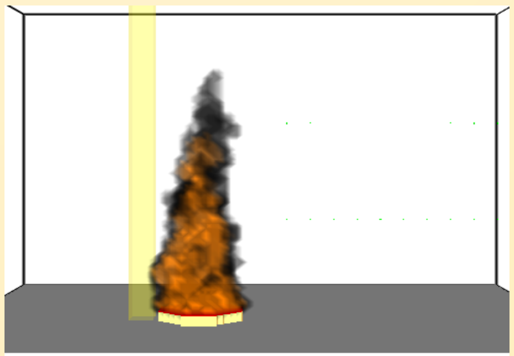
4.3. Simplified model

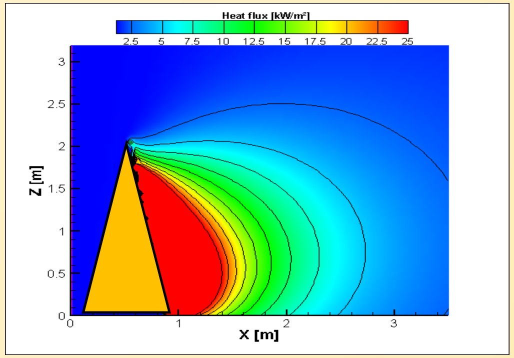
Model validation based on Ulster tests (and FDS modelling)

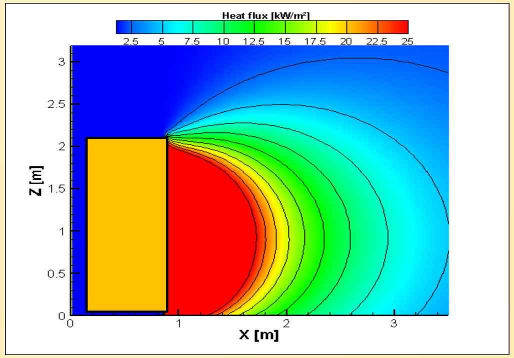








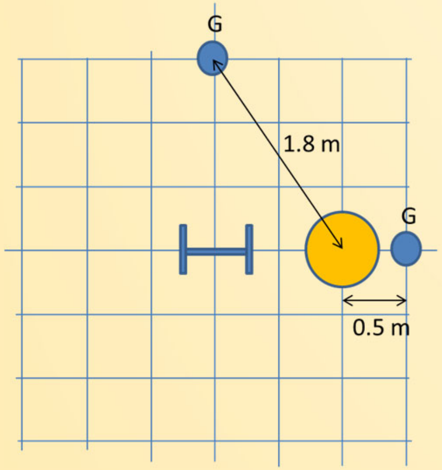




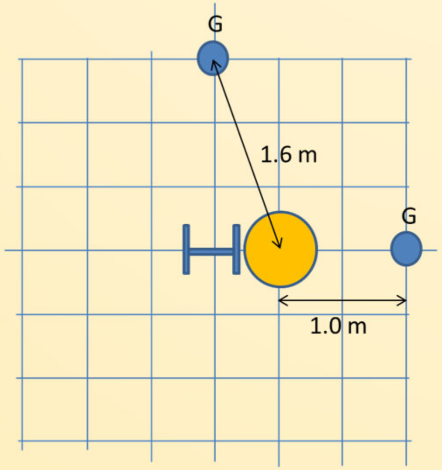
4. Analytical method and validation

4.3. Simplified model

Model validation based on Ulster tests (and FDS modelling)



Case 1a
1 pan
D = 0.7 m
Gauges at 0.5/1.8 m



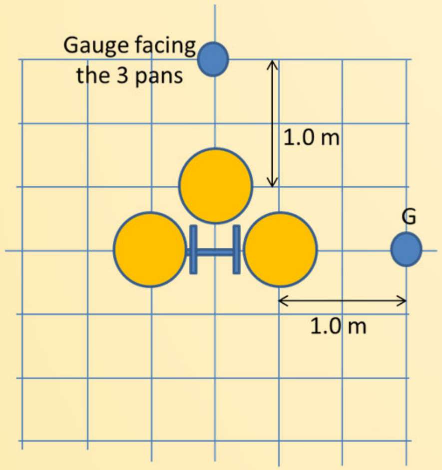
Case 1b
1 pan
D = 0.7 m
Gauges at 1.0/1.6 m

Gauge location		Experiment mean	FDS Simulation	Cylinder flame	Conic flame
Height	Distance				
m	m	kW/m²	kW/m²	kW/m²	kW/m²
1.0	0.5	30.6	28.5	74.0	39.0
1.0	1.0	13.8	12.9	33.2	17.9
1.0	1.6	5.9	5.5	15.5	8.5
1.0	1.8	4.2	3.8	10.8	6.0
2.0	0.5	6.2	11.2	22.0	5.9
2.0	1.0	4.5	5.9	14.1	5.5
2.0	1.6	3.0	3.7	8.8	4.1
2.0	1.8	2.3	2.6	6.7	3.3

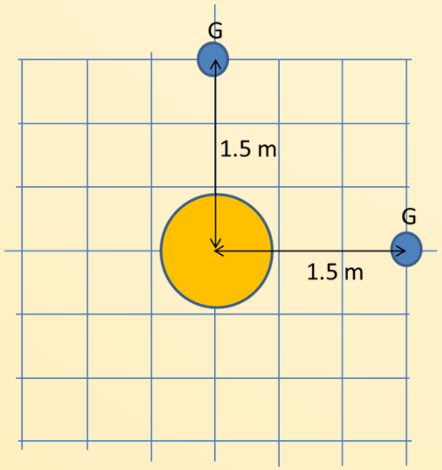
4. Analytical method and validation

4.3. Simplified model

Model validation based on Ulster tests (and FDS modelling)



Case 3
3 pans
D = 0.7 m
Gauges at 1.0 m



Case 5
1 pan
D = 1.6 m
Gauges at 1.5 m

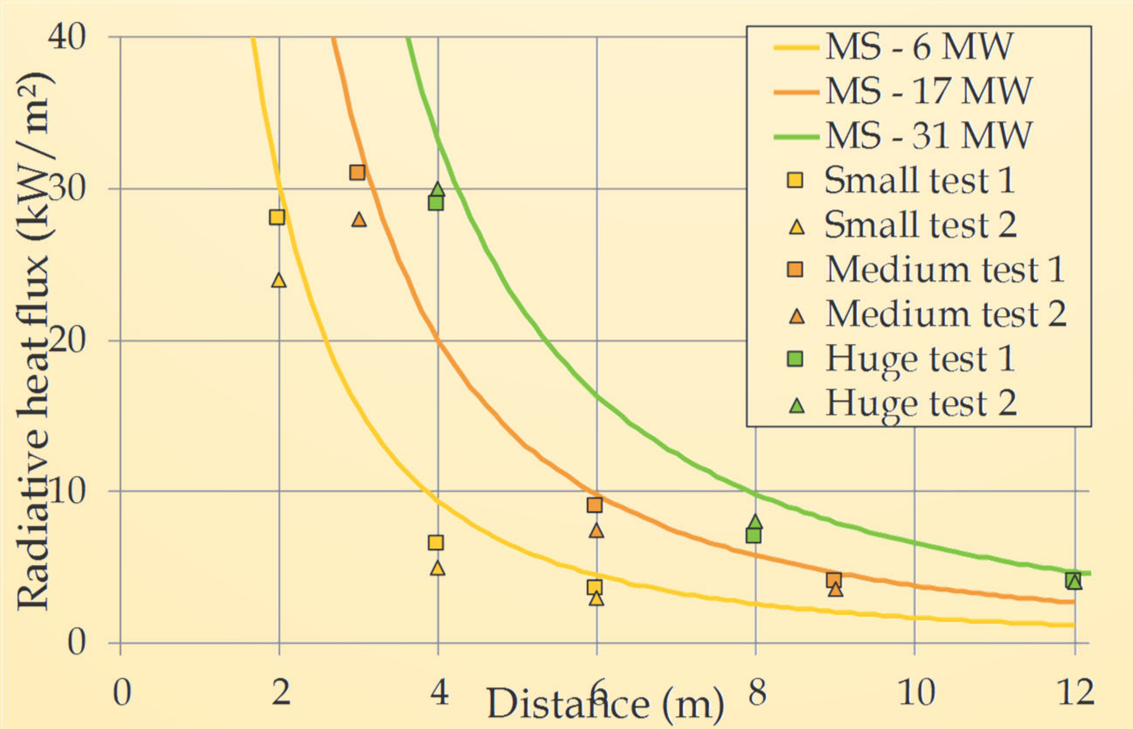
Gauge location		Experiment mean	Simulation mean	Cylinder flame	Conic flame
Height	Distance				
m	m	kW/m²	kW/m²	kW/m²	kW/m²
1.0	1.0	31.0	26.6	66.3	37.4
1.0	1.0	24.3	21.6	62.0	34.6
2.0	1.0	15.0	17.7	40.9	16.2
2.0	1.0	13.0	13.6	38.5	15.9

Gauge location		Experiment mean	Simulation mean	Cylinder flame	Conic flame
Height	Distance				
m	m	kW/m²	kW/m²	kW/m²	kW/m²
1.0	1.5	37.6	33.6	53.9	38.9
2.0	1.5	26.5	24.5	55.2	29.7

4. Analytical method and validation

4.3. Simplified model

Model validation for large diameters (LCPP tests)



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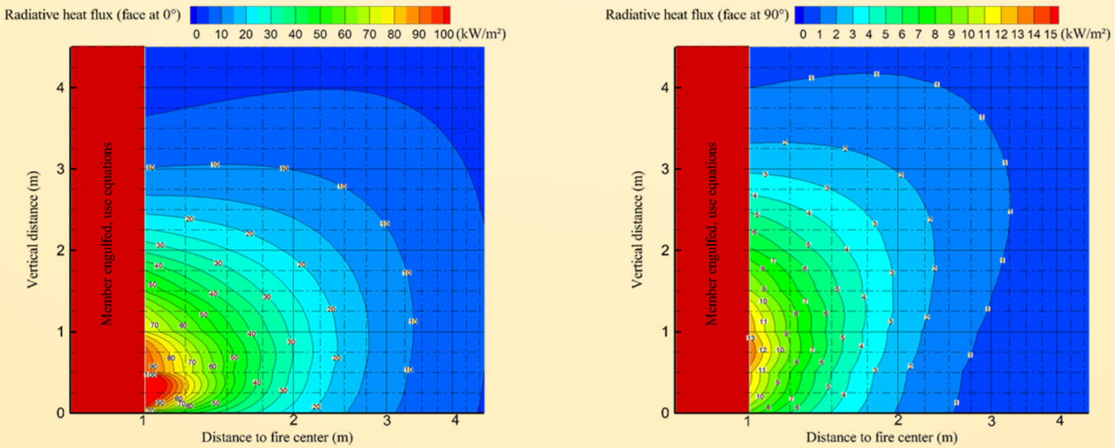
4. Analytical method and validation

4.4. Contour plots

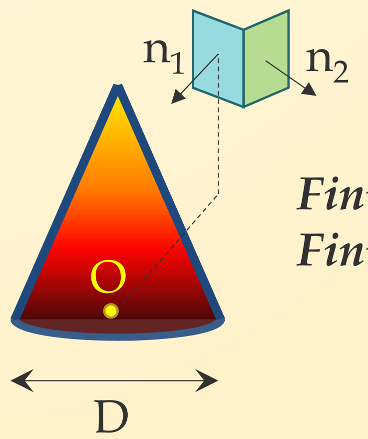
- Provide a new set of results for validation of SAFIR and OZone implementations
- Provide quick and safe results for a wide range of configurations (predesign) and an interpolation method to apply it to a much wider range of configurations
- Provide a set of reference results for validation of implementation of analytical methods by practitioners (spreadsheets or software)



D = 2m, RHR = 500 kW/m², θ = 0° (left) or θ = 90° (right)

4. Analytical method and validation

4.4. Contour plots



Finite Surface 1 : θ = 0°
Finite Surface 2 : θ = 90°

- Each nomogram is characterised by :
  - the diameter of the fire (m)
  - the RHR (kW/m^2)
  - the orientation of the receiving surface (°)
- Nomograms only account for radiation. Not used :
  - Inside the fire → HESKESTAD
  - At the ceiling level → HASEMI
- Assumes that the flame emissivity is 1.0
- Provides the incident flux, not the absorbed flux (must be multiplied by the emissivity !)

4. Analytical method and validation

4.4. Contour plots

Case	1	2	3	4	5	6	7	8	9	10	11	12
D (m)	2	2	2	2	3	3	3	3	4	4	4	4
HRR (kW/m²)	250	500	1000	1500	250	500	1000	1500	250	500	1000	1500
Power (MW)	0.8	1.6	3.1	4.7	1.8	3.5	7.1	10.6	3.1	6.3	12.6	18.8

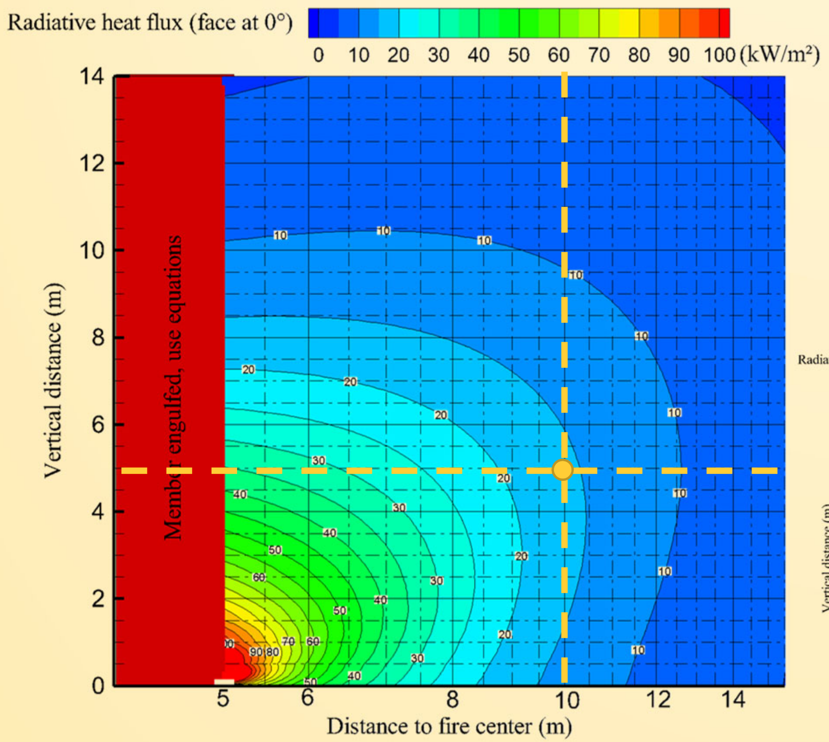
Case	13	14	15	16	17	18	19	20	21	22	23	24
D (m)	6	6	6	6	8	8	8	9	9	9	10	10
HRR (kW/m²)	250	500	1000	1500	250	500	1000	250	500	750	250	500
Power (MW)	7.1	14.1	28.3	42.4	12.6	25.1	50.3	47.7	15.9	31.8	19.6	39.3

Scope of application of the method (idem Annex C of EN 1991-1-2) : D ≤ 10 m ; Q ≤ 50 MW

→ The chosen configurations cover the field of application of the calculation method

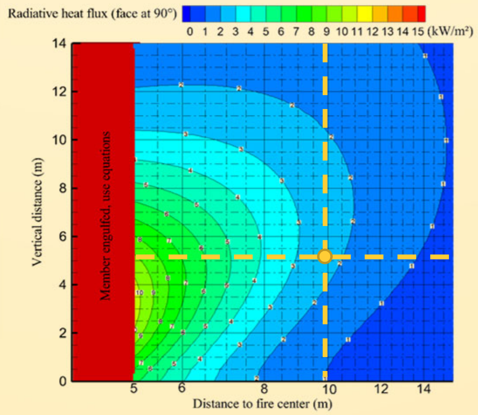
4. Analytical method and validation

4.4. Contour plots



- Localised fire characteristics :
  - D = 10 m
  - RHR : 500 kW/m^2
- Target position
  - Z = 5m
  - X = 10 m
  - Orientation : 0°

Incident Flux = 16 kW/m^2



- Target position
  - Z = 5m
  - X = 10 m
  - Orientation : 90°

Incident Flux = 2.4 kW/m^2

4. Analytical method and validation

4.5. Conclusions

- LOCAFI project introduces the new concept of Virtual Solid Flame.
- The distribution of temperature on the perimeter of the Virtual Solid Flame is based on existing equations of EN 1991-1-2 Annex C (Heskestad, Hasemi).
- The exchange of radiative fluxes is based on the configuration factor of EN 1991-1-2 Annex G.
- The simplified model is based on mathematical equations providing the radiative flux received by an infinitesimal surface from cylinders and rings.
- The convective fluxes must be calculated separately. However, convective heat fluxes have a significant effect only in configurations already covered by EN 1991-1-2 Annex C (members engulfed into fire or situated at the ceiling level).