FACULTY OF ENGINEERING
AND ARCHITECTURE

DEPARTMENT OF STRUCTURAL ENGINEERING AND BUILDING MATERIALS
FIRE SAFETY SCIENCE AND ENGINEERING

INTRODUCTION TO FIRE SAFETY SCIENCE AND ENGINEERING

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A SHORT MOVIE TO GET STARTED

- https://www.youtube.com/watch?v=lQZ_fv_NhAk

REFERENCES

- D. Drysdale, *An Introduction to Fire Dynamics*, 3rd Ed., Wiley (2011).
- J.G. Quintiere, *Fundamentals of Fire Phenomena*, Wiley (2006).
- The SFPE Handbook of Fire Protection Engineering (2016).
- B. Merci and T. Beji, ‘Fluid Mechanics Aspects of Fire and Smoke Dynamics in Enclosures’, CRC Press (2016).

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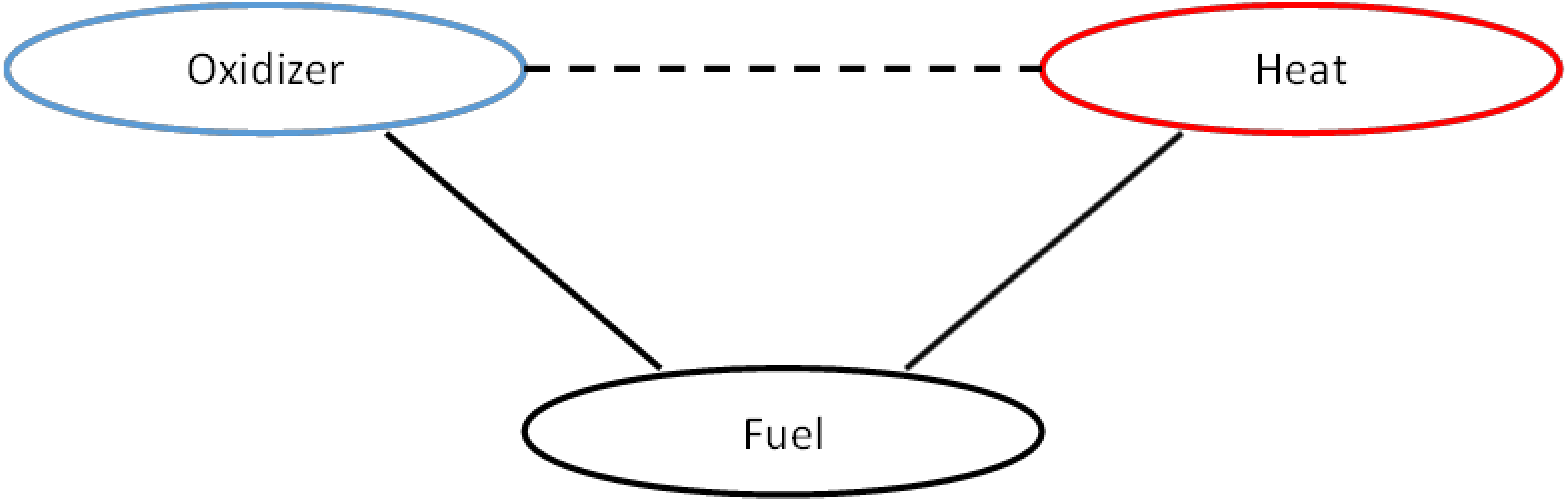
CONTENTS

- Ignition
- Fire growth
- Compartment fire dynamics
- The importance of the flow field
- There's (much) more

IGNITION

FIRE TRIANGLE

– Necessary ingredients: fire triangle.

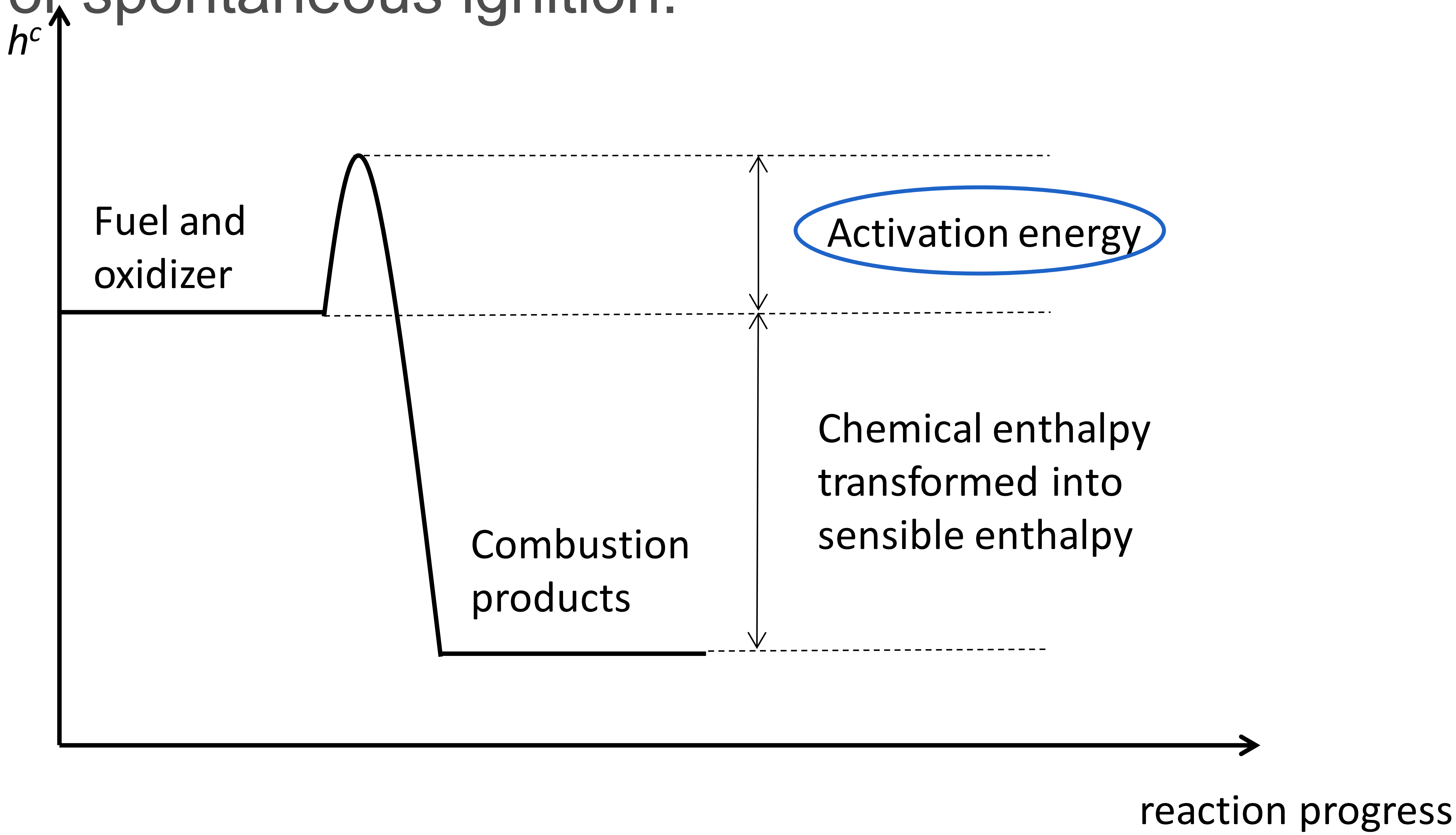


FIRE TRIANGLE

- Fuel: anything that can burn.
- Oxidizer: oxygen concentration in air is sufficient to sustain burning.
- Heat: ignition required. After that: heat flux from flames (and perhaps smoke and compartment boundaries).

THERMODYNAMICS

- Ignition is required to overcome ‘activation energy’.
- Piloted or spontaneous ignition.



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PILOTED IGNITION

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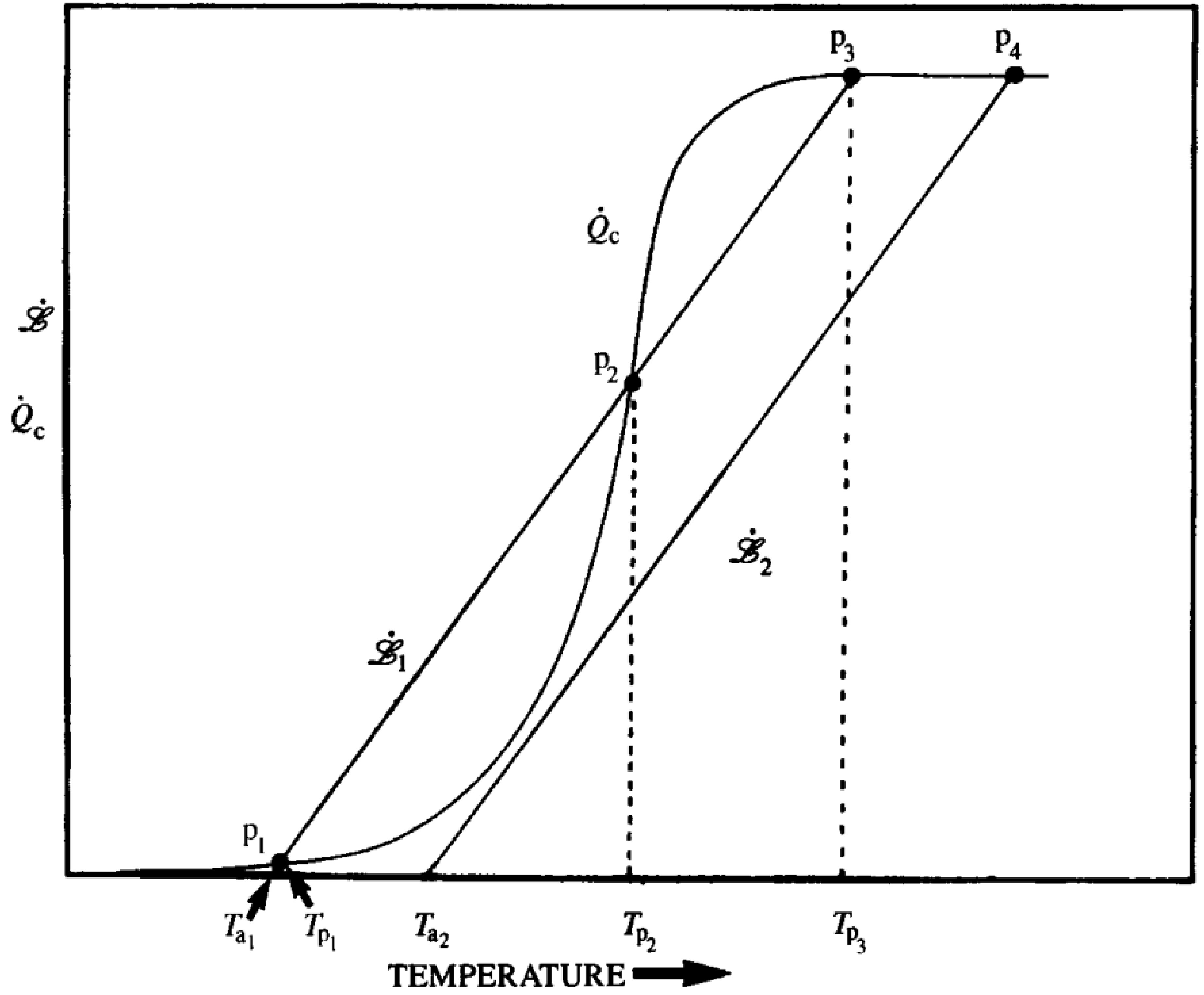
IGNITION OF GASES

- Imbalance between HRR and heat loss rate.



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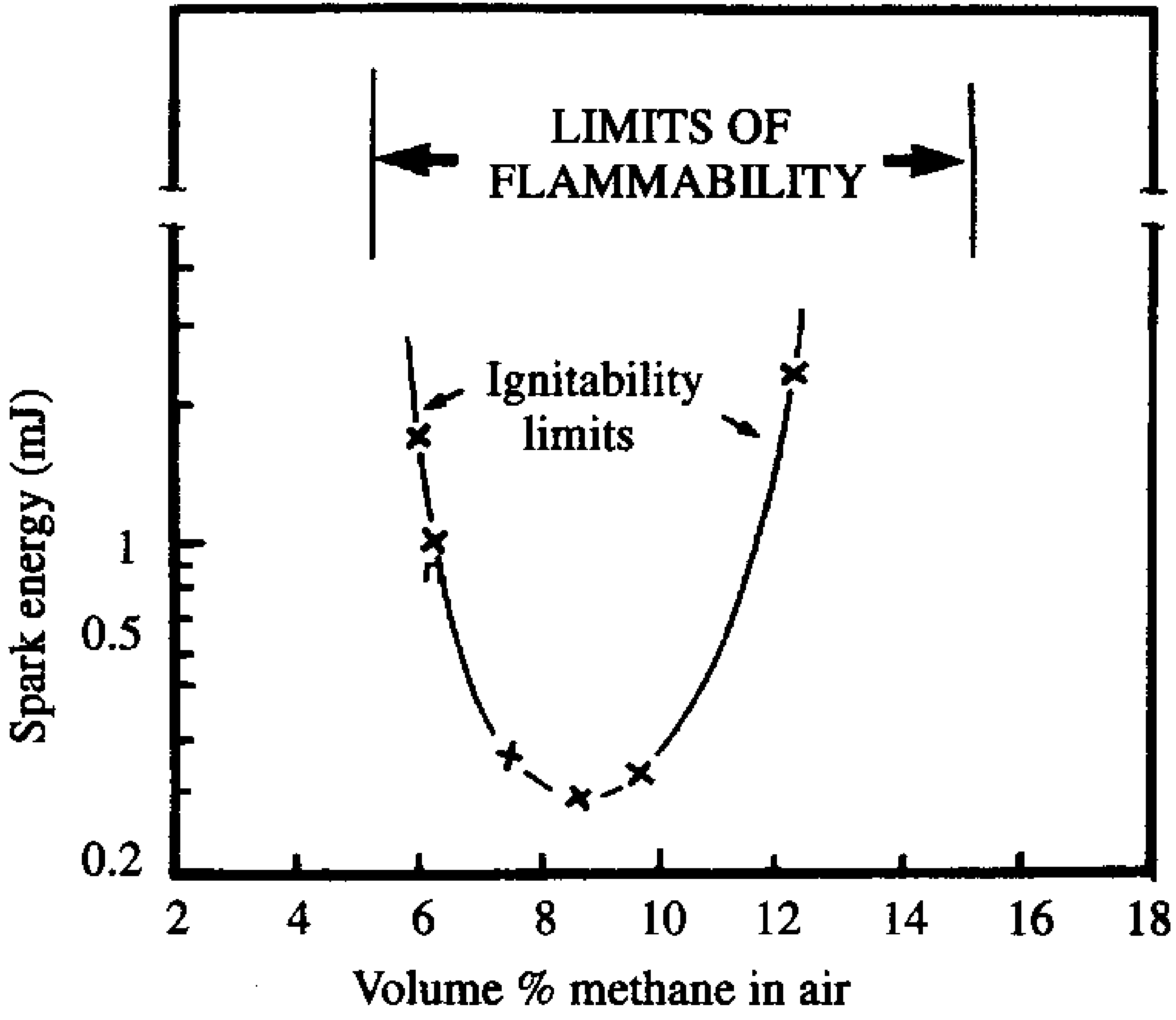
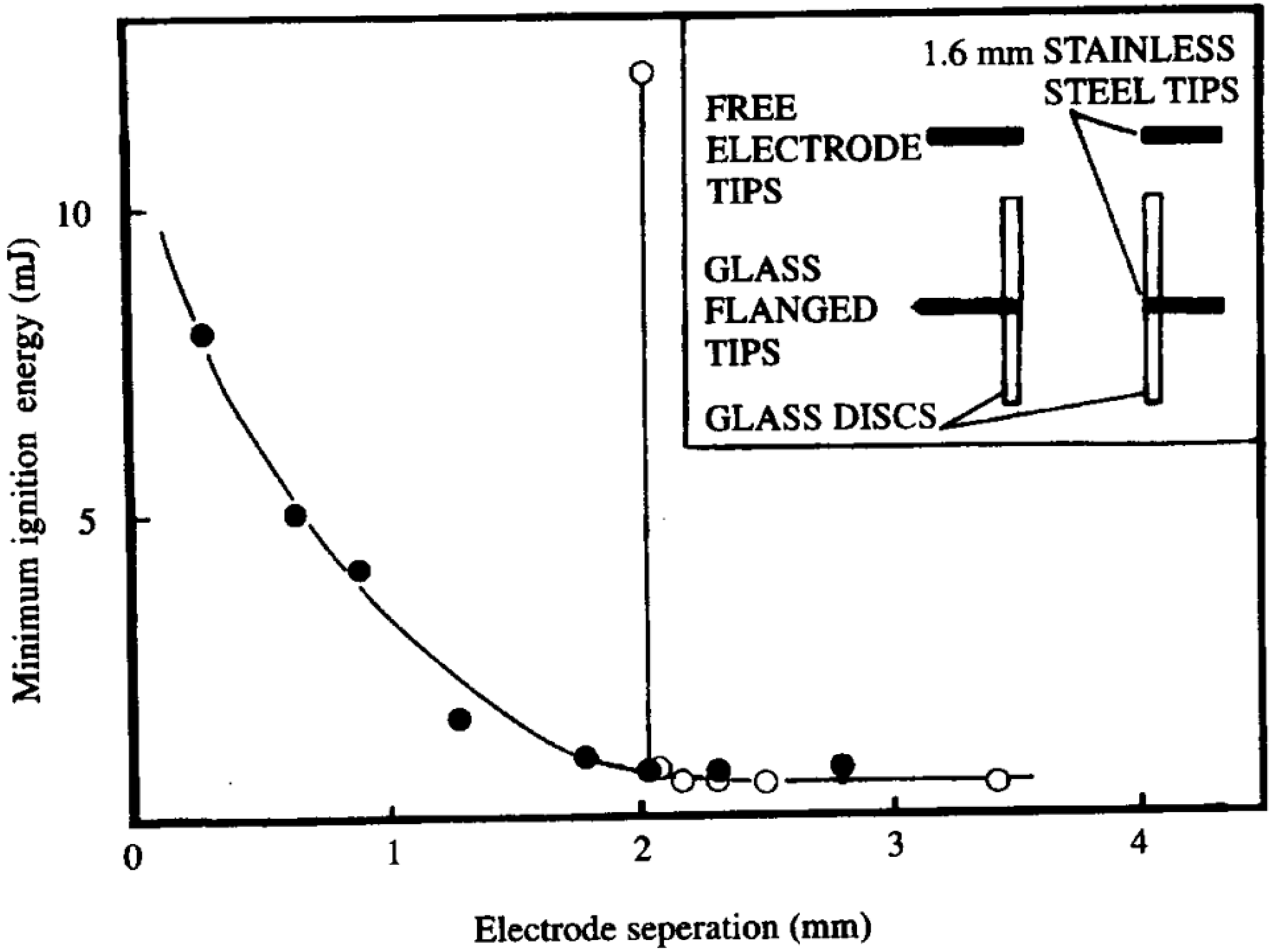
FLAMMABILITY LIMITS

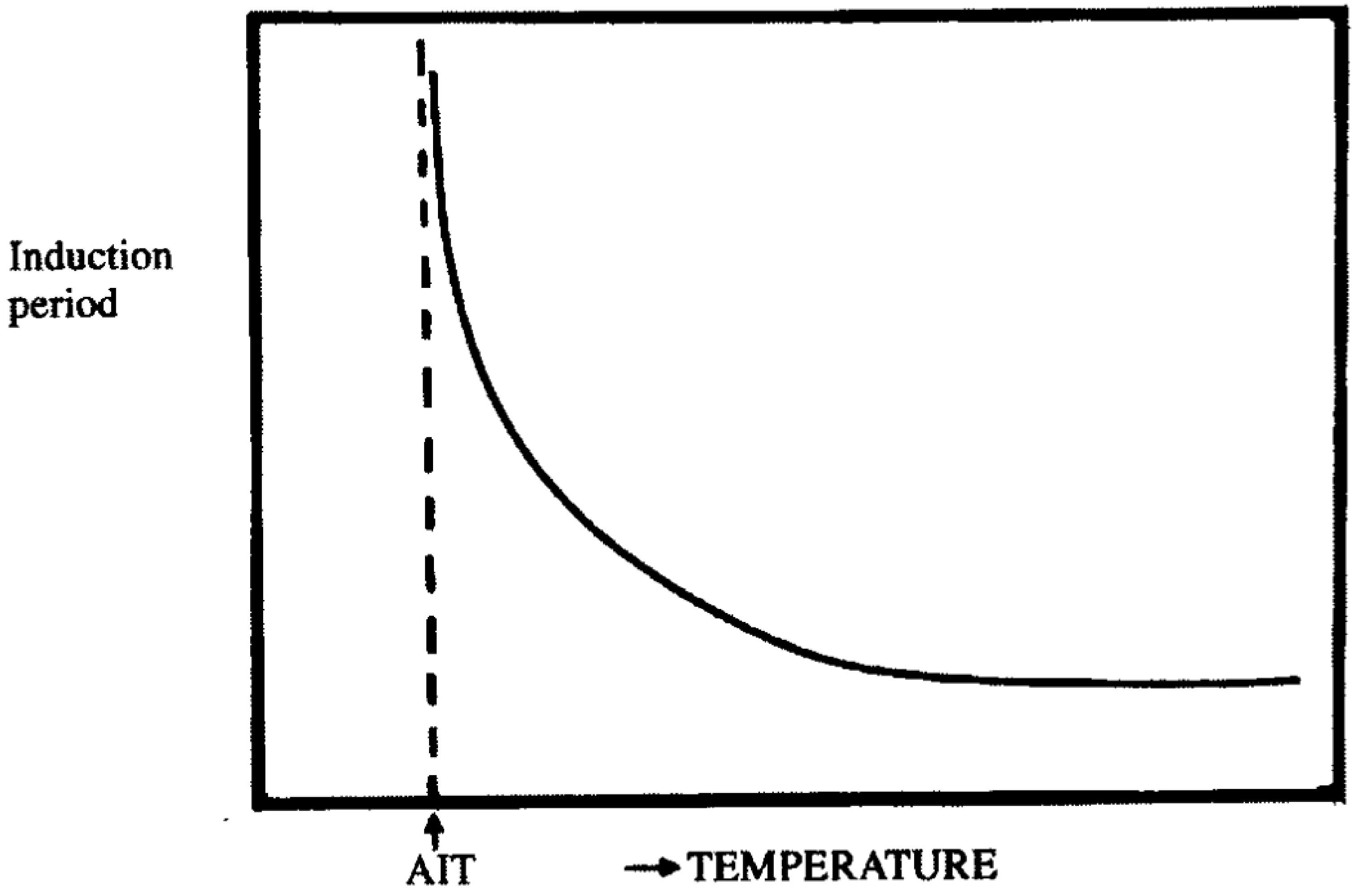
- Optimum for combustion: around stoichiometry.



IGNITION OF GASES

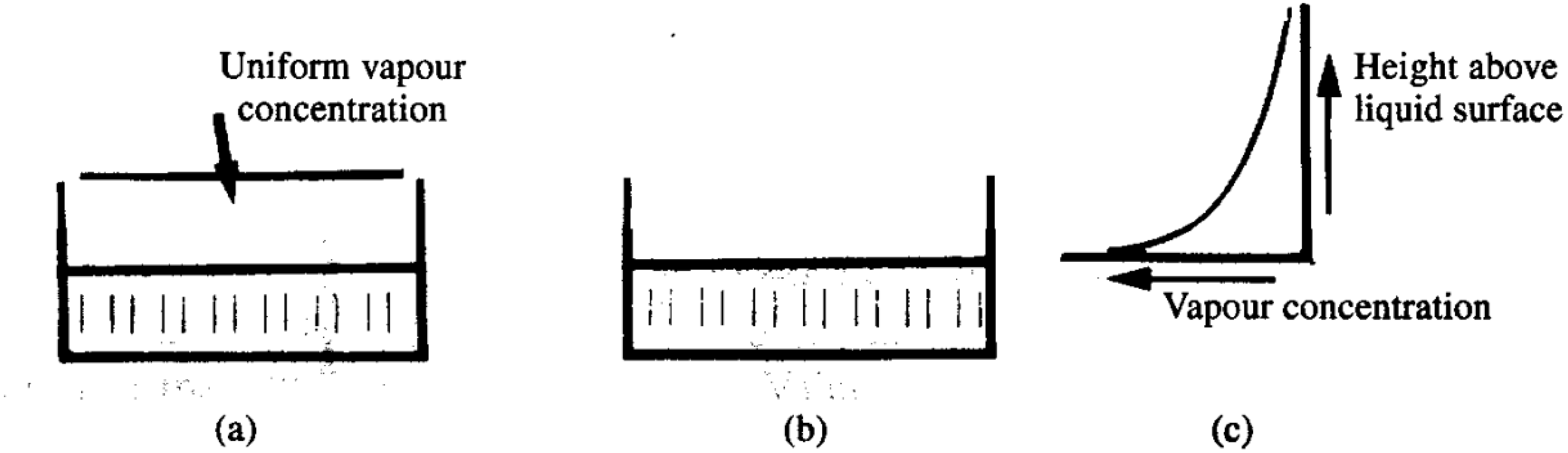
- Details matter.
- Above AIT: spontaneous ignition.





IGNITION OF LIQUIDS

– Combustible liquids are classified by their ‘flashpoint’: the lowest temperature at which a flammable vapour/air mixture exists at surface.



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IGNITION OF SOLIDS

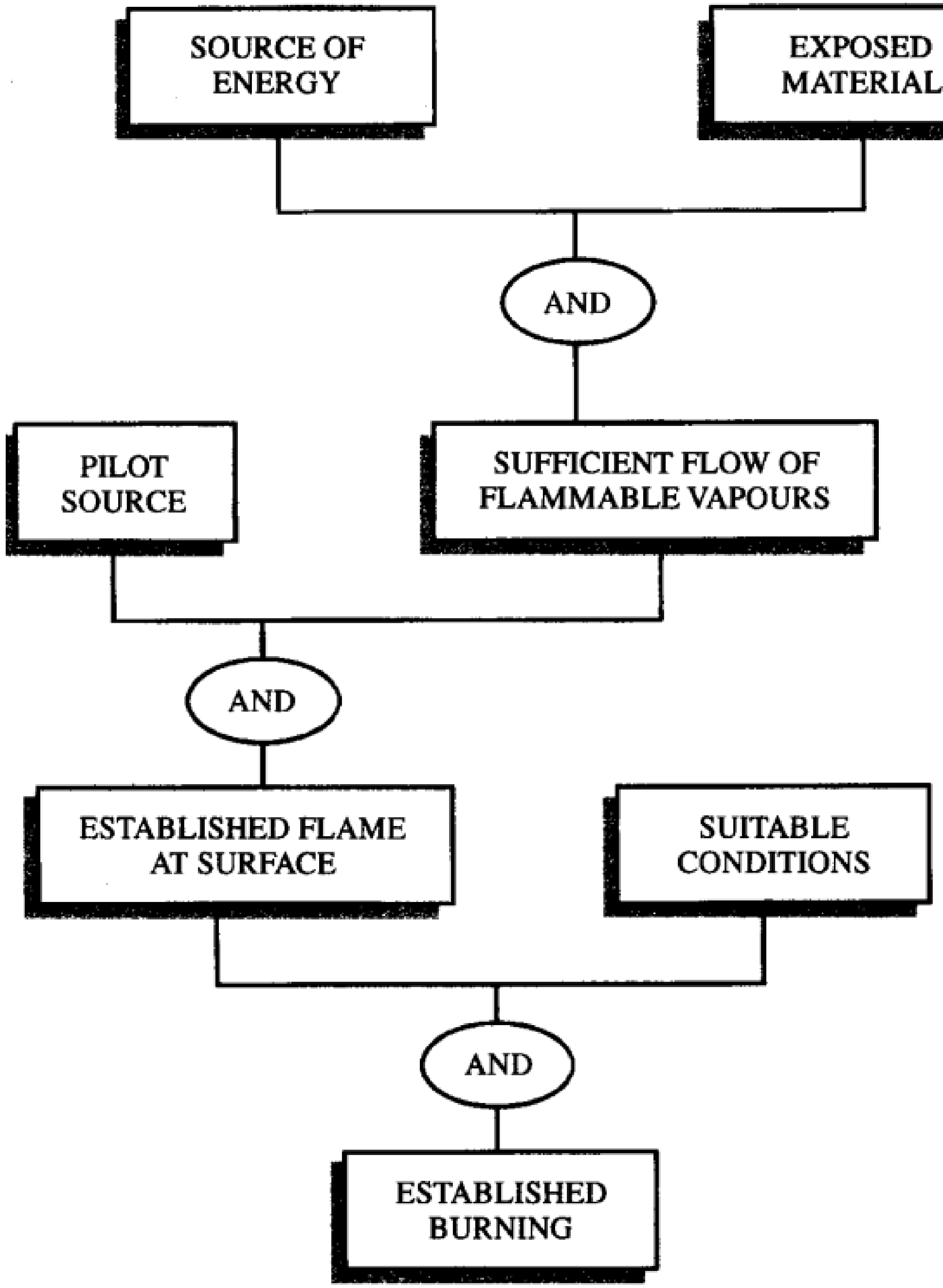
– There is no direct equivalent for the ‘flashpoint’: pyrolysis is irreversible.

– Still: reasonably similar phenomena (for flaming combustion) → ‘ignition temperature’ (note: this is NOT a material property).

– The mass flow rate must be sufficient to sustain combustion (‘critical mass flow rate’).

– Critical heat flux: no ignition below that (incoming) heat flux.

IGNITION OF SOLIDS



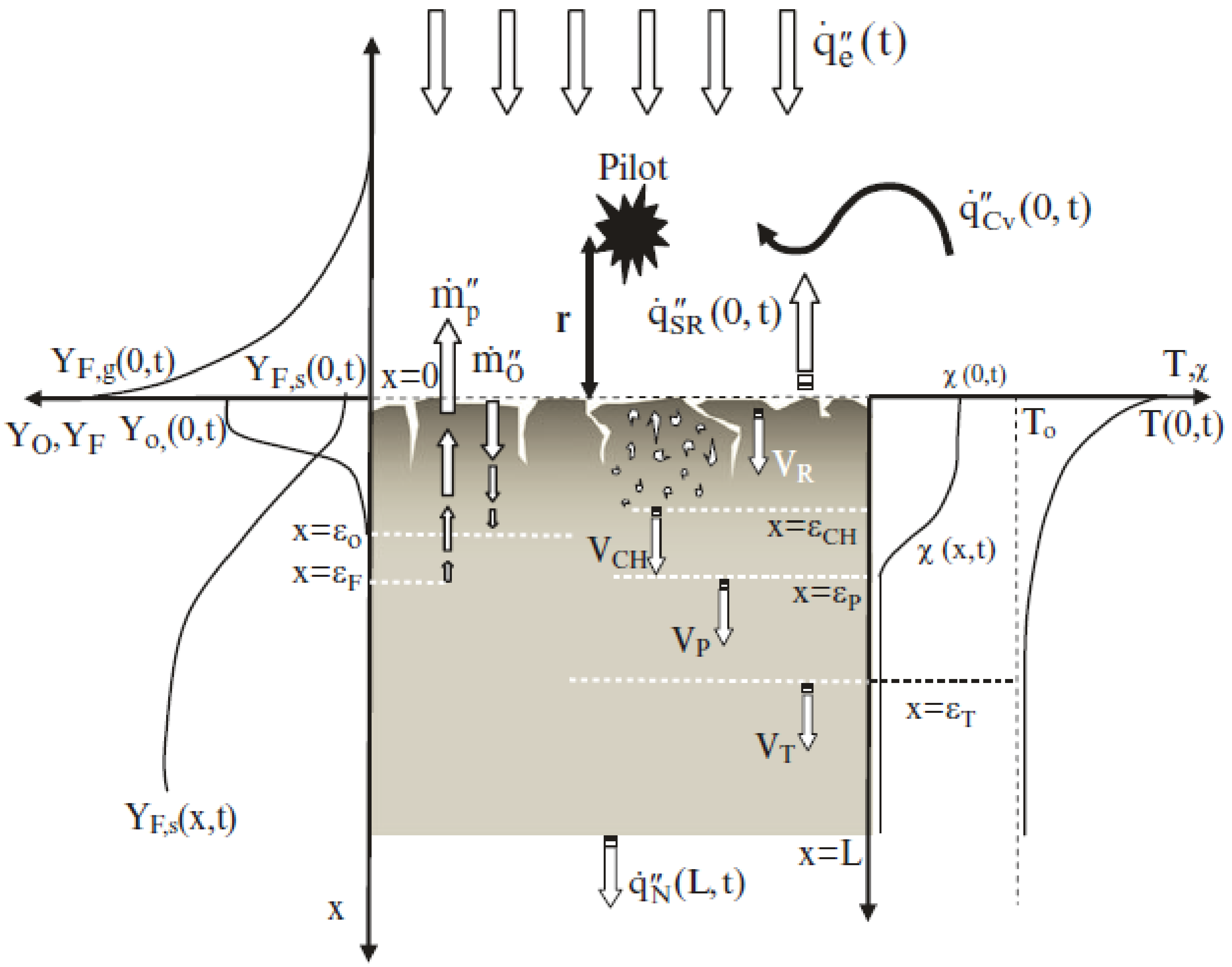


Fig. 21.1 Schematic of the different processes occurring as a material undergoes degradation prior to ignition induced by an external source of heat

FIRE PROPAGATION APPARATUS (FPA)

- Developed at FM Global.
- Uses CDG (carbon dioxide generation) and OC (oxygen consumption) calorimetry to determine HRR (see later).
- Measures flammability characteristics under various air flow (ventilation) conditions.

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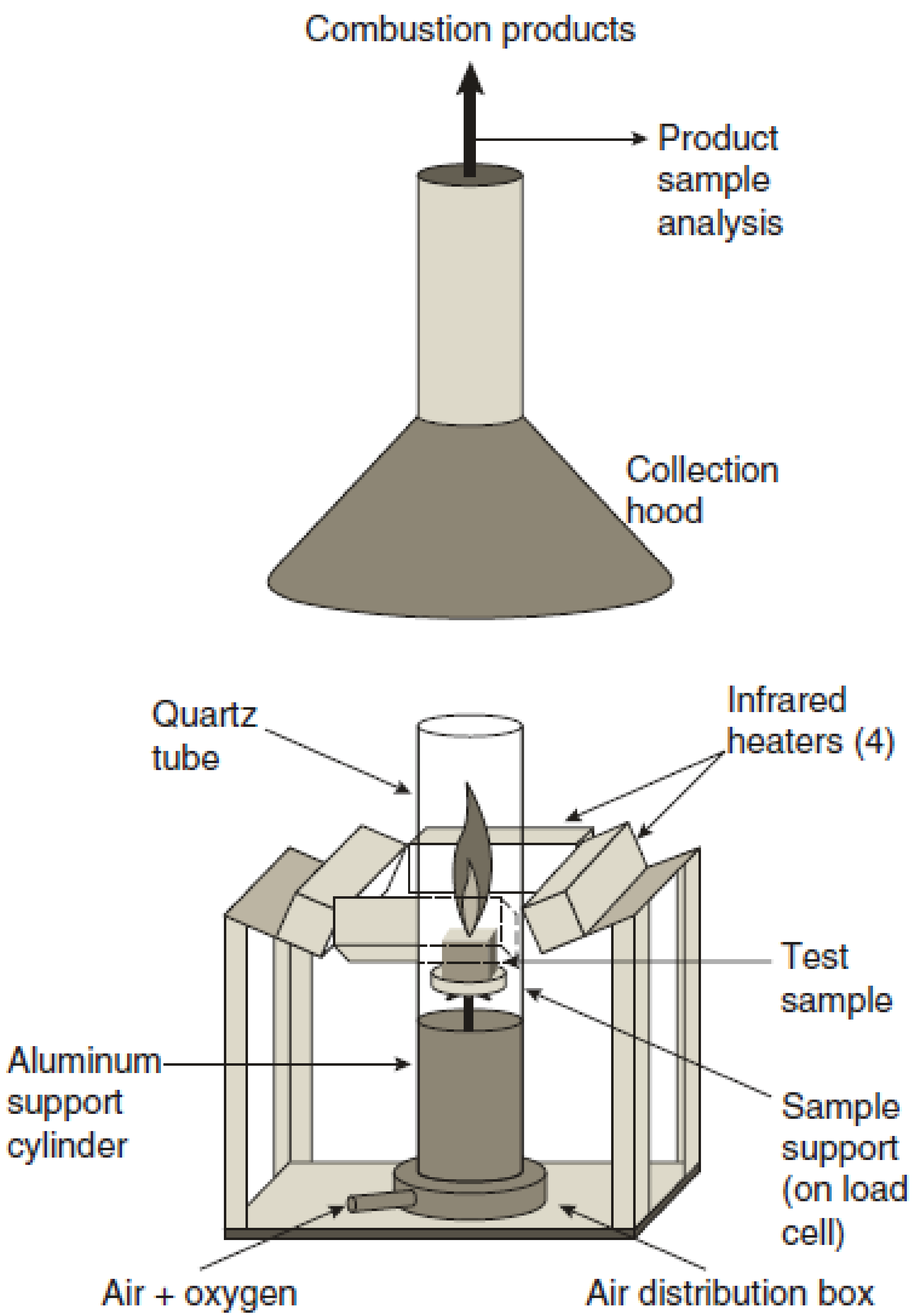
FIRE PROPAGATION APPARATUS (FPA)



FIRE PROPAGATION APPARATUS (FPA)

– Time to ignition for a thermally thick material:

$$t_{ig,thick} = \frac{\frac{\pi}{4}\rho k c\left(T_{ig} - T_0\right)^2}{(\dot{q}''_e - \chi \dot{q}''_{cr})^2}$$

– Critical heat flux (CHF): $\dot{q}''_{cr}$ (kW/m^2).

– Heat losses are important → flammability measurements are sample holder/apparatus dependent.

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FIRE PROPAGATION APPARATUS (FPA)

- Underlying assumption: radiation is dominant (→ important to minimize other heat losses).
- Thermal response parameter (TRP):

$$TRP = \left(\frac{\pi}{4}\rho k c\right)^{1/2}\left(T_{ig} - T_0\right)$$

- Note: Materials behave as thermally thick at high heating rates → most typical for fires.

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FIRE PROPAGATION APPARATUS (FPA)

- TRP relates to time to ignition:
  - Higher value → less prone to ignition;
  - Lower value → more prone to ignition.
- Note: easy ignition means fast flame spread (see later).

FIRE PROPAGATION APPARATUS (FPA)

- CHF and TRP determined from measurements:

$$t_{ig,thick} = \frac{\frac{\pi}{4}\rho k c\left(T_{ig} - T_0\right)^2}{\left(\dot{q}_e'' - \chi\dot{q}_{cr}''\right)^2} \rightarrow \frac{1}{\sqrt{t_{ig,thick}}} = \frac{\dot{q}_e'' - CHF}{TRP}$$

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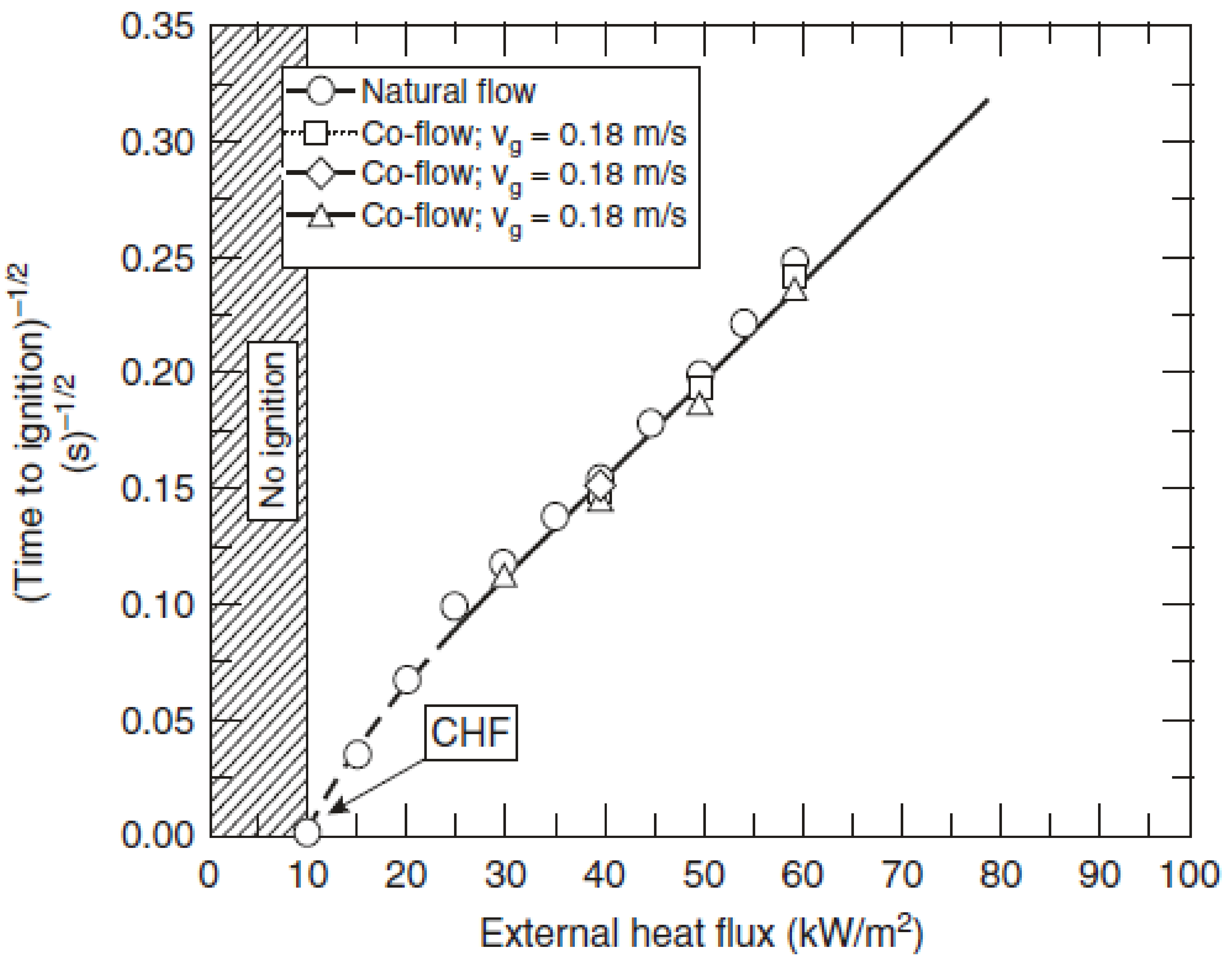
FIRE PROPAGATION APPARATUS (FPA)

Fig. 36.6 Square root of the inverse of time to ignition versus external heat flux for 100-mm × 100-mm × 25-mm-thick polymethylmethacrylate (PMMA) slab with a blackened surface. Data measured in the Fire Propagation Apparatus [31]



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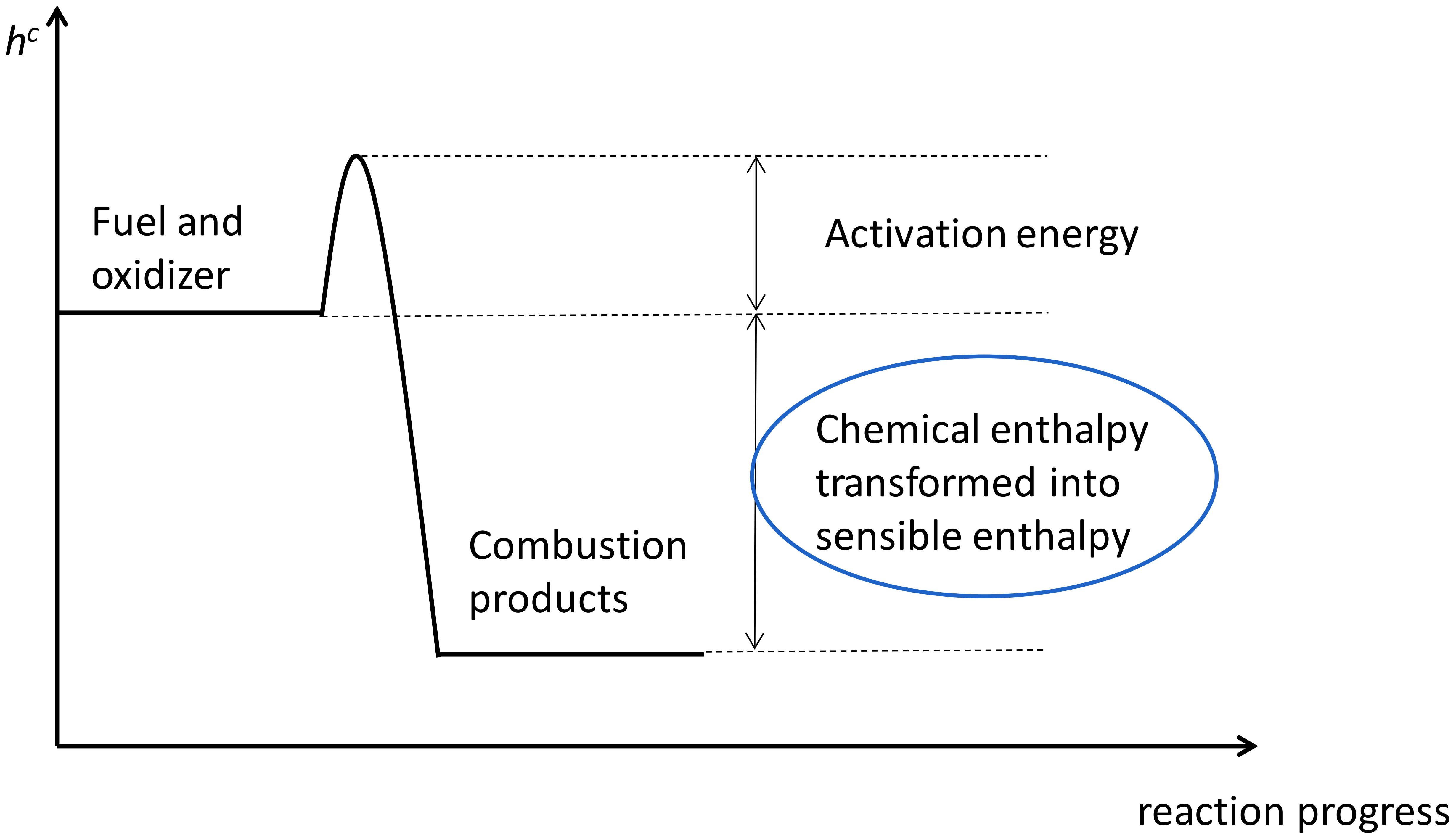
FIRE GROWTH

FLAME SPREAD OVER SURFACES

- Concept: advancing ignition ‘front’ (where the temperature reaches the ‘ignition temperature’).
- Strong impact of the flow field, compared to the direction of the flame spread.
- Strong difference between thermally thin and thermally thick.
- The heat required for pyrolysis is supplied by the flame.

THERMODYNAMICS



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HEAT FEEDBACK

- Combustion is an exothermic process → heat is generated.
- Heat of combustion ΔH_c: the amount of energy (in J/kg or kJ/kg or MJ/kg) released by complete combustion of 1 kg of fuel.
- This is related to the (theoretical) ‘fire load’ inside an enclosure (see later).

FIRE – SOME BASICS

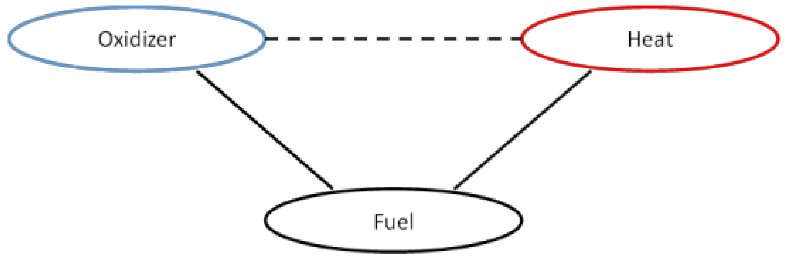

Table 1.13 Heats of combustion[a] of selected fuels at 25°C (298 K)

		$-\Delta H_c$ (kJ/mol)	$-\Delta H_c$ (kJ/g)	$-\Delta H_{c,air}$ (kJ/g(air))	$-\Delta H_{c,ox}$ (kJ/g(O_2))
Carbon monoxide	CO	283	10.10	4.10	17.69
Methane	CH_4	800	50.00	2.91	12.54
Ethane	C_2H_6	1423	47.45	2.96	11.21
Ethene	C_2H_4	1411	50.35	3.42	14.74
Ethyne	C_2H_2	1253	48.20	3.65	15.73
Propane	C_3H_8	2044	46.45	2.97	12.80
n-Butane	*n*-C_4H_{10}	2650	45.69	2.97	12.80
n-Pentane	*n*-C_5H_{12}	3259	45.27	2.97	12.80
n-Octane	*n*-C_8H_{18}	5104	44.77	2.97	12.80
c-Hexane	*c*-C_6H_{12}	3680	43.81	2.97	12.80
Benzene	C_6H_6	3120	40.00	3.03	13.06
Methanol	CH_3OH	635	19.83	3.07	13.22
Ethanol	C_2H_5OH	1232	26.78	2.99	12.88
Acetone	$(CH_3)_2CO$	1786	30.79	3.25	14.00
D-Glucose	$C_6H_{12}O_6$	2772	15.4	3.08	13.27
Cellulose		—	16.09	3.15	13.59
Polyethylene		—	43.28	2.93	12.65
Polypropylene		—	43.31	2.94	12.66
Polystyrene		—	39.85	3.01	12.97
Polyvinylchloride		—	16.43	2.98	12.84
Polymethylmethacrylate		—	24.89	3.01	12.98
Polyacrylonitrile		—	30.80	3.16	13.61
Polyoxymethylene		—	15.46	3.36	14.50
Polyethyleneterephthalate		—	22.00	3.06	13.21
Polycarbonate		—	29.72	3.04	13.12
Nylon 6,6		—	29.58	2.94	12.67

[a] The initial states of the fuels correspond to their natural states at normal temperature and pressure (298°C and 1 atm pressure). All products are taken to be in their gaseous state—thus these are the net heats of combustion.

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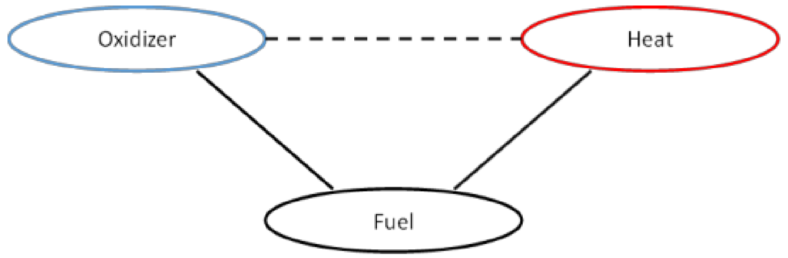
FIRE – SOME BASICS



- Note: heat of combustion per kg oxygen or per kg air consumed is independent of the fuel for many (hydrocarbon) fuels: $\Delta H_{c,ox} = 13 kJ / g\ O_2 \quad \Delta H_{c,air} = 3 kJ / g\ air$
- Use:
  - Ventilation-controlled fires.
  - Oxygen-depletion calorimetry to determine HRR:

$$\dot{Q}_c = \left(0.21 - \eta_{O_2}\right).\dot{V}.10^3.\rho_{O_2}.\Delta H_{c,ox}$$

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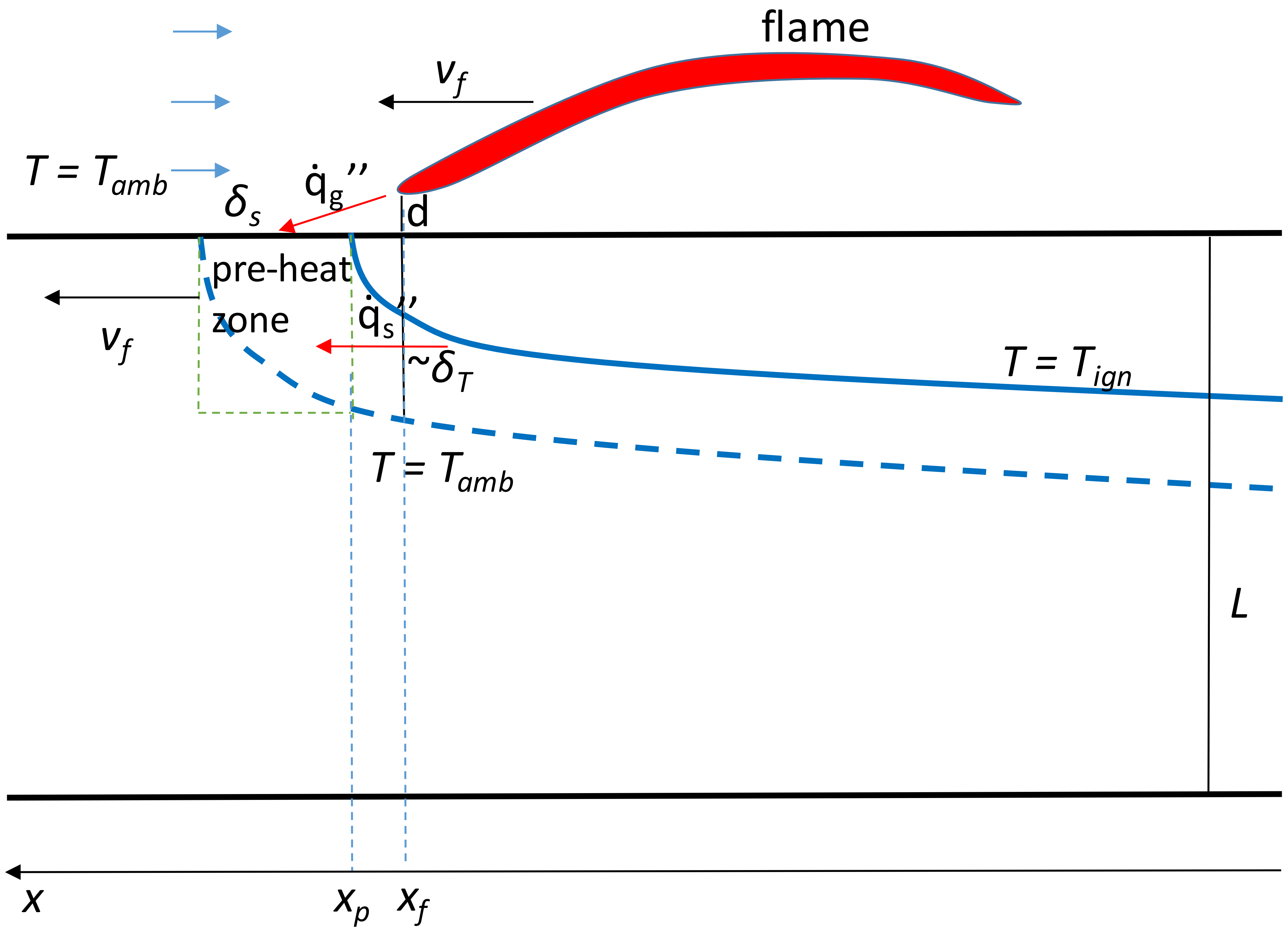
FLAME SPREAD OVER SURFACES

- Opposed flow / vertically downward – thermally thick



FLAME SPREAD OVER SURFACES

- Opposed flow / vertically downward – thermally thick:

$$\delta_T = C\sqrt{\alpha_F t} = C\sqrt{\frac{k_F}{\rho_F c_F} t}$$

$$\dot{Q}' \propto \frac{1}{2}\rho_F \delta_T v_f c_F \left(T_{ign} - T_{amb}\right)$$

$$\dot{q}_g \approx \frac{k_g\left(T_f - T_{s,av}\right)}{d_f} \qquad \dot{Q}'_g = \dot{q}_g \delta_s$$

$$\dot{q}_s \approx \frac{k_F\left(T_{s,av} - T_{amb}\right)}{\delta_s} = \frac{1}{2}\frac{k_F\left(T_{ign} - T_{amb}\right)}{\delta_s} \qquad \dot{Q}'_s = \dot{q}_s \delta_T$$

$$\frac{1}{2}\rho_F \delta_T v_f c_F \left(T_{ign} - T_{amb}\right) = \frac{k_g\left(T_f - T_{s,av}\right)}{d_f}\delta_s + \frac{1}{2}\frac{k_F\left(T_{ign} - T_{amb}\right)}{\delta_s}\delta_T$$

$$v_f \propto \delta_s \frac{1}{\rho_F k_F c_F}\left(\frac{\dot{q}}{T_{ign} - T_{amb}}\right)^2$$

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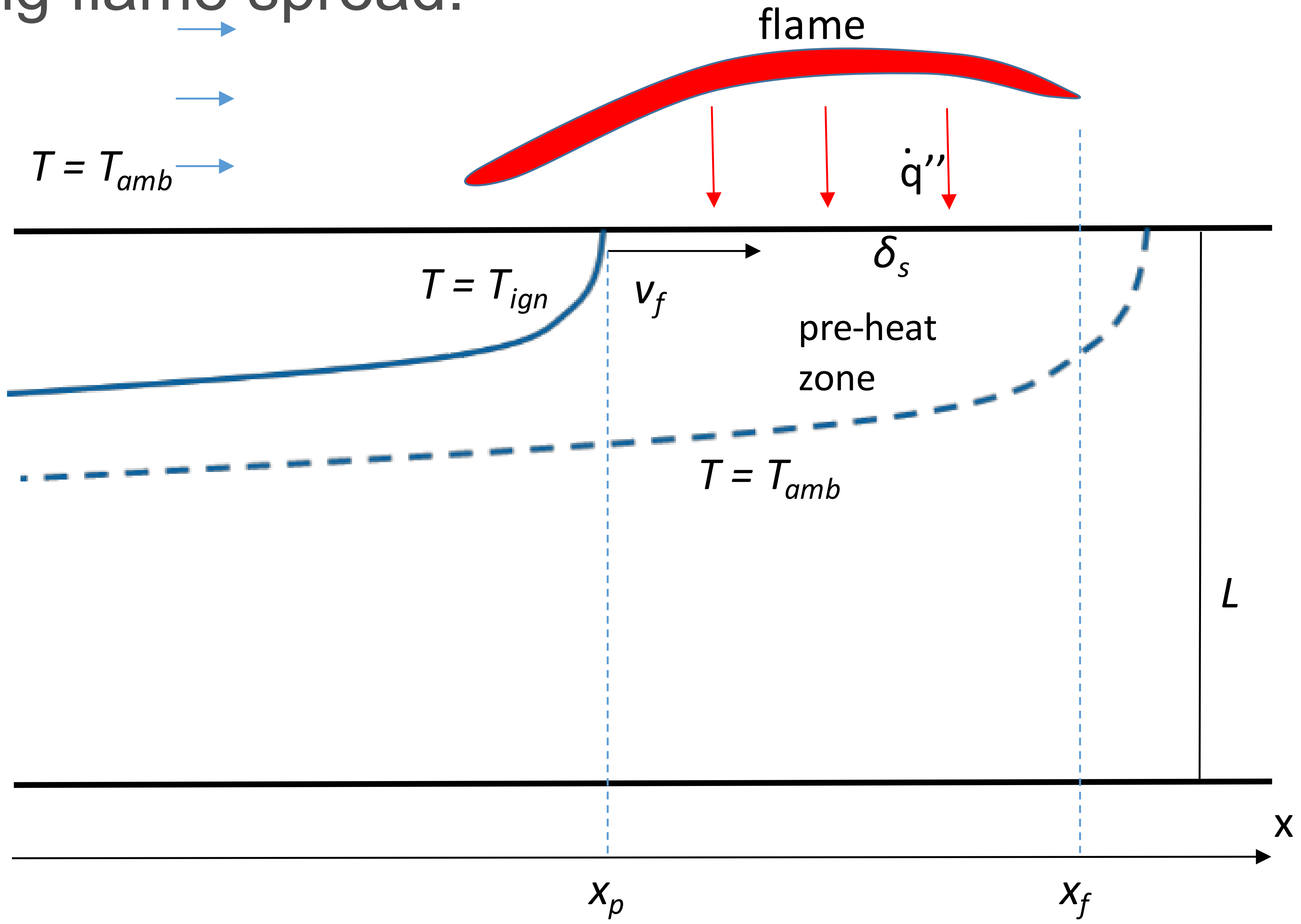
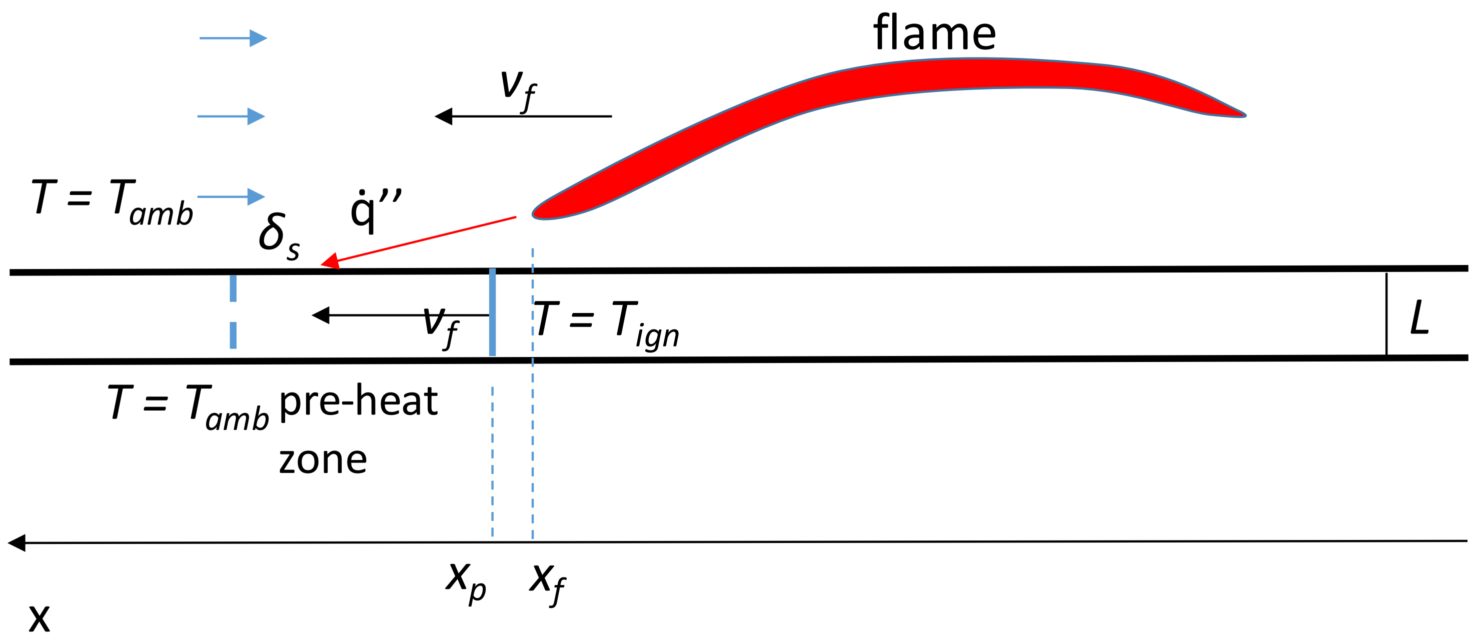
FLAME SPREAD OVER SURFACES

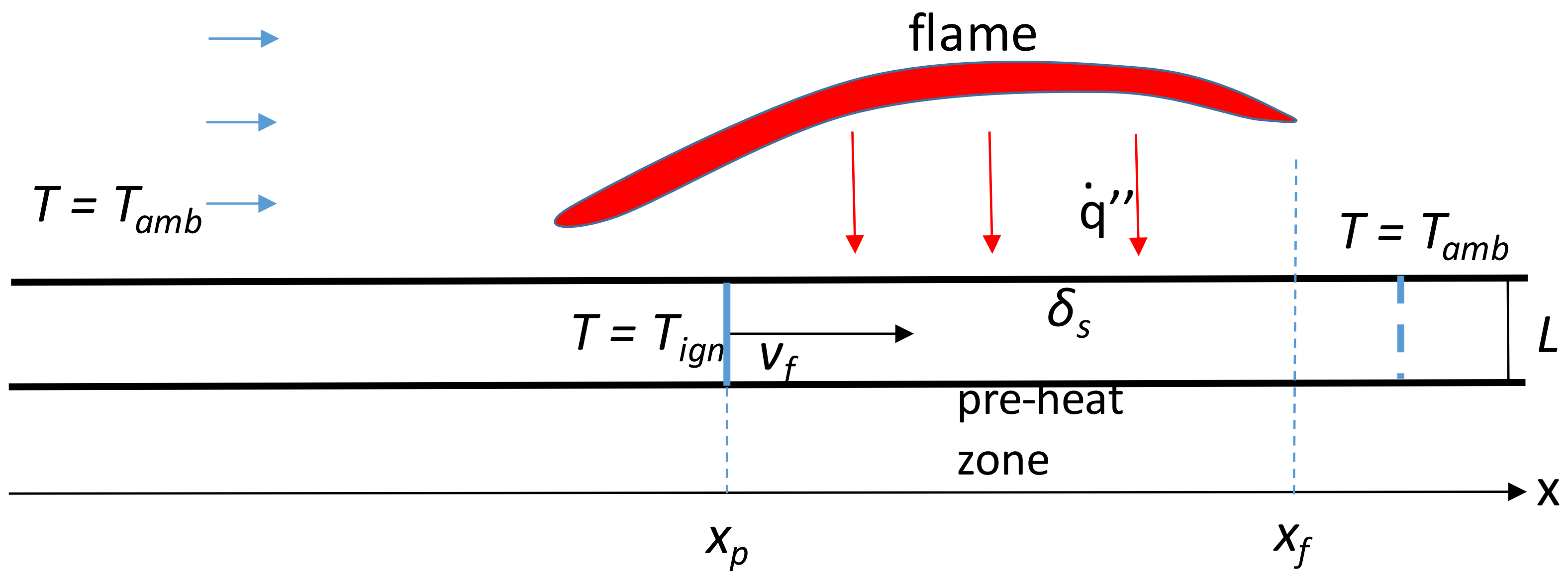
- Concurrent flow / vertically upward: thermal runaway → accelerating flame spread.



FLAME SPREAD OVER SURFACES

- Thermally thin fuels: time to ignition scales linearly with the thickness of the material → faster flame spread for thinner materials. Note: flames on both sides → even faster flame spread.





REACTION-TO-FIRE TESTS

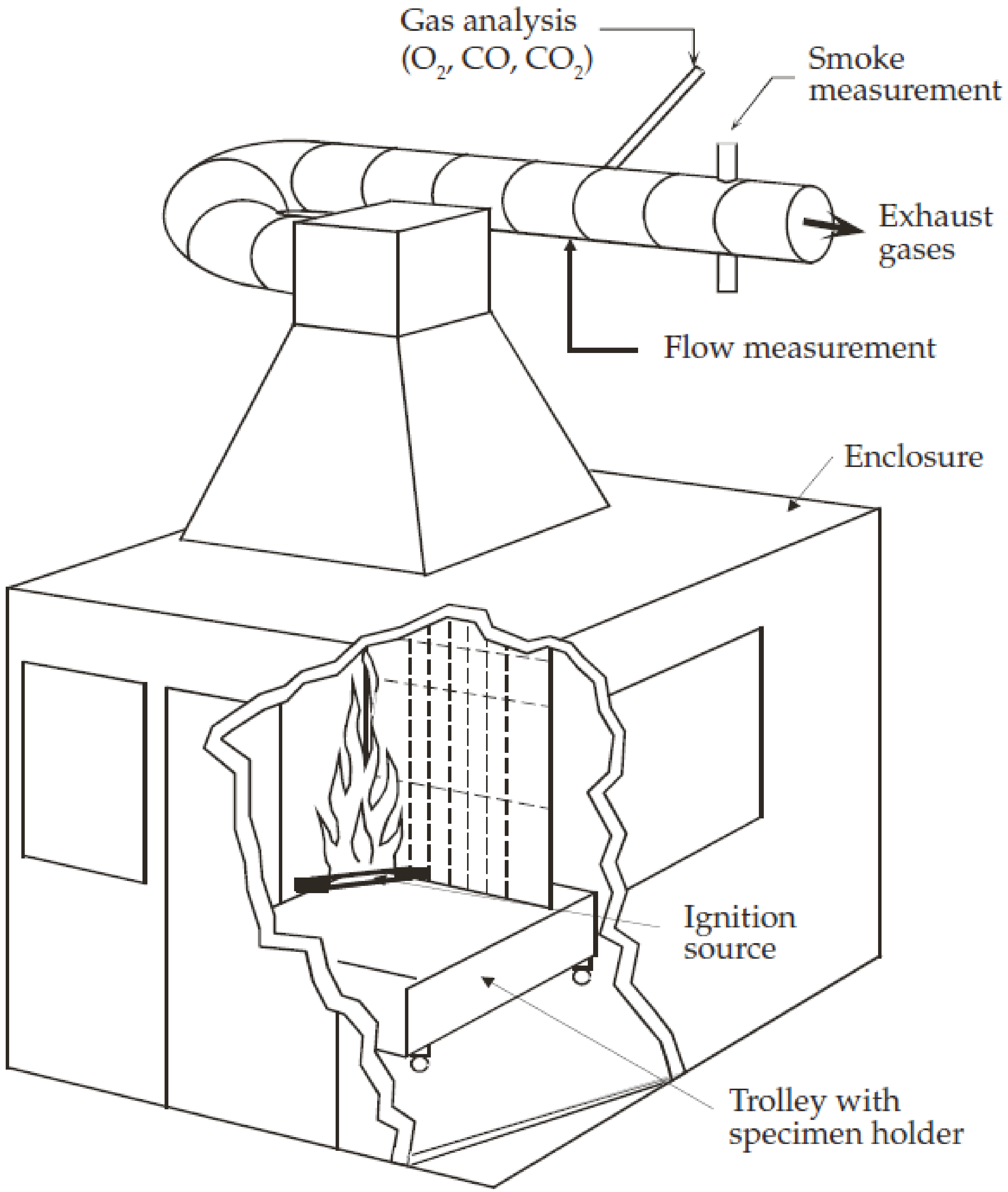
- Classification of products in ‘end use’ application.

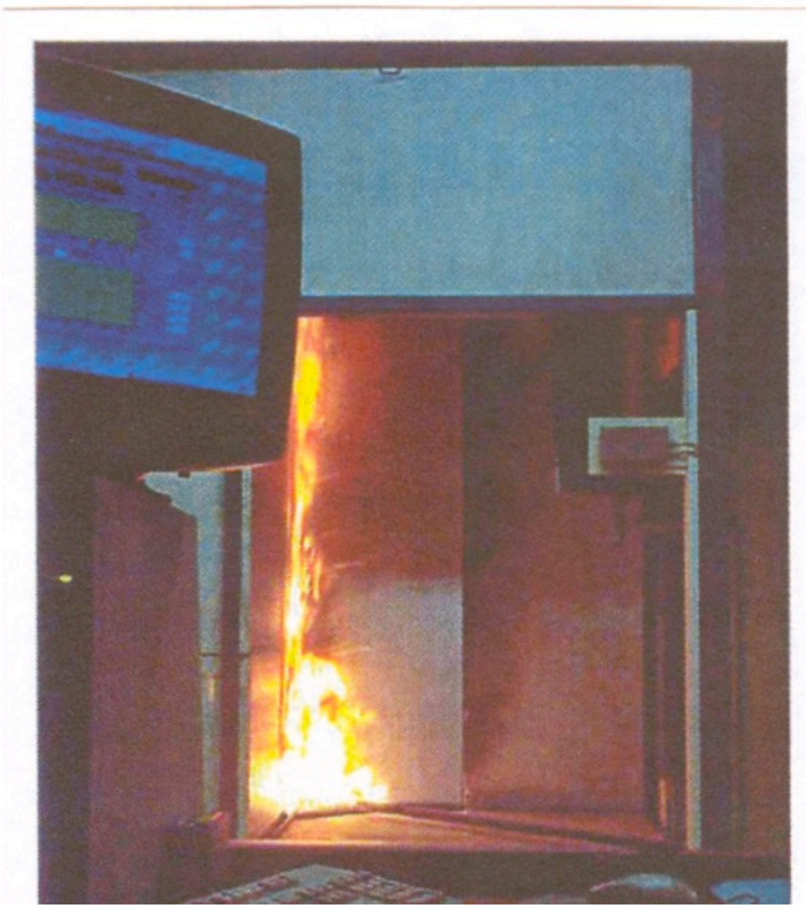
Fire behaviour	Smoke production	Falling droplets
A1 *No contribution to fire*		
A2 *Almost no contribution to fire*	s1 *limited smoke production;* s2 *average smoke production;* s3 *large smoke production*	d0 *no droplets;* d1 *burning droplets < 10s;* d2 *burning droplets > 10s*
B *Very limited contribution to fire*	s1, s2, s3	d0, d1, d2
C *Limited contribution to fire*	s1, s2, s3	d0, d1, d2
D *Import contribution to fire*	s1, s2, s3	d0, d1, d2
E *Very import contribution to fire*		d2
F *No performance determined*		

SINGLE BURNING ITEM (SBI)

- Corner set-up:
  - Long panel: 1 m x 1.5 m;
  - Short panel: 0.5 m x 1.5 m;
- Triangular burner – 30 kW.
- Exposure during 20 minutes.

SINGLE BURNING ITEM (SBI)





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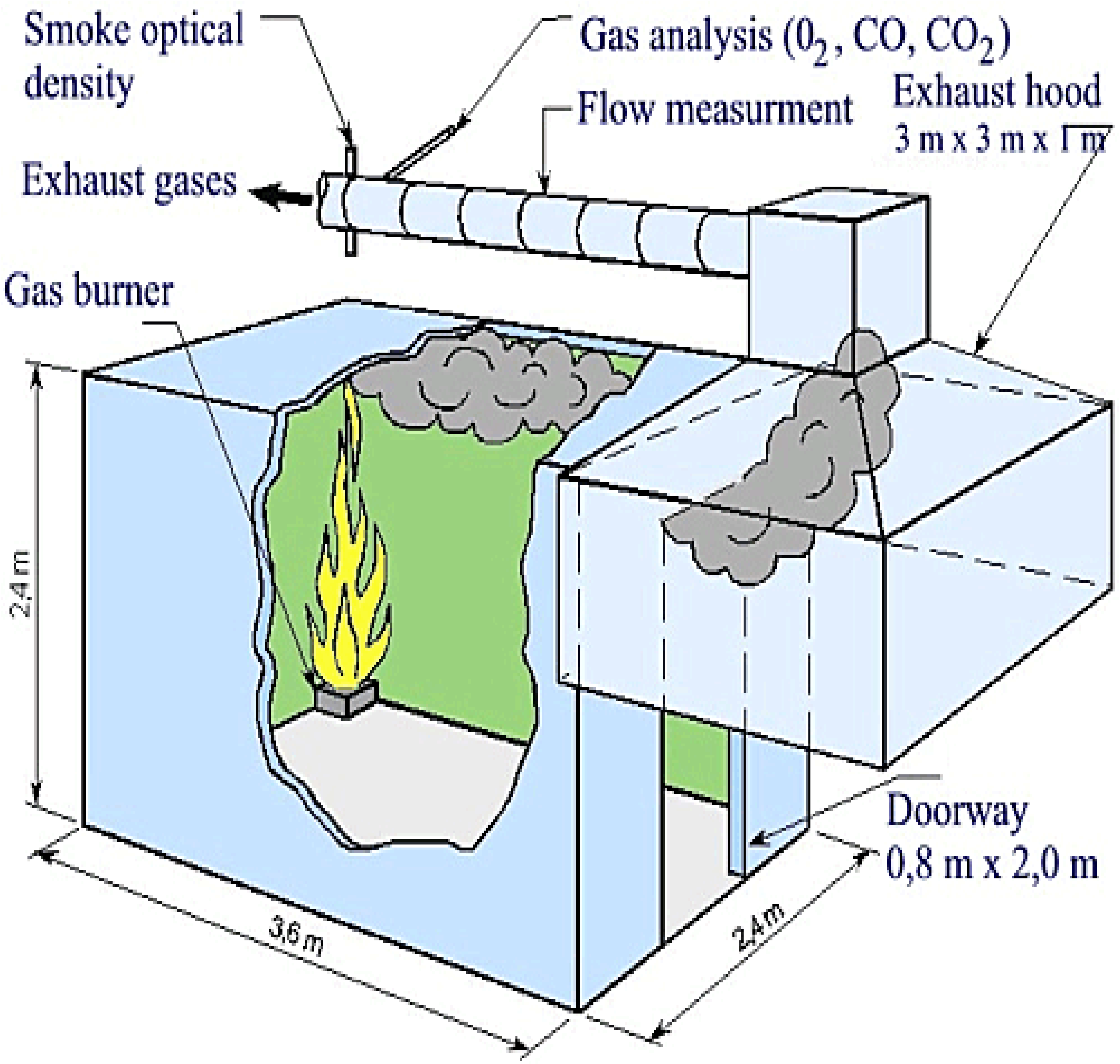
ROOM CORNER (RC)

- Room corner test – EN 9750:
  - Test sample mounted on the inside of the room, on the ceiling and on all the walls except for the wall with the door opening.
  - Propane gas burner, located in one of the corners, produces a heat release rate of 100 kW during 10 minutes, and then 300 kW the following 10 minutes.

ROOM CORNER (RC)

Euroclass	Flashover in the Room Corner Reference test
A1	No flashover
A2	No flashover
B	No flashover
C	Flashover between 10 - 20 minutes
D	Flashover between 2 to 10 minutes
E	Flashover before 2 minutes
F	NPD No data available



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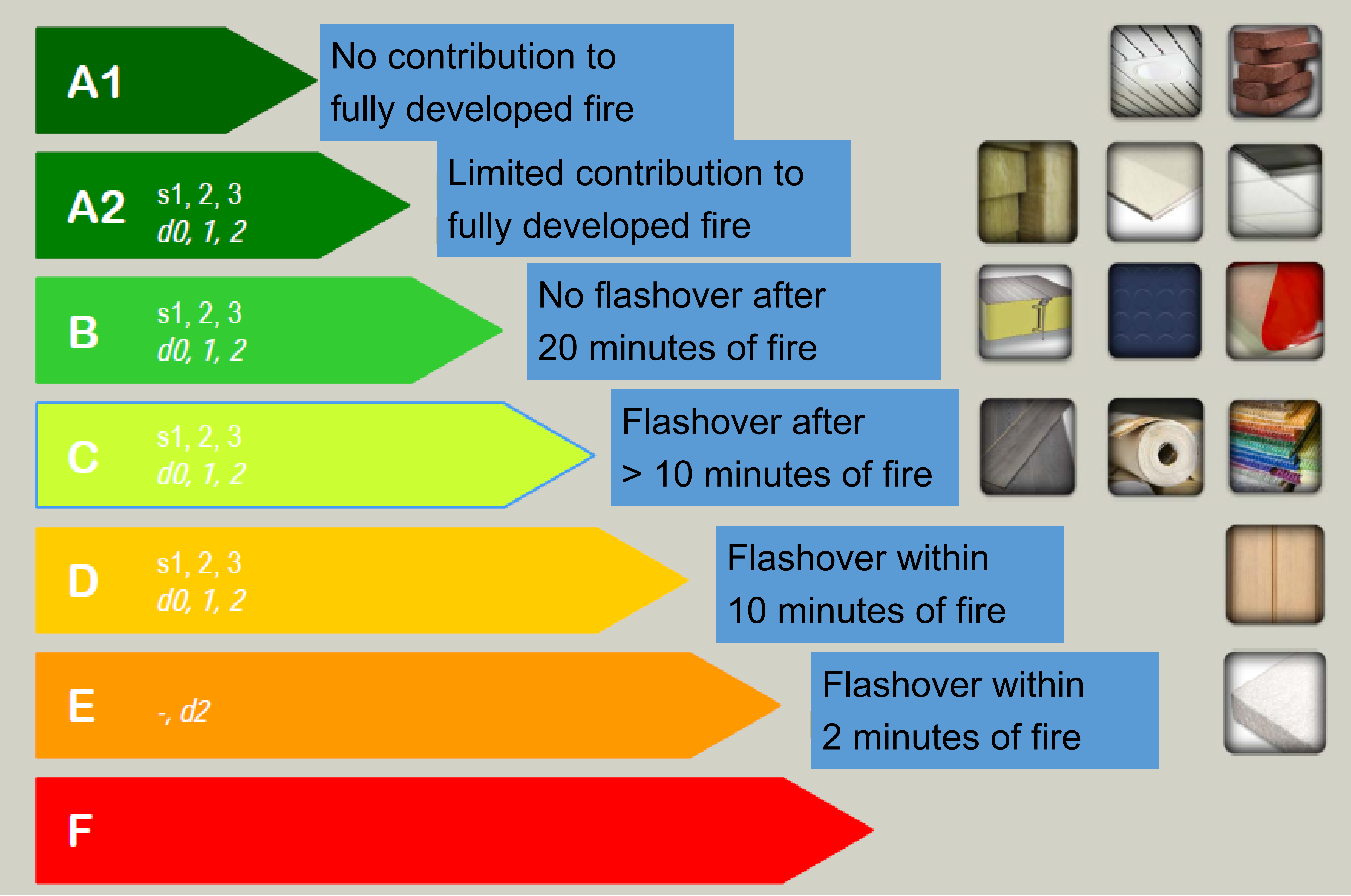
ROOM CORNER (RC)

- Room corner test – EN 9750:
  - Combustion gases collected through a hood → measurement of heat release rate and smoke production rate.
  - Flame spread along walls and ceiling observed visually.
  - If flames emerge from the door opening: flashover → test terminated. HRR at flashover is generally about 1 MW.

ROOM CORNER (RC)



COMPARTMENT FIRE DYNAMICS

HEAT FEEDBACK: FREE FIRE PLUME

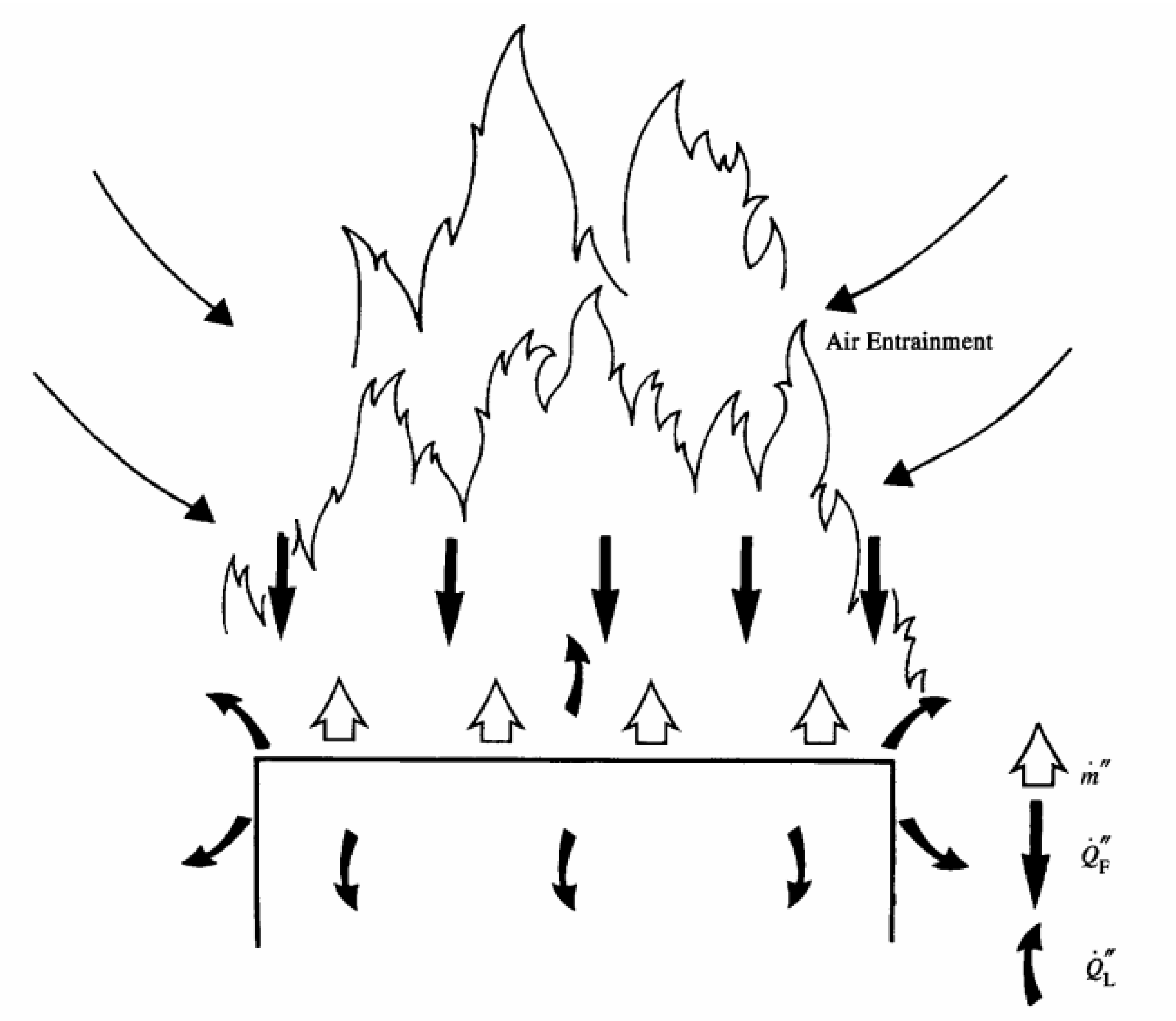
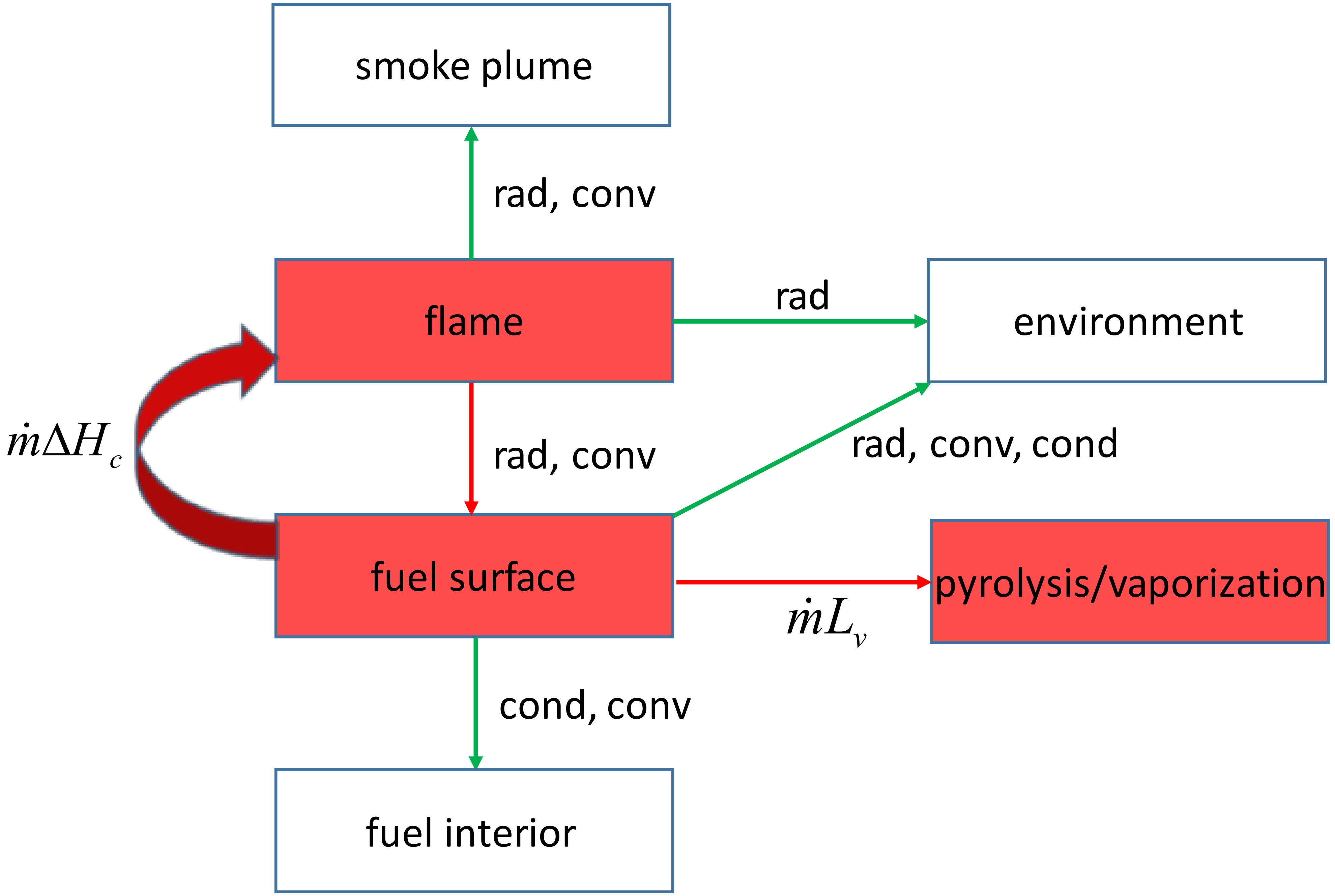


Figure 1.4 Schematic representation of a burning surface, showing the heat and mass transfer processes. $\dot{m}''$, mass flux from the surface: $\dot{Q}''_F$, heat flux from the flame to the surface; $\dot{Q}''_L$, heat losses (expressed as a flux from the surface)



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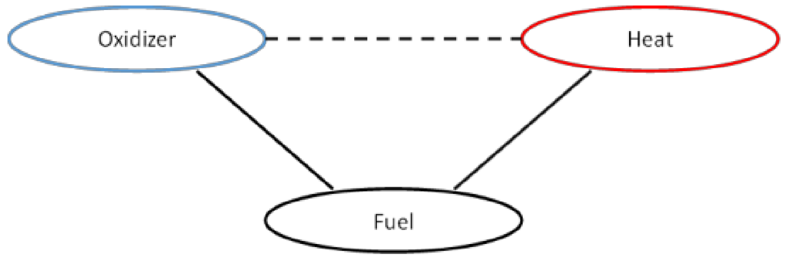
HEAT FEEDBACK: FREE FIRE PLUME

- Notations:
  - Mass flow rate per unit area (kg/(m²s)): $\dot{m}''$
  - Heat flux from the flames per unit area (W/m²): $\dot{Q}_F''$
  - Heat losses per unit area (W/m²): $\dot{Q}_L''$
  - Mass flow rate (kg/s): $\dot{m}$ $(= \dot{m}'' A_F)$
  - Heat of combustion (J/kg): ΔH_c.

FIRE – SOME BASICS



- Heat feedback loop:
  - Heat generated per unit time (W/kW/MW): heat release rate (HRR): $\dot{Q} = \chi \dot{m}'' A_F \Delta H_c$:
    - χ: completeness of combustion;
    - $\dot{m}''$: mass flow rate per unit area (kg/(m²s));
    - A_F:area involved in the fire (m²)
    - ΔH_c: theoretical heat of combustion (J/kg, kJ/kg, MJ/kg).

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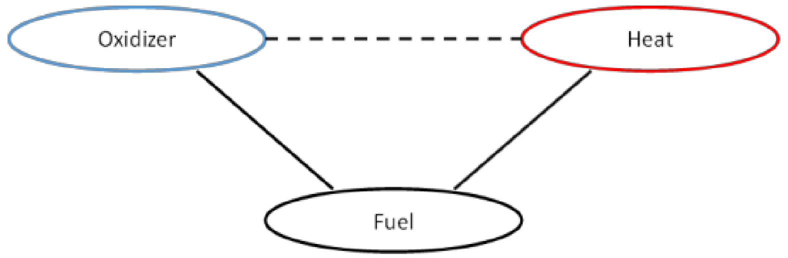
FIRE – SOME BASICS



- Heat feedback loop (ctd.):
  - Heat required per unit time is related to the fuel mass loss rate:

$$\dot{m}" = \frac{\dot{q}_{in,net}}{L_v}$$

    - L_v: : latent heat of vaporization / heat of pyrolysis (J/kg, kJ/kg, MJ/kg)
    - $\dot{q}_{in,net}$: net incident heat flux onto the fuel surface (in W/m^2, kW/m^2, MW/m^2).

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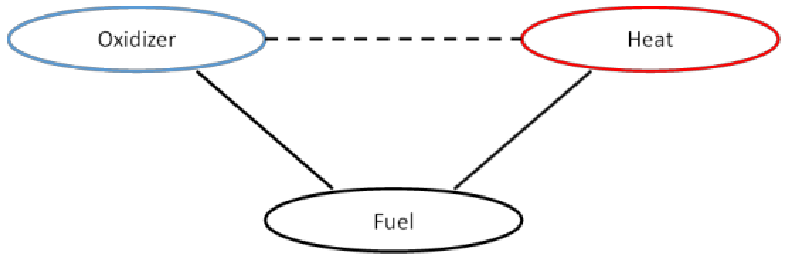
FIRE – SOME BASICS



- Heat feedback loop (ctd.):
  - Combination: heat release rate (HRR):

$$\dot{Q} = \chi \dot{m}'' A_F \Delta H_c = \chi \frac{\dot{q}_{in,net}}{L_v} A_F \Delta H_c = \chi \dot{q}_{in,net} A_F \frac{\Delta H_c}{L_v}$$

$\frac{\Delta H_c}{L_v}$: ‘combustibility ratio’.

FIRE DEVELOPMENT IN ENCLOSURES

- Example:

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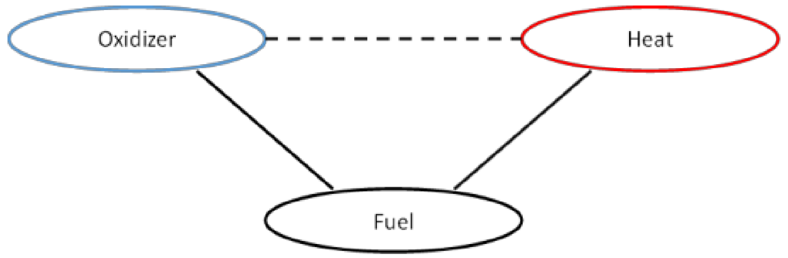
FIRE – SOME BASICS



- For fire dynamics, often the heat release rate (in W or kW or MW) is more important than the total energy contents (fire load). [Note: for the stability of structures, the fire load is important, as it affects the duration of the fire.]

FIRE DEVELOPMENT IN ENCLOSURES

- Basic equation: $\dot{Q} = \chi \frac{\dot{q}_{in,net}}{L_v} A_F \Delta H_c = \dot{q}_{in,net} A_F \frac{\Delta H_{c,eff}}{L_v}$
- Two main effects: heat transfer and ventilation are key!
  - Increased thermal feedback (see next slide) → increased net incident heat flux ($\dot{q}_{in,net}$).
  - Possibly reduced ventilation (air supply) → reduction in completeness of combustion (χ or $\Delta H_{c,eff}$).

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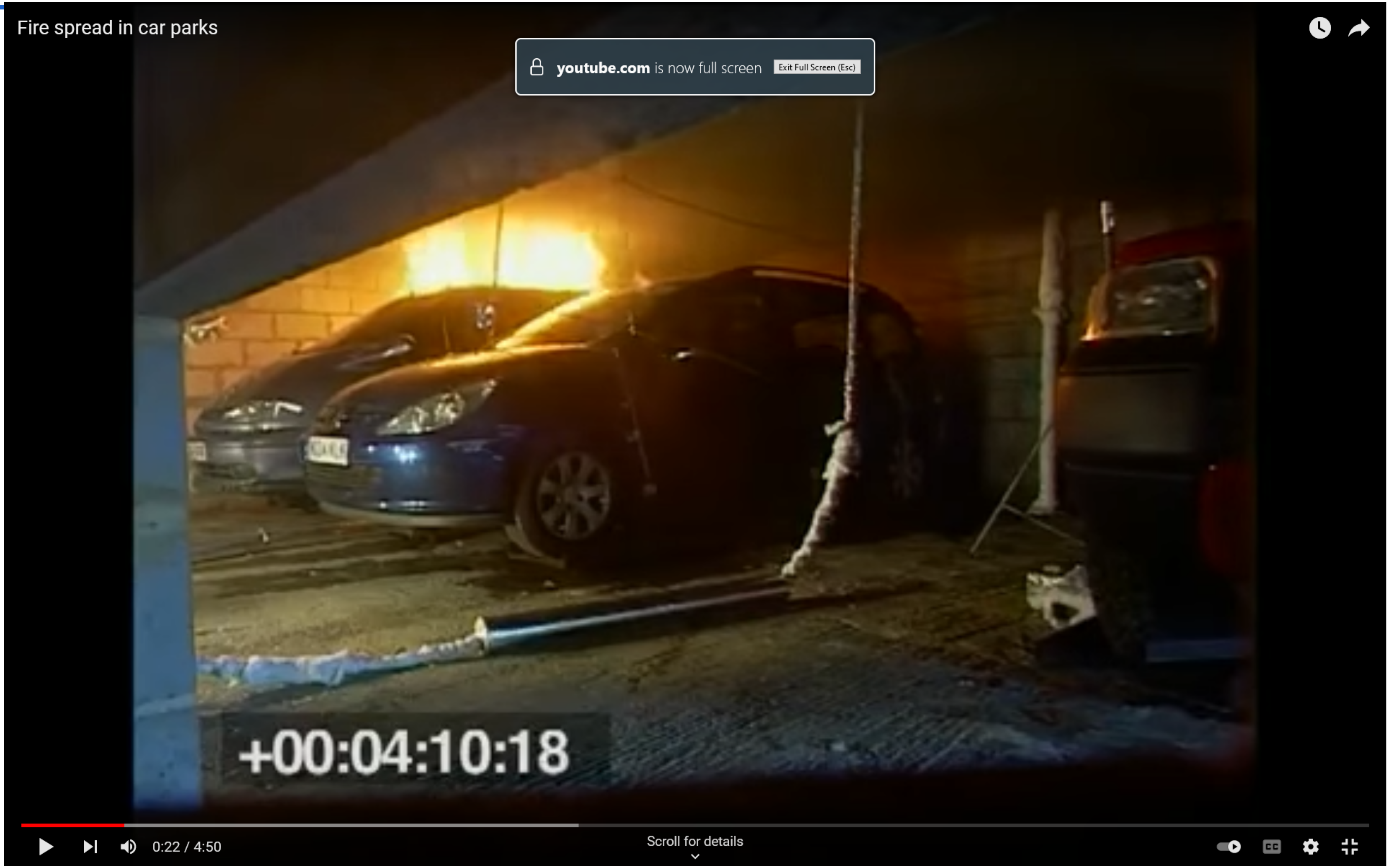
FIRE DEVELOPMENT IN ENCLOSURES



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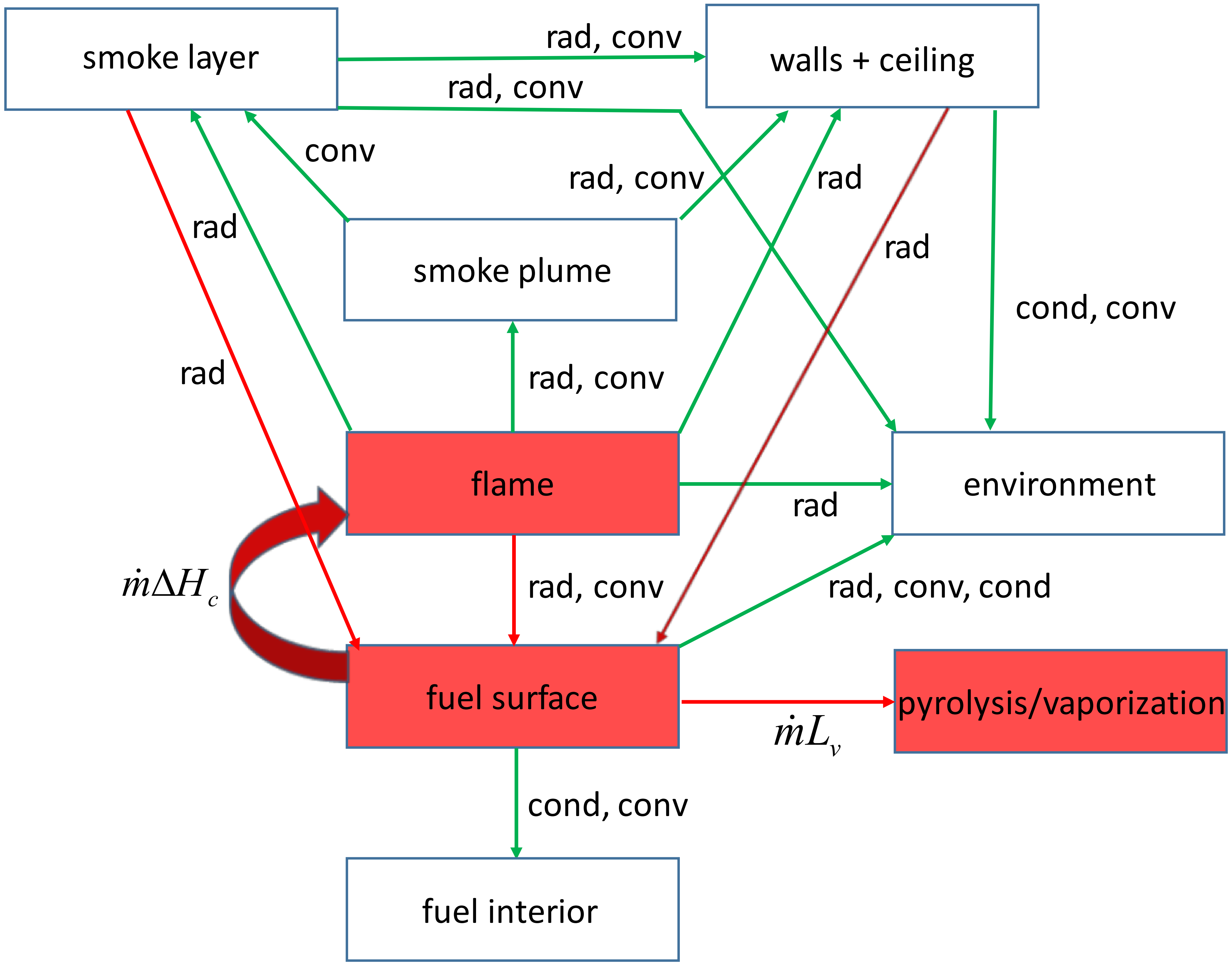
FIRE DEVELOPMENT IN ENCLOSURES



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FIRE DEVELOPMENT IN ENCLOSURES

- Important factors that determine the fire development in enclosures:
  - The geometry and material of the enclosure (strong impact on thermal heat feedback).
  - The ventilation conditions.
  - The fuel (type, amount and surface area).

FIRE DEVELOPMENT IN ENCLOSURES - HEAT

- Heat transfer by conduction:
  - Important in solids (there is also conduction in fluids, but in case of motion it is masked by convection).
  - Heat flows from high temperature to low temperature.
  - Equation: 'Fourier's law': $\dot{\vec{q}} = -k\nabla T = -\lambda\nabla T$
  - Thermal conductivity (k, λ): W/(m.K).
  - In 1 direction: $\dot{Q}_{cond} = -kA\frac{dT}{dx} = -\lambda A\frac{dT}{dx}$, with A the area through which heat is transferred.

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FIRE DEVELOPMENT IN ENCLOSURES - HEAT

- Heat transfer by conduction:

Table 2.1 Thermal properties of some common materials[a]

Material	k (W/m.K)	c_p (J/kg.K)	ρ (kg/m^3)	α (m^2/s)	$k\rho c_p$ (W^2.s/m^{4}K^2)
Copper	387	380	8940	1.14×10^{-4}	1.3×10^{9}
Steel (mild)	45.8	460	7850	1.26×10^{-5}	1.6×10^{8}
Brick (common)	0.69	840	1600	5.2×10^{-7}	9.3×10^{5}
Concrete	0.8–1.4	880	1900–2300	5.7×10^{-7}	2×10^{6}
Glass (plate)	0.76	840	2700	3.3×10^{-7}	1.7×10^{6}
Gypsum plaster	0.48	840	1440	4.1×10^{-7}	5.8×10^{5}
PMMA[b]	0.19	1420	1190	1.1×10^{-7}	3.2×10^{5}
Oak[c]	0.17	2380	800	8.9×10^{-8}	3.2×10^{5}
Yellow pine[c]	0.14	2850	640	8.3×10^{-8}	2.5×10^{5}
Asbestos	0.15	1050	577	2.5×10^{-7}	9.1×10^{4}
Fibre insulating board	0.041	2090	229	8.6×10^{-8}	2.0×10^{4}
Polyurethane foam[d]	0.034	1400	20	1.2×10^{-6}	9.5×10^{2}
Air	0.026	1040	1.1	2.2×10^{-5}	—

[a] From Pitts and Sissom (1977) and others. Most values for 0 or 20°C. Figures have been rounded off.
[b] Polymethylmethacrylate. Values of k, c_p and ρ for other plastics are given in Table 1.2.
[c] Properties measured perpendicular to the grain.
[d] Typical values only.

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FIRE DEVELOPMENT IN ENCLOSURES - HEAT

- Heat transfer by convection:
  - Heat transfer to or from a solid by motion of a fluid in contact with that solid.
  - Empirical relationship (Newton): $\dot{q}_{conv} = h\Delta T$
  - Convection coefficient (h), in W/(m^{2}K): this is NOT a material property: it also depends on the system, the geometry, the fluid and flow parameters.
  - Range of values for h : 5-25W/(m^{2}K) (free convection) and 10-500W/(m^{2}K) (forced convection in air).
  - $\dot{Q}_{conv} = hA\Delta T$, with A the area through which heat is transferred.

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FIRE DEVELOPMENT IN ENCLOSURES - HEAT

- Heat transfer by radiation:
  - Stefan-Boltzmann: the total energy emitted per unit time and per unit area by a body is proportional to its temperature (in K) to the fourth power: $E = \varepsilon\sigma T^4$
  - σ: Stefan-Boltzmann constant (5.67 10^{-8}W/(m^2K^4)).
  - ε: emissivity (non-dimensional). $\varepsilon = 1$: black body.

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FIRE DEVELOPMENT IN ENCLOSURES - HEAT

Table 9.5 Critical temperature for different exposure conditions

Type and period of exposure	Effect	Temperature (°C)
Radiation	Severe skin pain	185†
Conduction (metal) (1 second)	Skin burns	60
Convection (30 minutes)	Hyperthermia	100
Convection (< 5 minutes)	Skin/lungs burns by hot gases	120
Convection (< 1 minute)	Skin/lungs burns by hot gases	190

† black-body: 2.5 kW m^{-2}

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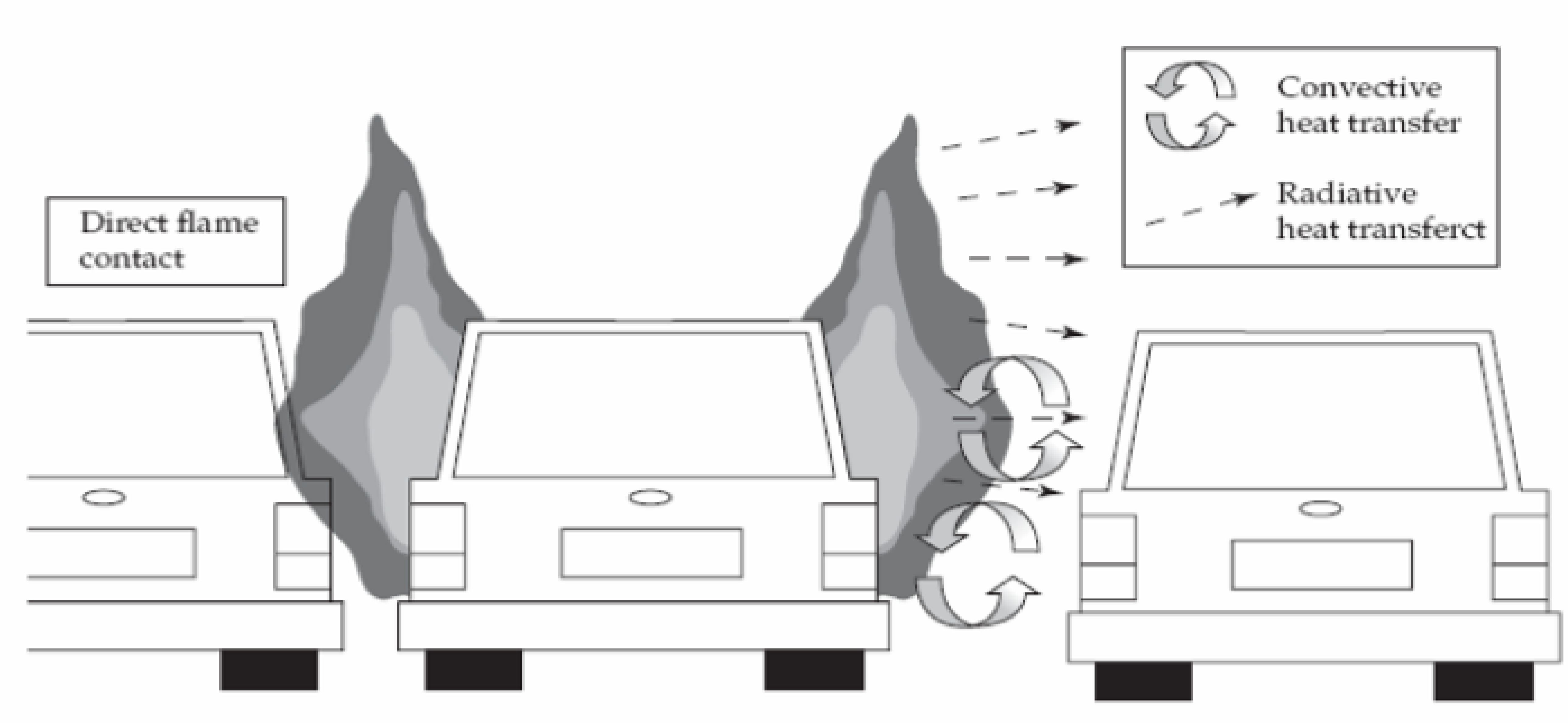
FIRE DEVELOPMENT IN ENCLOSURES - HEAT

- Heat transfer by radiation:
  - Radiative heat exchange between bodies: depends on the temperature, emissivities (absorptivities) and the geometry (i.e., how large are the surfaces and how do they 'see' each other).
  - View factor / configuration factor φ: determines the fraction of incident radiation, stemming from the emitted radiation (emission is in all directions in principle) → for black bodies: $\dot{Q}_{1-2} = \sigma\varphi(T_1^4 - T_2^4)$

FIRE DEVELOPMENT IN ENCLOSURES - HEAT

Source: MSc thesis Toni Christiansen (DTU)



Figur 12 – Brandspredning fra bil til bil

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FIRE DEVELOPMENT IN ENCLOSURES - HEAT

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FIRE DEVELOPMENT IN ENCLOSURES - HEAT

- Heat accumulation in solids:
  - Mass density (ρ, kg/m^3): more mass per unit volume means more heat is needed for a change in temperature → more heat accumulation is possible.
  - Specific heat, aka heat capacity (c, J/(kg.K)): indicates how much heat is required to increase the temperature of 1 kg material by 1 K / 1 ^{o}C → if c is higher, more heat accumulation is possible.
  - The product $\rho k c$ is called 'thermal inertia'.

FIRE DEVELOPMENT IN ENCLOSURES - HEAT

- Heat accumulation in solids:
  - If $\rho k c$ is low, the temperature of the material rises quickly → the temperature of the solid (ceiling, wall, floor) can follow the gas temperature (which rises due to the fire) well → small temperature differences → less heat is taken from the gas phase → more heat is available for the pyrolysis / evaporation → a quicker fire development is possible.
  - Vice versa is $\rho k c$ is high.
  - Note: passive housing (although airtightness is more important).

FIRE DEVELOPMENT IN ENCLOSURES - HEAT

	ρ (kg/m^3)	k (W/(m.K))	c (J/(kg.K))	α (m^2/s)	$\sqrt{\rho k c}$
Steel	8000	15	500	$3.75\ 10^{-6}$	7750
Brick	2000	1	850	$5.9\ 10^{-7}$	1300
Wood	700	0.15	1250	$1.7\ 10^{-7}$	360
Insulation	70	0.025	1000	$3.6\ 10^{-7}$	42
Human skin					1200

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FIRE DEVELOPMENT IN ENCLOSURES - HEAT

Table 2.1 Thermal properties of some common materials[a]

Material	k (W/m.K)	c_p (J/kg.K)	ρ (kg/m^3)	α (m^2/s)	$k\rho c_p$ (W^2.s/m^{4}K^2)
Copper	387	380	8940	1.14×10^{-4}	1.3×10^9
Steel (mild)	45.8	460	7850	1.26×10^{-5}	1.6×10^8
Brick (common)	0.69	840	1600	5.2×10^{-7}	9.3×10^5
Concrete	0.8–1.4	880	1900–2300	5.7×10^{-7}	2×10^6
Glass (plate)	0.76	840	2700	3.3×10^{-7}	1.7×10^6
Gypsum plaster	0.48	840	1440	4.1×10^{-7}	5.8×10^5
PMMA[b]	0.19	1420	1190	1.1×10^{-7}	3.2×10^5
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[a] From Pitts and Sissom (1977) and others. Most values for 0 or 20°C. Figures have been rounded off.
[b] Polymethylmethacrylate. Values of k, c_p and ρ for other plastics are given in Table 1.2.
[c] Properties measured perpendicular to the grain.
[d] Typical values only.

FIRE IN ENCLOSURES – VENTILATION

- Flammability:
  - Simplified chemical reaction: $F(uel) + O(xidizer) \to P(roducts)$
  - ‘Stoichiometric conditions’: there is just enough oxidizer to allow complete reaction of all the fuel → maximum temperature.
  - Fuel lean: over-ventilated, ‘fuel-controlled’.
  - Fuel-rich: under-ventilated, ‘ventilation-controlled’.
  - Too little fuel or too little oxygen: not flammable anymore.

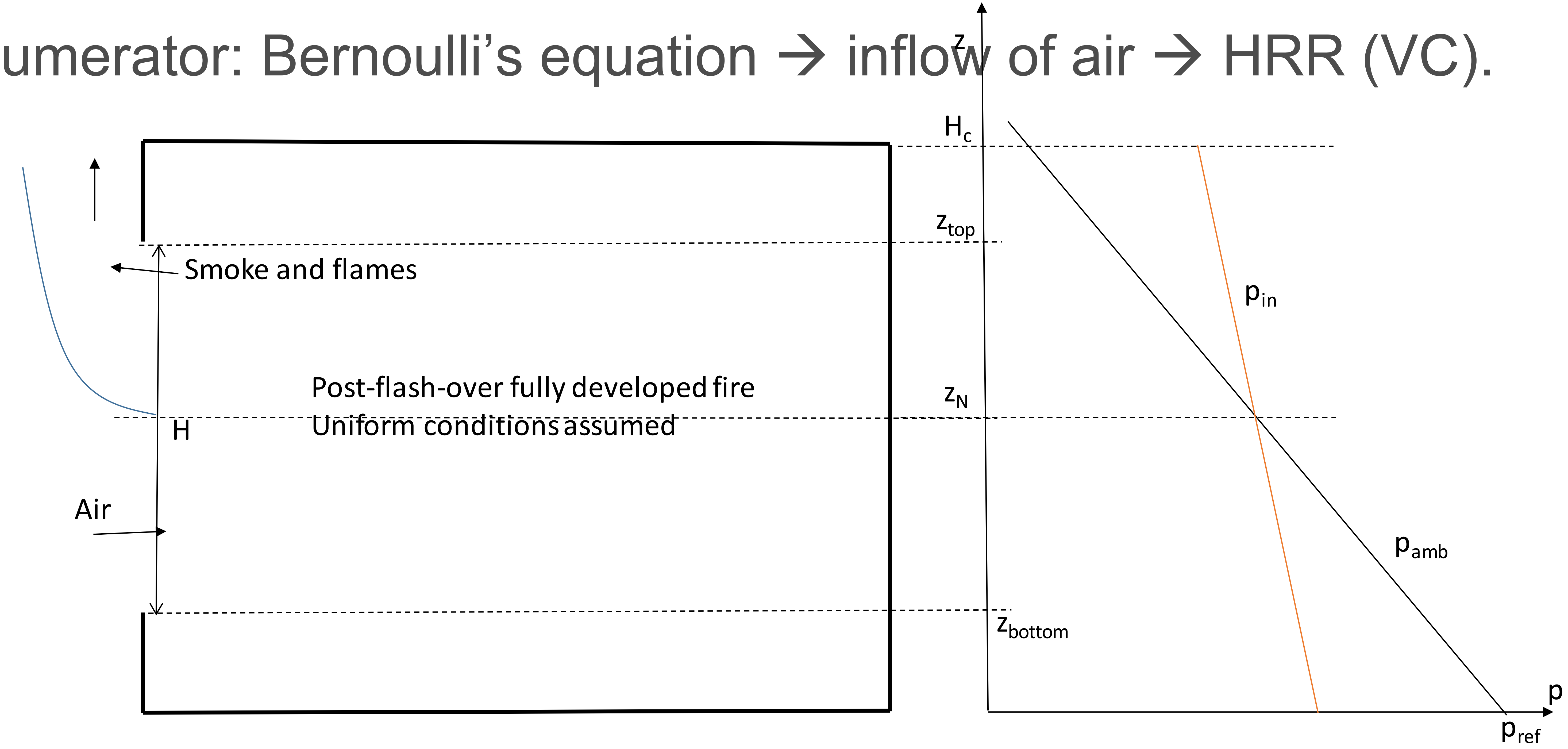
FIRE IN ENCLOSURES – VENTILATION

- Fully-developed phase: is typically ventilation-controlled.

  - Importance of the 'opening factor': $O.F. = \frac{A\sqrt{H}}{A_T}$.
    - A: total surface area of the ventilation openings;
    - H: height of the ventilation openings (assumed unique);
    - A_T: total area for heat exchange in the enclosure.

FIRE IN ENCLOSURES – VENTILATION

- Denominator: linked to heat losses.
- Numerator: Bernoulli's equation → inflow of air → HRR (VC).



FIRE IN ENCLOSURES – VENTILATION

- Numerator: Bernoulli's equation.

$$\dot{m}_{out} = C_{d,out} \int_{z_N}^{z_{top}} \rho \sqrt{2\left(\frac{\rho_{amb}}{\rho} - 1\right) g(z - z_N) W(z) dz}$$

$$\dot{m}_{out} = \frac{2}{3} C_{d,out} \rho W \sqrt{2\left(\frac{T}{T_{amb}} - 1\right) g\left(z_{top} - z_N\right)^{3/2}}$$

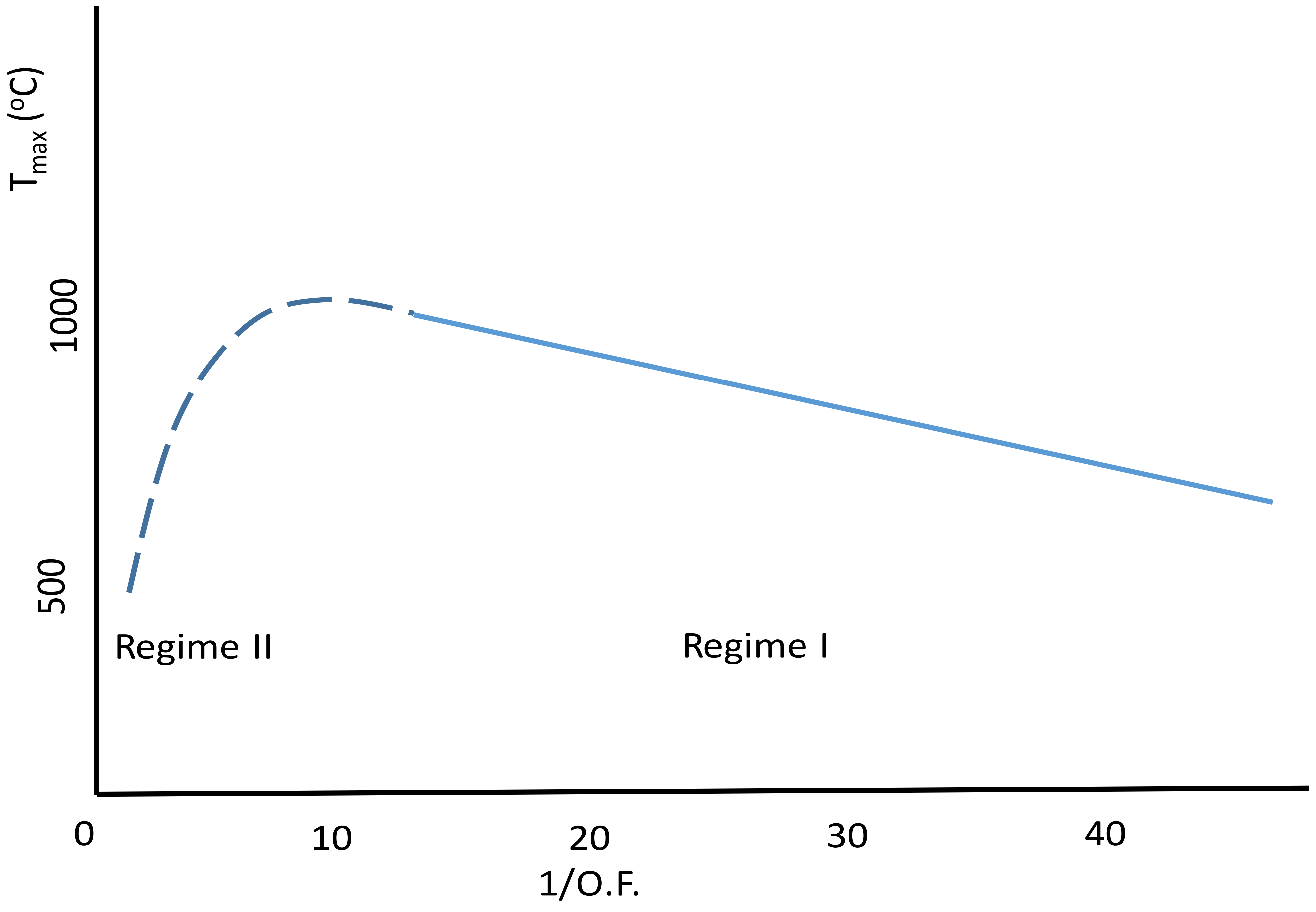
$$\frac{z_N - z_{bottom}}{z_{top} - z_N} = \left(\frac{T_{amb}}{T}\right)^{1/3}$$

$$\dot{m}_{out} = \frac{2}{3} C_{d,out} \rho \sqrt{2\left(\frac{T}{T_{amb}} - 1\right) g} W H^{3/2} \left(\frac{1}{1 + \left(\frac{T_{amb}}{T}\right)^{1/3}}\right)^{3/2}$$

$$W H^{3/2} = A\sqrt{H}$$

FIRE IN ENCLOSURES – VENTILATION

- The opening factor determines the expected temperature. [Does it?]



FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Note: ‘regime II’ fires strongly depend on the flows (‘momentum driven’).
- Many different types of fire are possible, particularly in large compartments (growing; travelling; evolution to flash-over).
- This is a very lively research area (e.g., work done at UQ):
  - Travelling fire: $\frac{v_F}{v_{BO}} \approx 1$;
  - Growing fire: $\frac{v_F}{v_{BO}} > 1$;
  - Fully developed fire: $\frac{v_F}{v_{BO}} \to \infty$.

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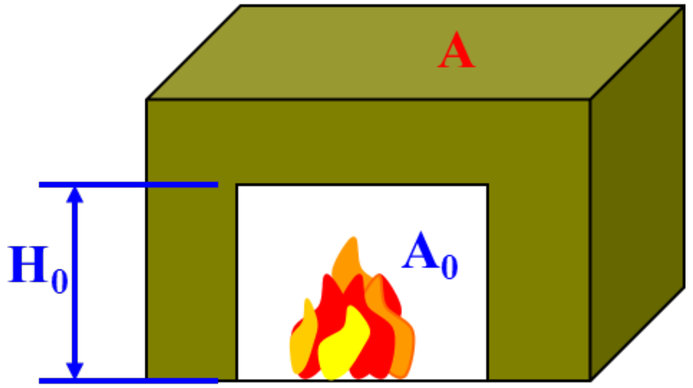
Courtesy dr. Vinny Gupta

- Immense body of experimental and theoretical research from the 1950s to 1970s
- Classification of **fully-developed fires** into two distinct *regimes* based on the ratio of the opening area and enclosure area (Thomas & Heselden, 1972)

Ventilation-controlled regime

Simplified solution

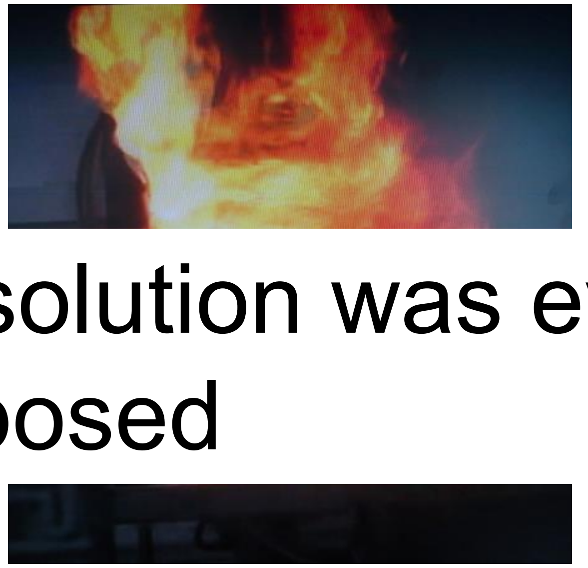
- Small openings
- Homogenous temperature
- Hydrostatically-driven
- *Temperature and burning rate determined by oxygen transport*



Opening factor

$$A_T/A_0\sqrt{H_0}$$

Momentum-controlled regime



No solution was ever proposed

- Large openings
- Non-homogenous temperature (x,y,z,t)
- Very large scatter
- Inertia-driven (geometry/fuel dependent)
- Burning rate governed by residence time

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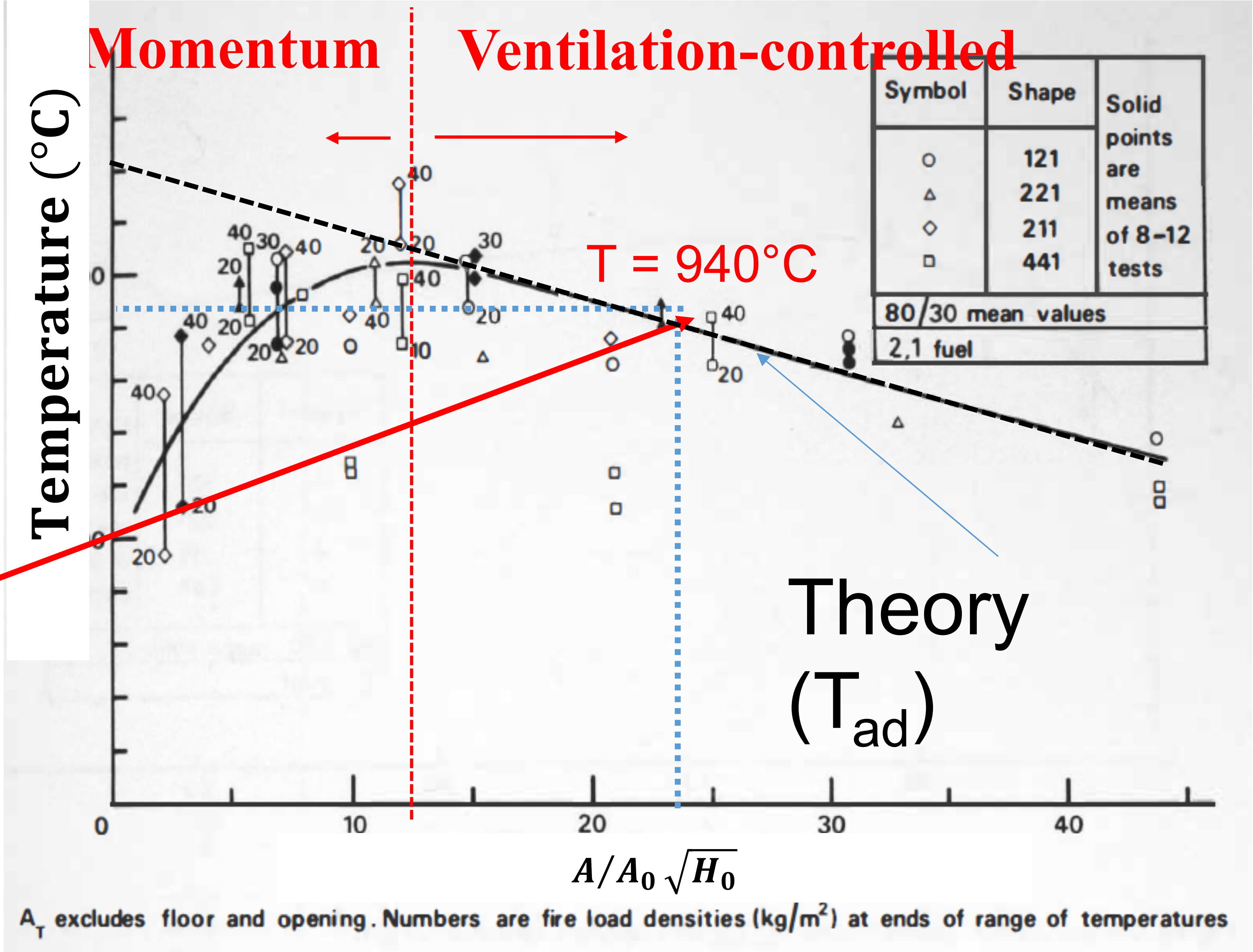
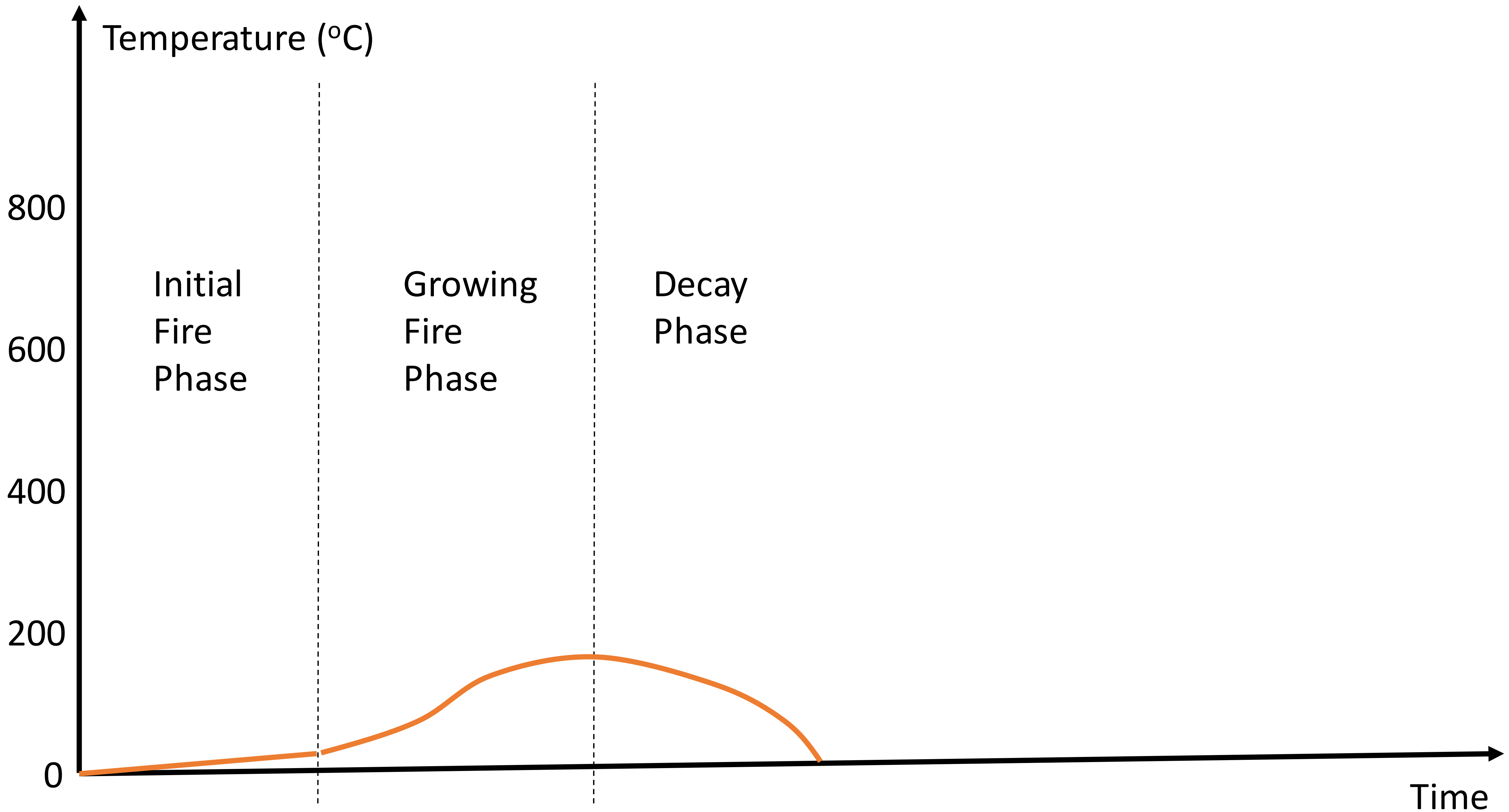
Rein, G., Abecassis Empis, C., and Carvel, R., “The Dalmarnock Fire Tests: Experiments and Modelling", The University of Edinburgh, Edinburgh, Scotland, UK, 2006.



Thomas, P.H., and Heselden, A.J.M., "Fully developed fires in single compartments", CIB Report No 20. Fire Research Note 923, Fire Research Station, Borehamwood, England, UK, 1972.

FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Growth phase:
  - Fire can die due to lack of fuel (fuel-controlled);



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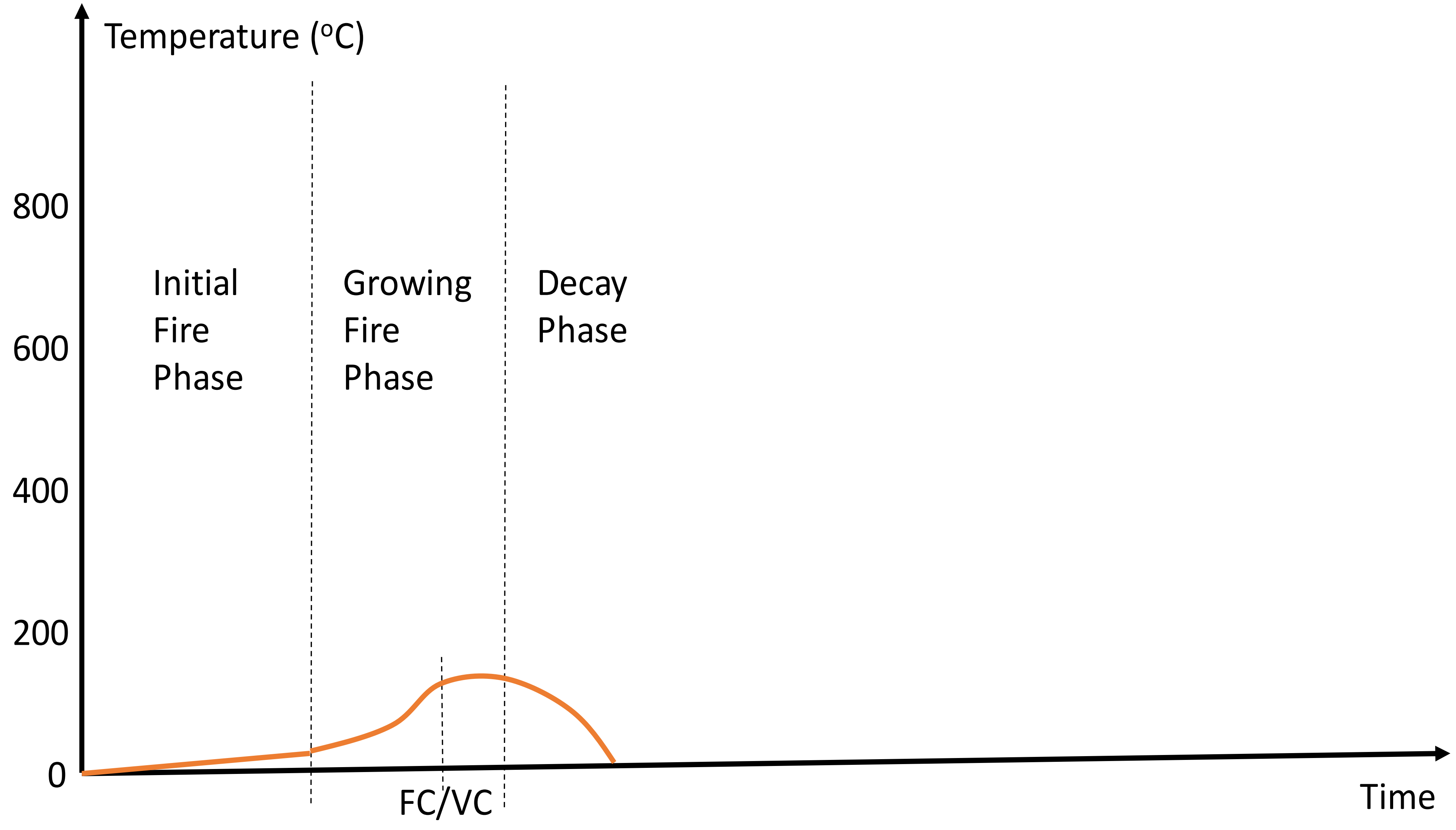
FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Growth phase:
  - Fire can die due to lack of fuel (fuel-controlled);
  - Fire can die due to lack of oxygen (ventilation-controlled);



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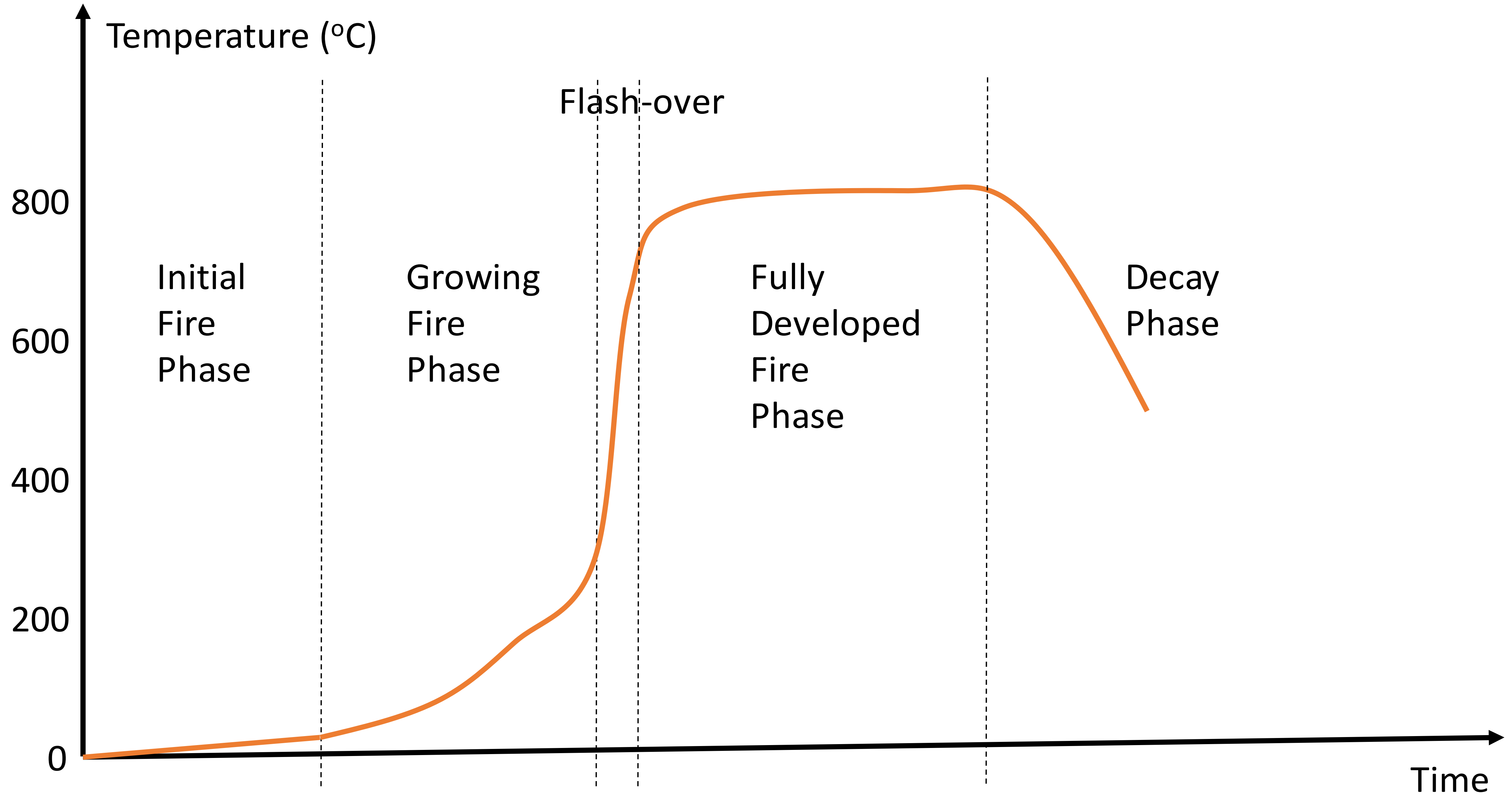
FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Growth phase:
  - Fire can die due to lack of fuel (fuel-controlled);
  - Fire can die due to lack of oxygen (ventilation-controlled);
  - Fire can grow due to a positive thermal feedback loop: more heat can be provided than what is needed for evaporation/pyrolysis per unit time.

FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Growth phase:
  - Fuel-controlled growth:



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FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Growth phase: complex process → simplified into t^2-fire: $\dot{Q} = \alpha(t - t_0)^2$.
- t_0: ‘incubation’ period between ignition and the first flames.
- α: determines the growth rate (note: a t^2-fire corresponds to a constant HRR per unit area, growing horizontally at constant speed in all directions).

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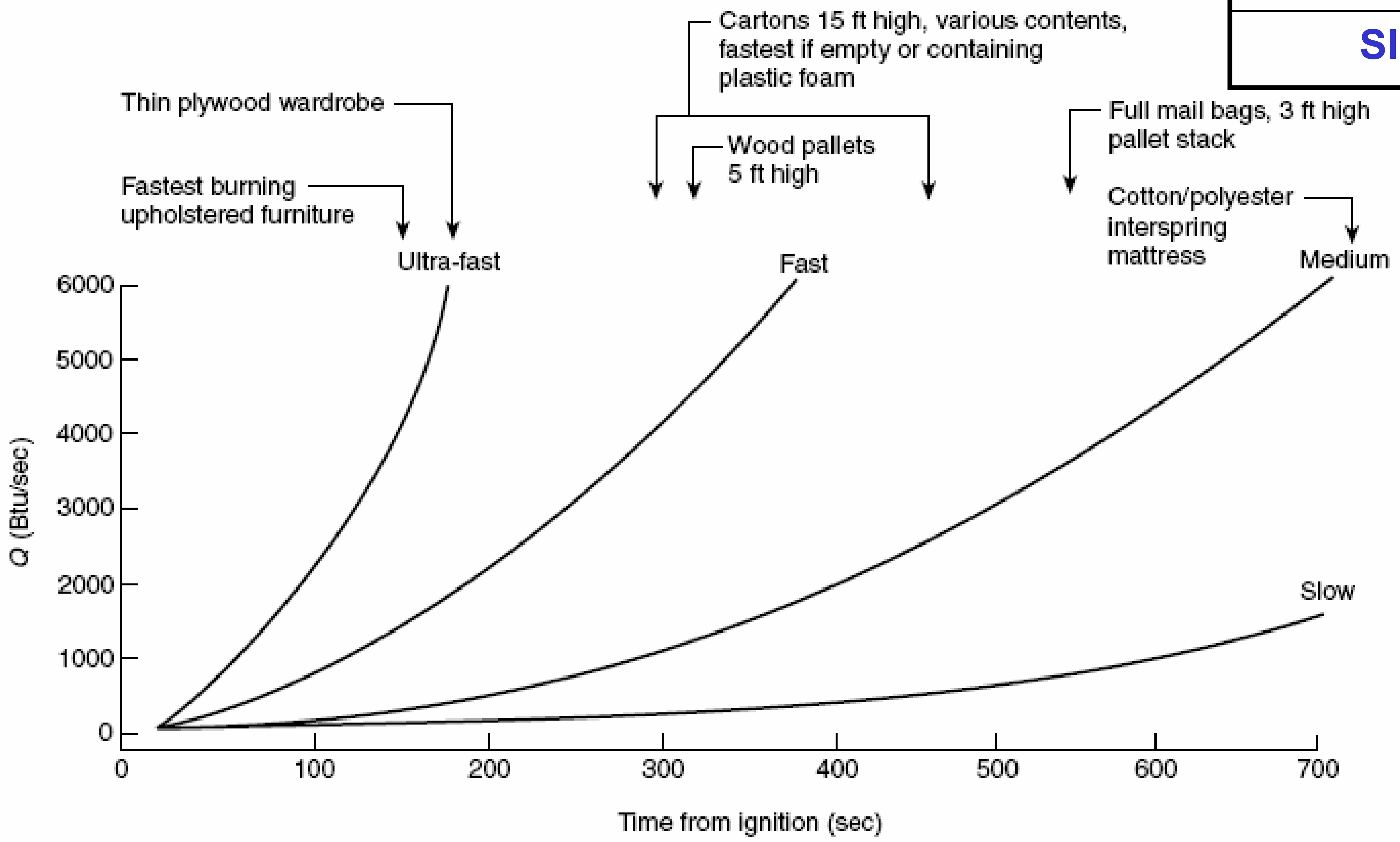
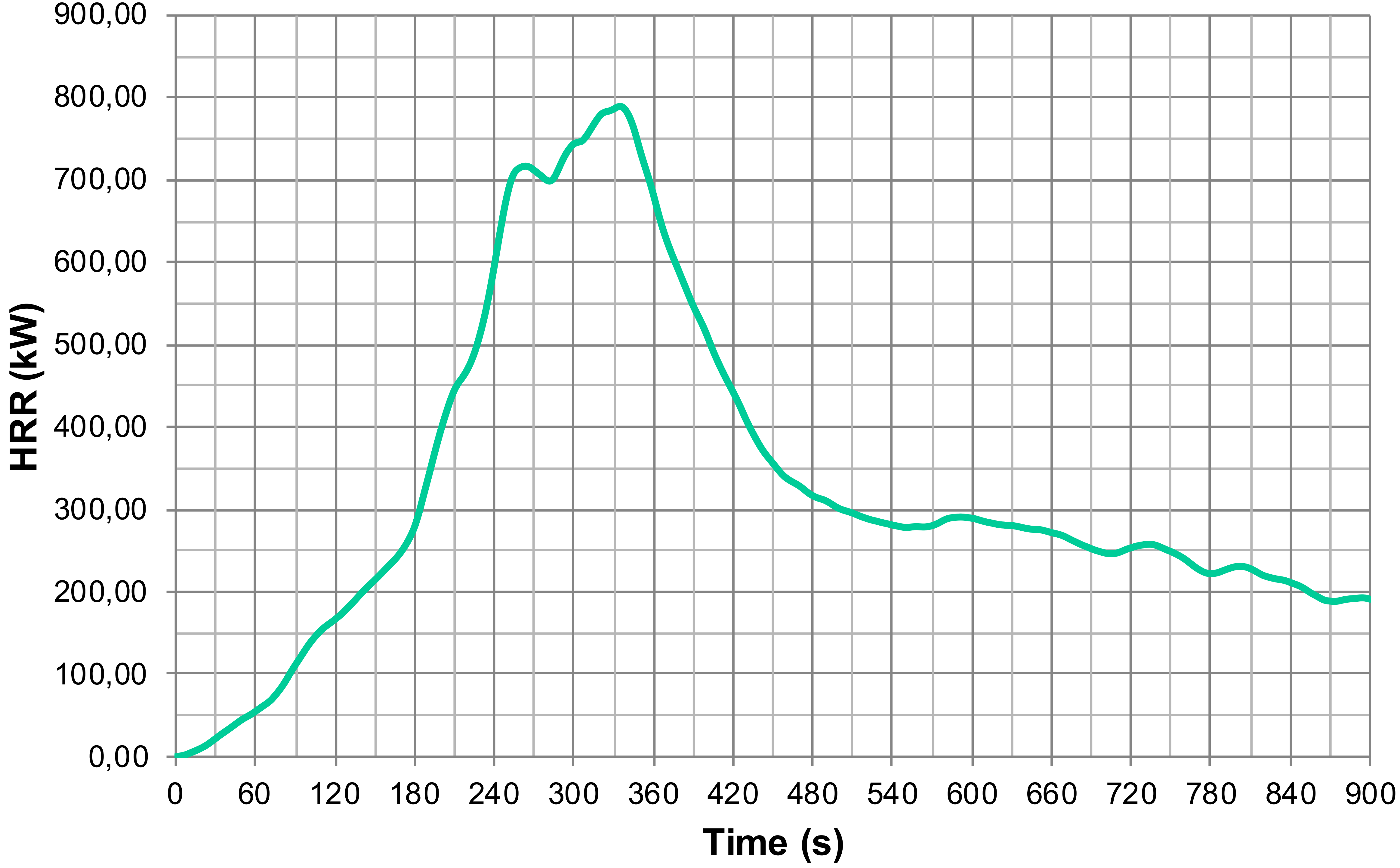
FIRE DEVELOPMENT IN ENCLOSURES - STAGES

Fire growth	Time to 1MW (s)	α (kW/s^2)
Ultra-fast	75	0.1876
Fast	150	0.0469
Medium	300	0.01172
Slow	600	0.00293



FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Example of a measurement: burning sofa.



- Courtesy WarringtonFireGent

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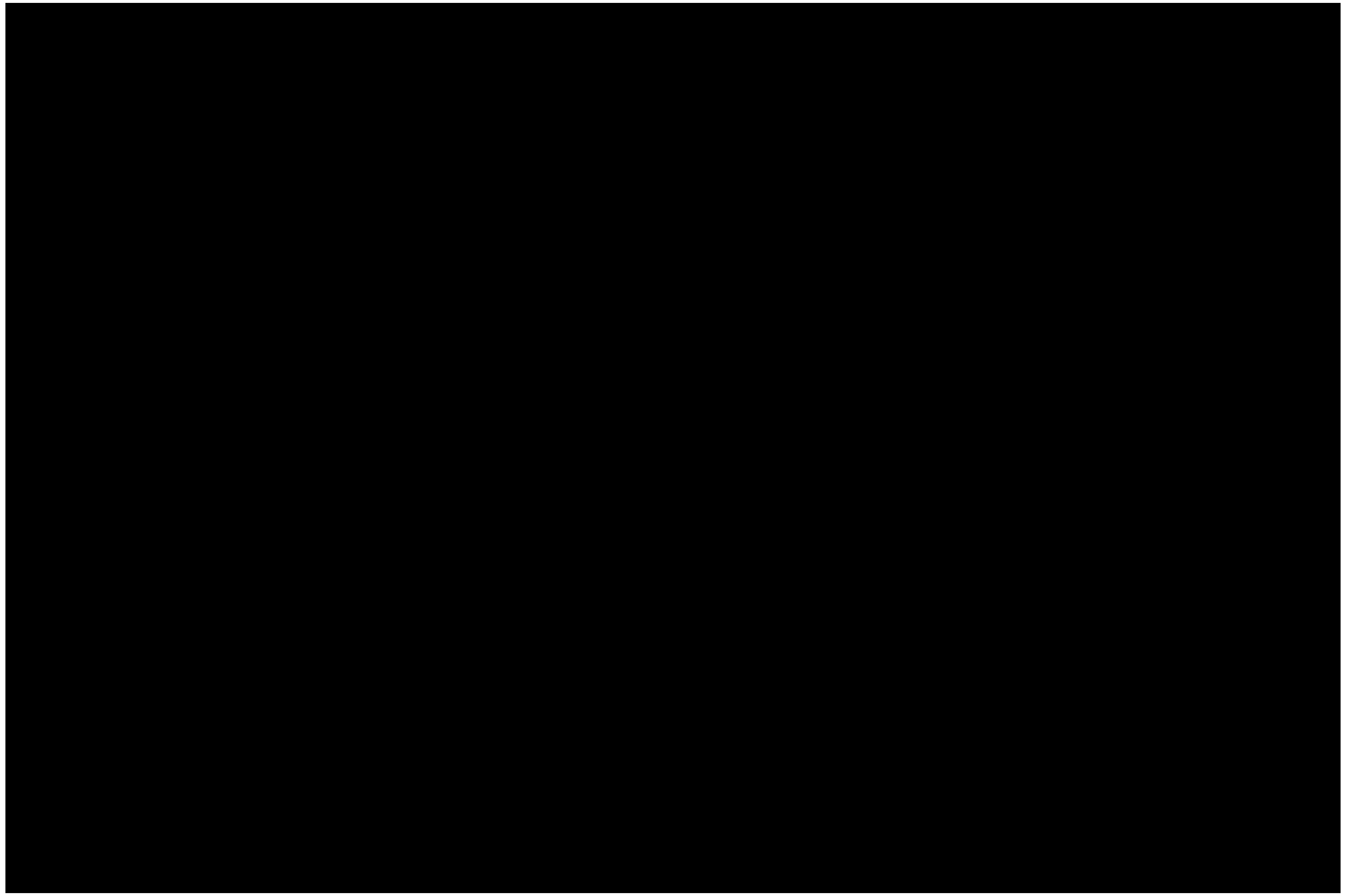
FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Growth phase:
  - Flash-over: very rapid transition to involvement of all the fuel in the combustion process.



FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Growth phase:
  - Flash-over criteria:
    - Smoke layer temperature reaches 500 – 600^{o}C (danger for smoke layer ignition);
    - Radiation heat flux at floor level reaches 15 – 20kW/m^2 (critical heat flux for ignition for many materials);
    - Flames are visible at openings (excess fuel, not burning inside the enclosure).

FIRE DEVELOPMENT IN ENCLOSURES - STAGES

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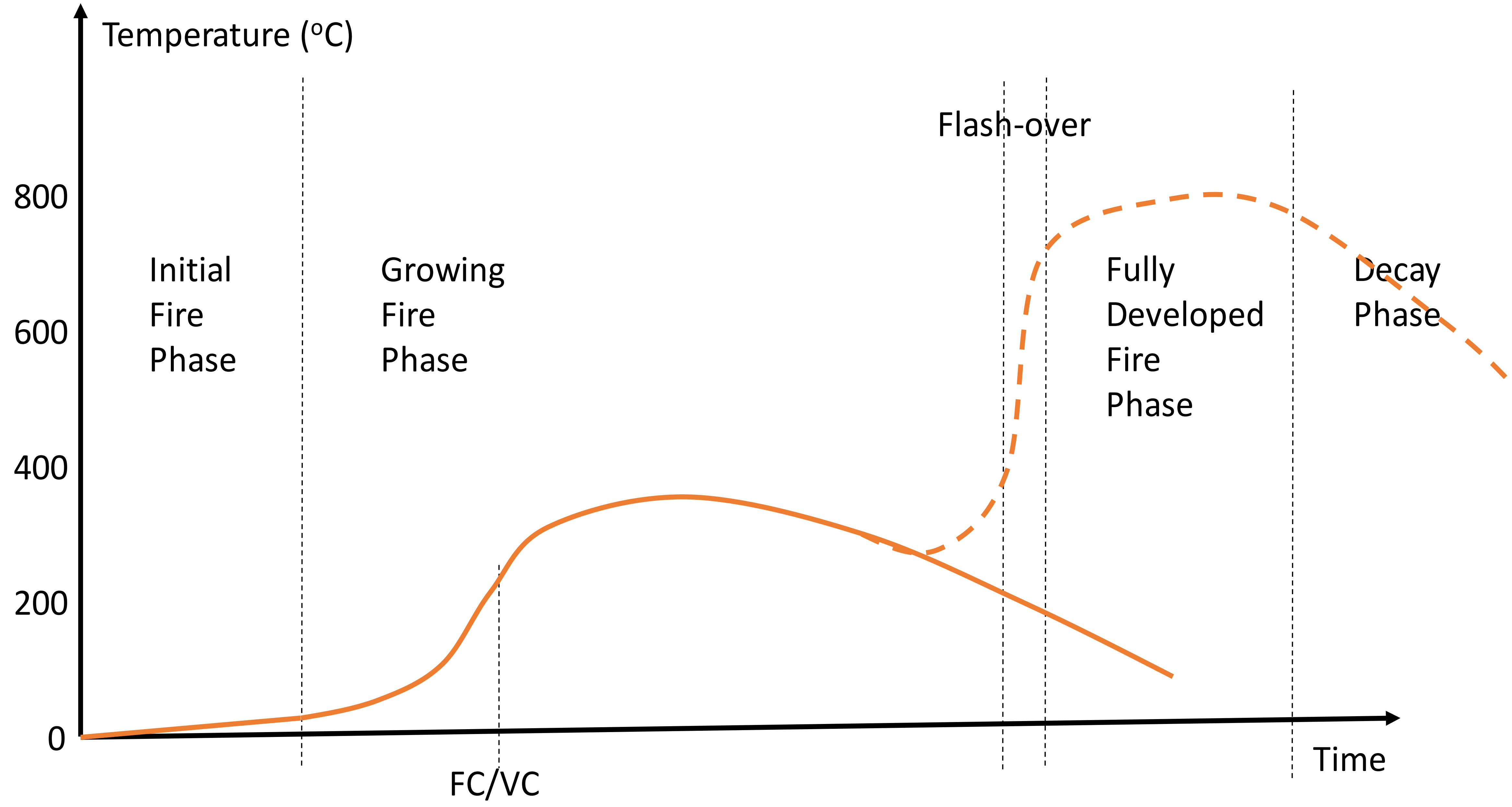
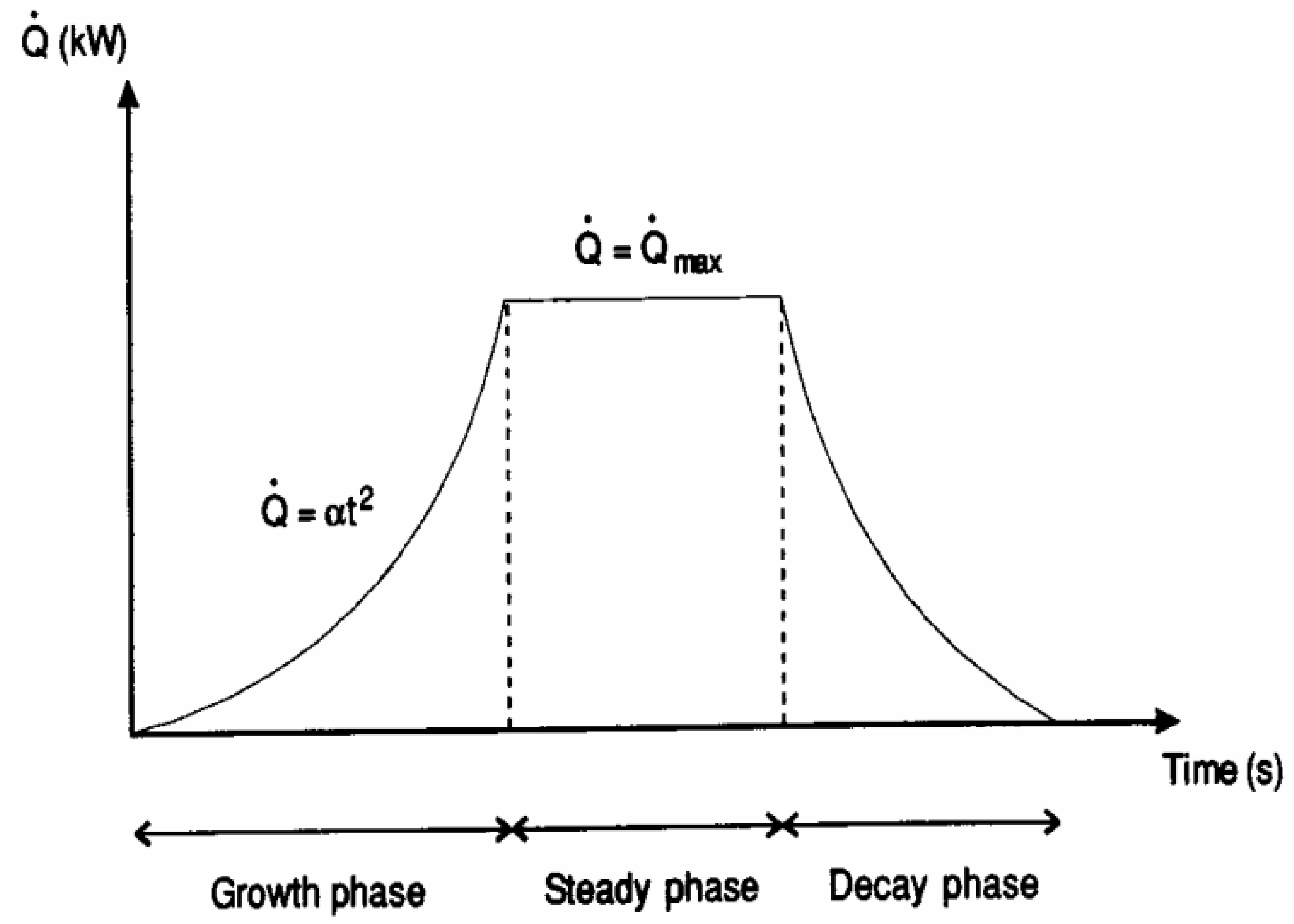
FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Growth phase:
  - Ventilation-controlled growth:



FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Fully-developed phase: the duration depends on the fire load and on the (maximum) HRR.



FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Fire load (theoretical): $F = \sum_i m_i \Delta H_{c,i}$
- Fire load (theoretical) per unit floor area: $F = \dfrac{\sum_i m_i \Delta H_{c,i}}{S}$
- ‘Effective’ fire load: takes into account incomplete combustion.
- Sometimes the fire load is expressed as ‘equivalent kg wood per m^2’. It is then implicitly assumed that 1 kg wood corresponds to 16MJ.

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FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- For a given (maximum) HRR, the duration of the fully developed phase increases linearly with F.
- For a given fire load, the duration of the fully developed phase decreases (inversely proportional) with (maximum) HRR.

FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Fully-developed phase: typically ventilation-controlled → the HRR is related to the mass flow rate of air through the openings.
- Recall: $\Delta H_{c,air} = 3kJ/g\ air$
- The mass flow rate through an opening is proportional to $A\sqrt{H}$ (see lecture on smoke dynamics).

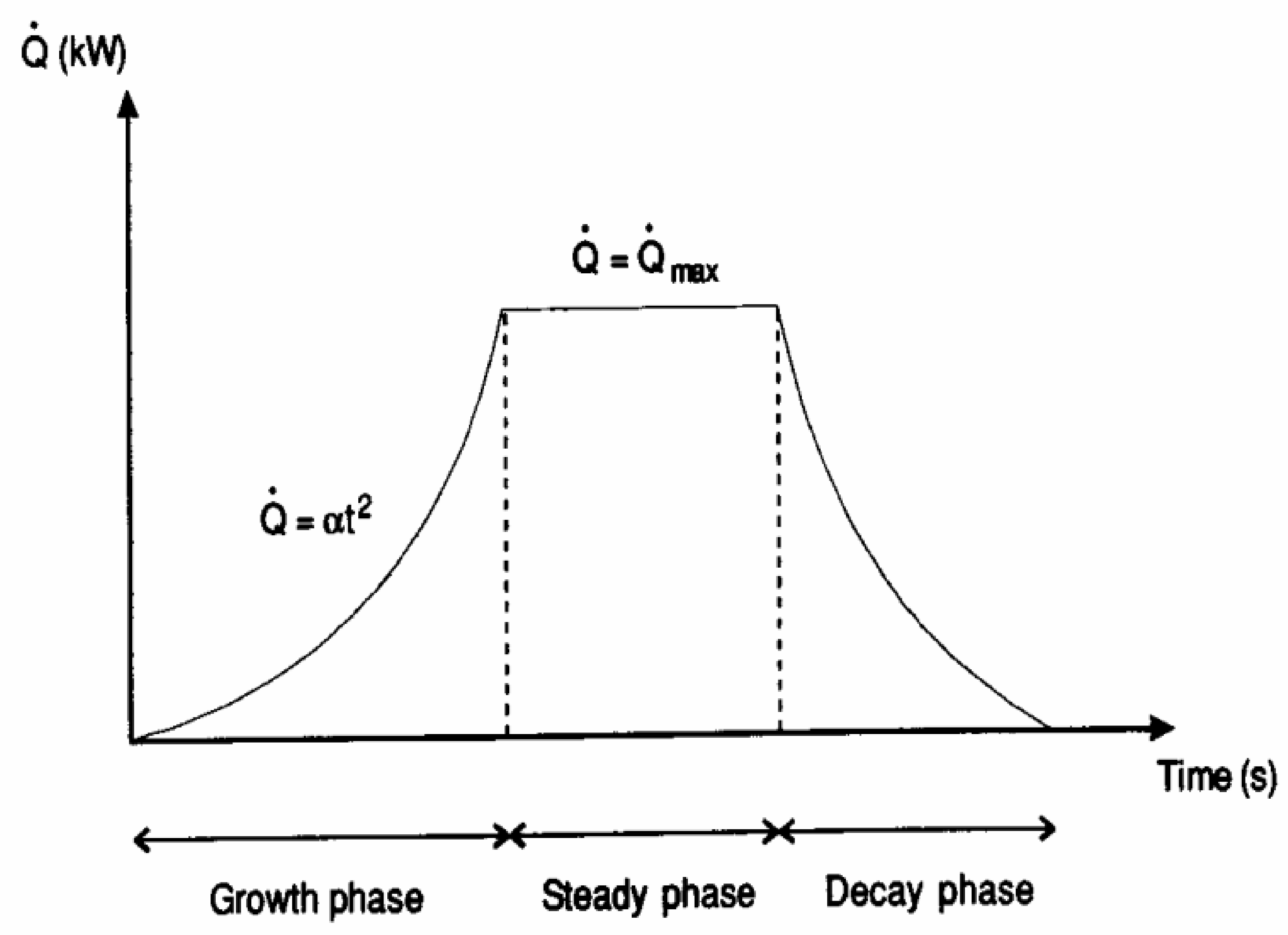
FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Combination: $\dot{Q} = 1260A\sqrt{H}$. [Units: HRR in kW; lengths in m]
  Caveat: not universally valid.

A_w (m^2) / H (m)	**0.5**	**1.0**	**2.0**	**4.0**	**6.0**
0.5	445	890	1780	3560	5350
1.0	630	1260	2520	5040	7560
2.0	890	1780	3560	7120	10700
3.0	1090	2180	4360	8730	13100

FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Decay phase: the fire becomes fuel-controlled again.

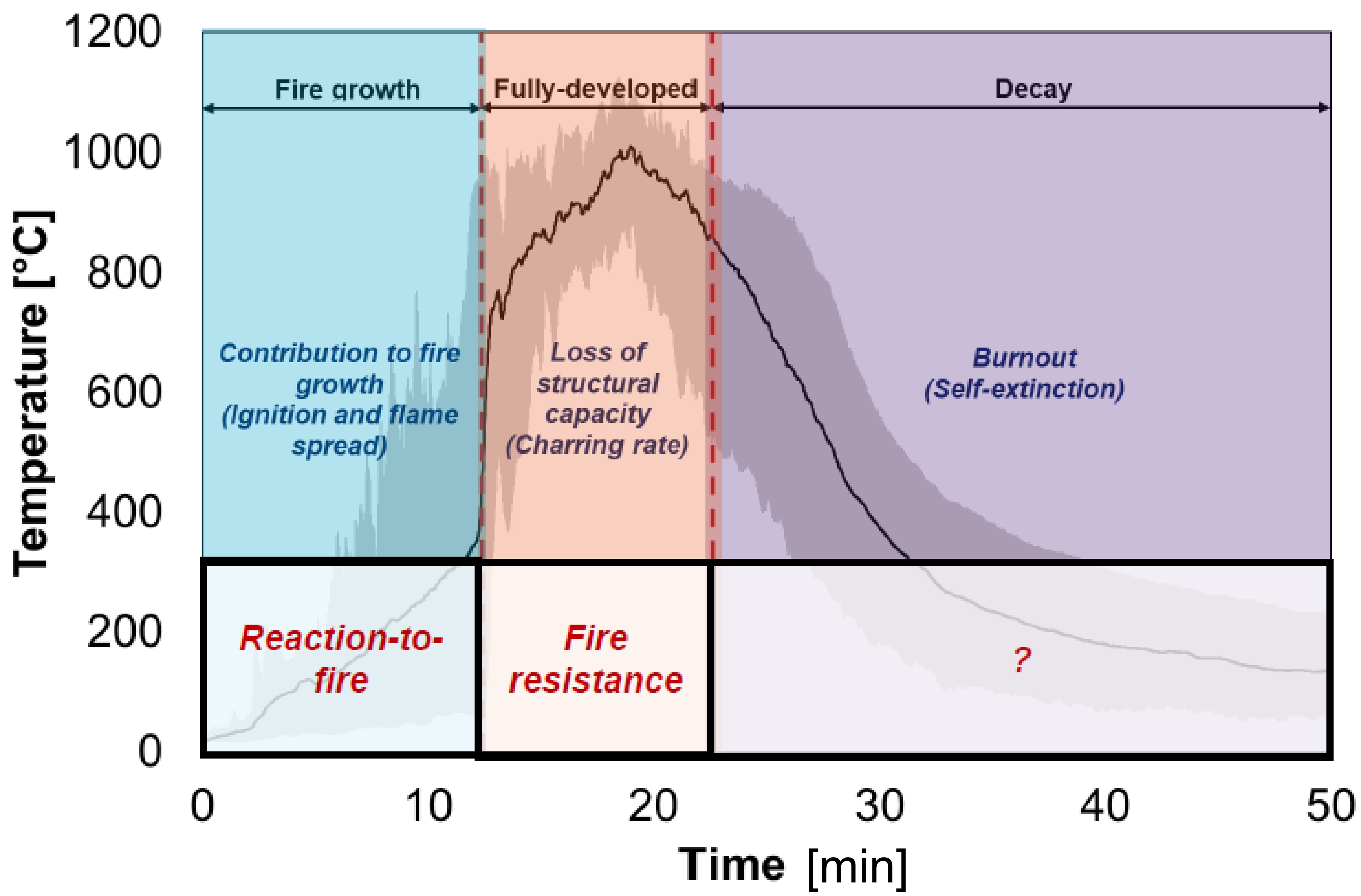


FIRE DEVELOPMENT IN ENCLOSURES - STAGES

- Importance of phases:
  - Growth phase: life safety.
  - Fully-developed phase: structural stability.
  - Decay phase: often considered less important (but: timber buildings! High-rise buildings! → lively research area).

FIRE RESISTANCE TESTS

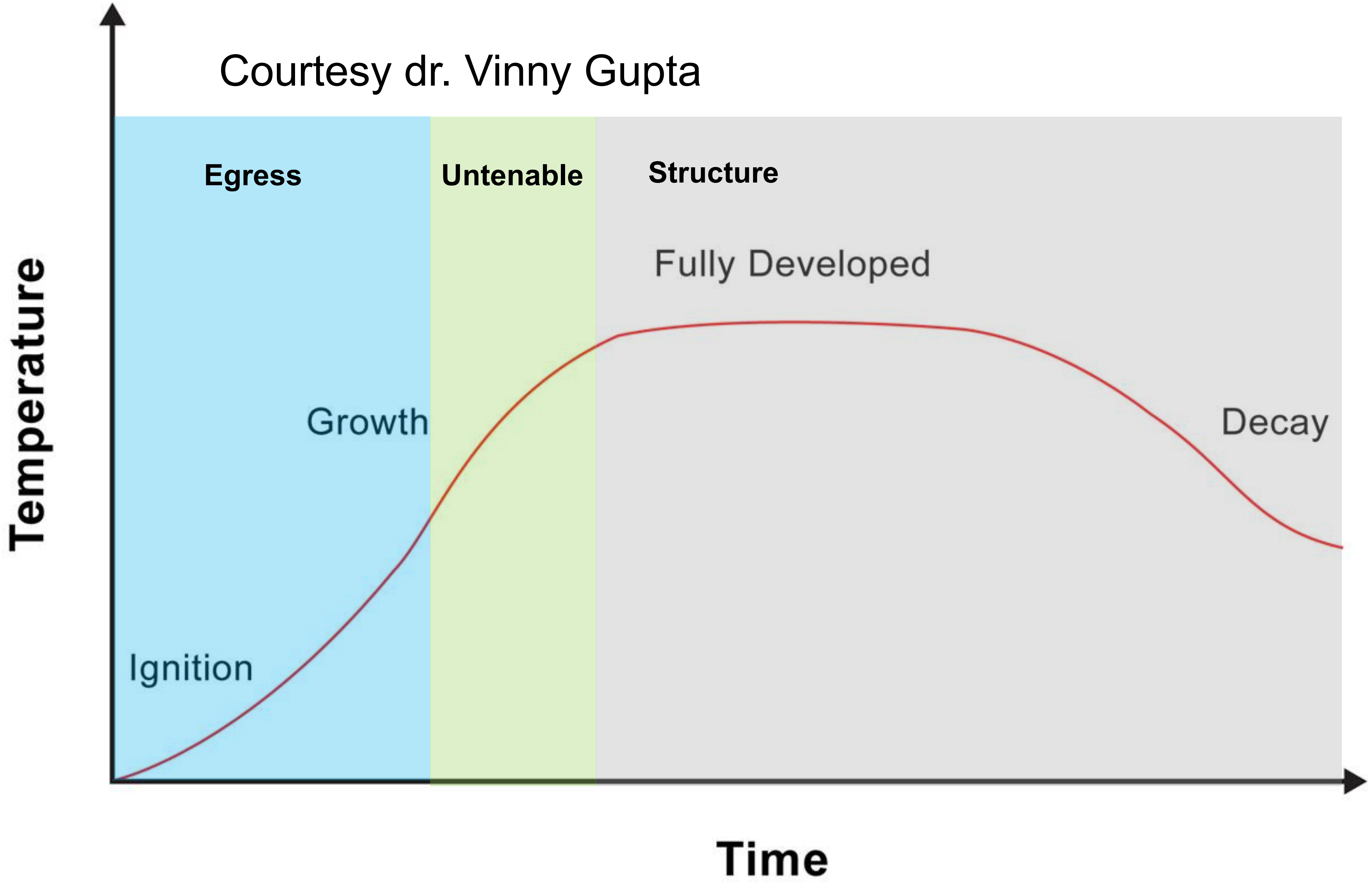
Existing frameworks to address fire-safe design of timber…



Adapted from Emberley at al. (2017) Description of small and large-scale cross laminated timber tests, Fire Safety Journal, 91:327-335.

Courtesy dr. Juan Hidalgo (UQ)

FIRE STAGES – FIRE SAFETY STRATEGY



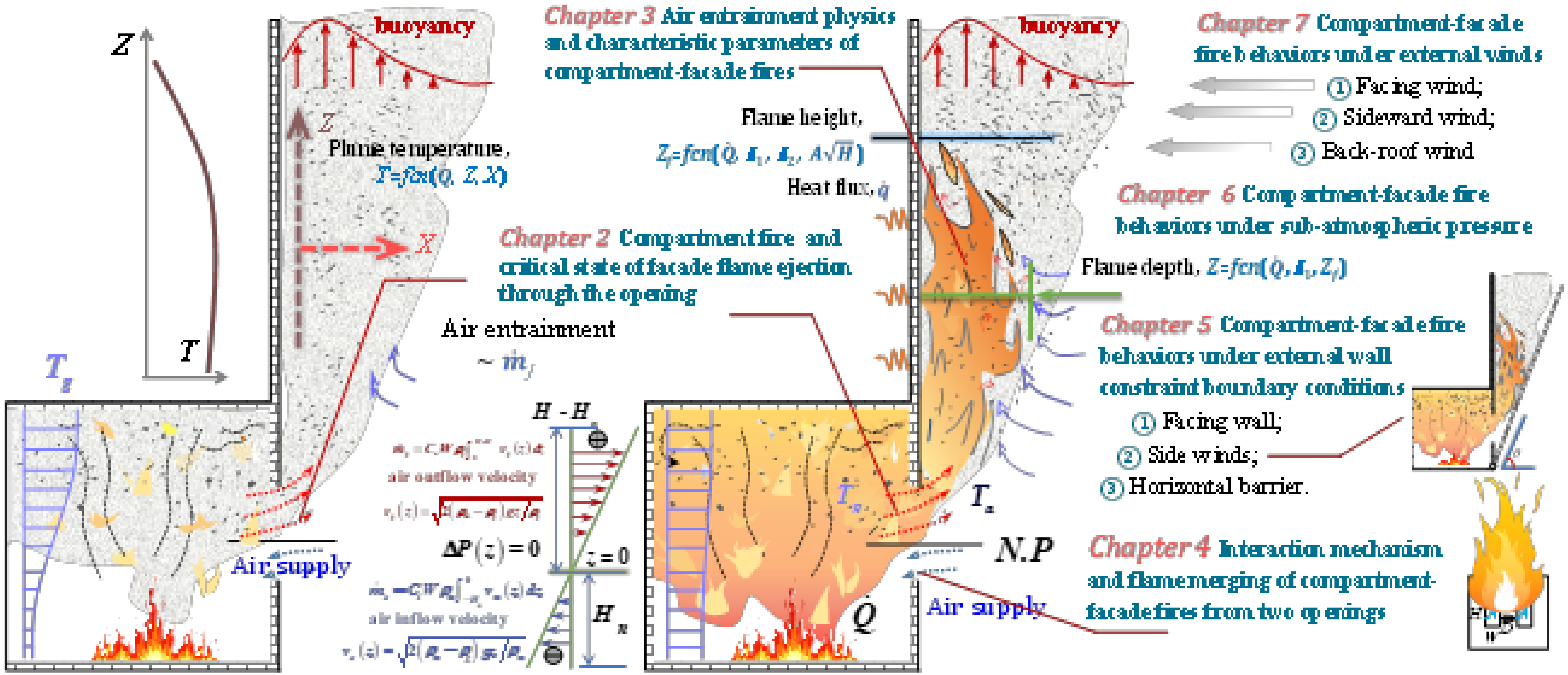
1. **Egress**
2. **Compartmentation**
3. **Structural integrity (beyond burnout)**

Relevant timescales

- Note: if the egress takes longer, the structural integrity is important.
- Note: firefighting can take long.

EJECTING FLAMES

- In VC fires, ejecting flames are possible (‘excess’ HRR).
- Many complex flow phenomena are possible, including wind.



Courtesy: Prof Longhua Hu, USTC

THE IMPORTANCE OF THE FLOW FIELD

THE IMPORTANCE OF THE FLOW FIELD

- Only in a limited sub-set of configurations, namely relatively small compartments (‘boxes’) with a limited number of openings (1?), the fire drives everything and the flow field is simplified to Bernoulli’s equation (static pressure difference over the opening(s)).
- In all other circumstances, the flow field is important.
- In other words: the problem is ‘momentum-driven’, rather than ’buoyancy-driven’.
- Useful tool to quantify the flow field: CFD.

CFD – BRIEF INTRODUCTION

- CFD = Computational Fluid Dynamics.
- CFD models are the most sophisticated deterministic models.
- Other name in literature: ‘Field Models’.
- Volume in which calculations are performed, is subdivided into a large number of sub-volumes (computational mesh or grid).
- Quantities are assumed uniform in the individual sub-volumes.

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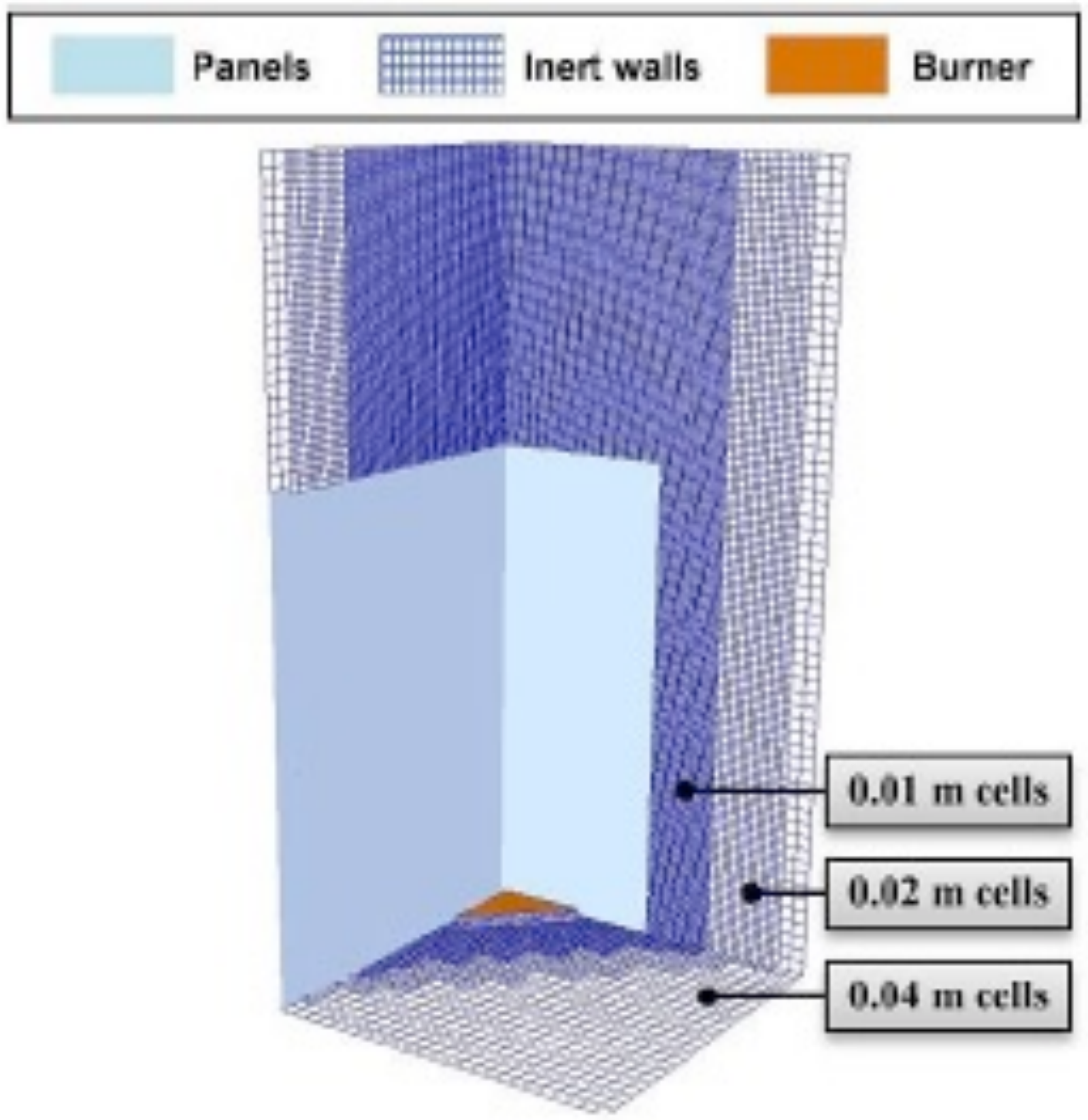
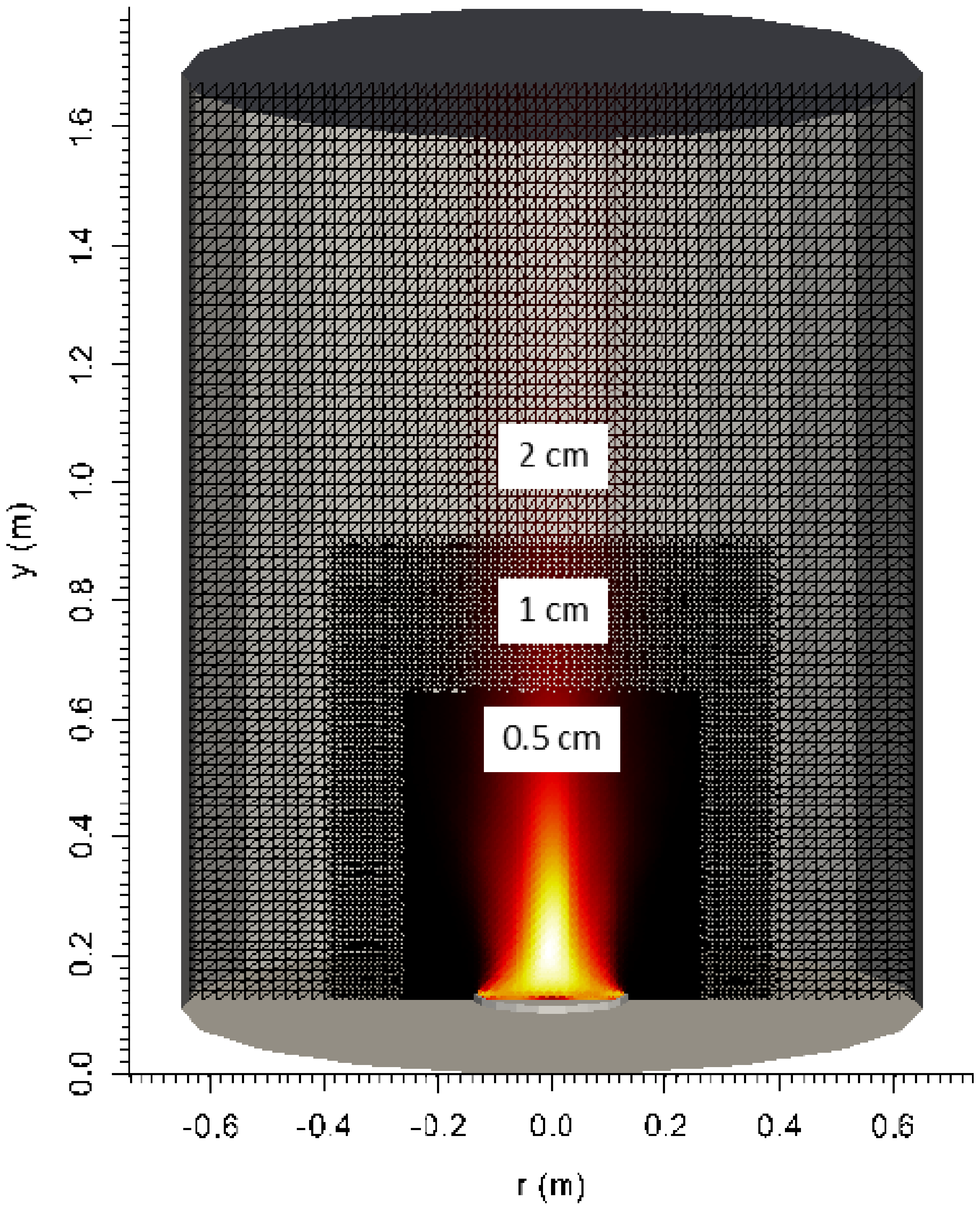
CFD – BRIEF INTRODUCTION





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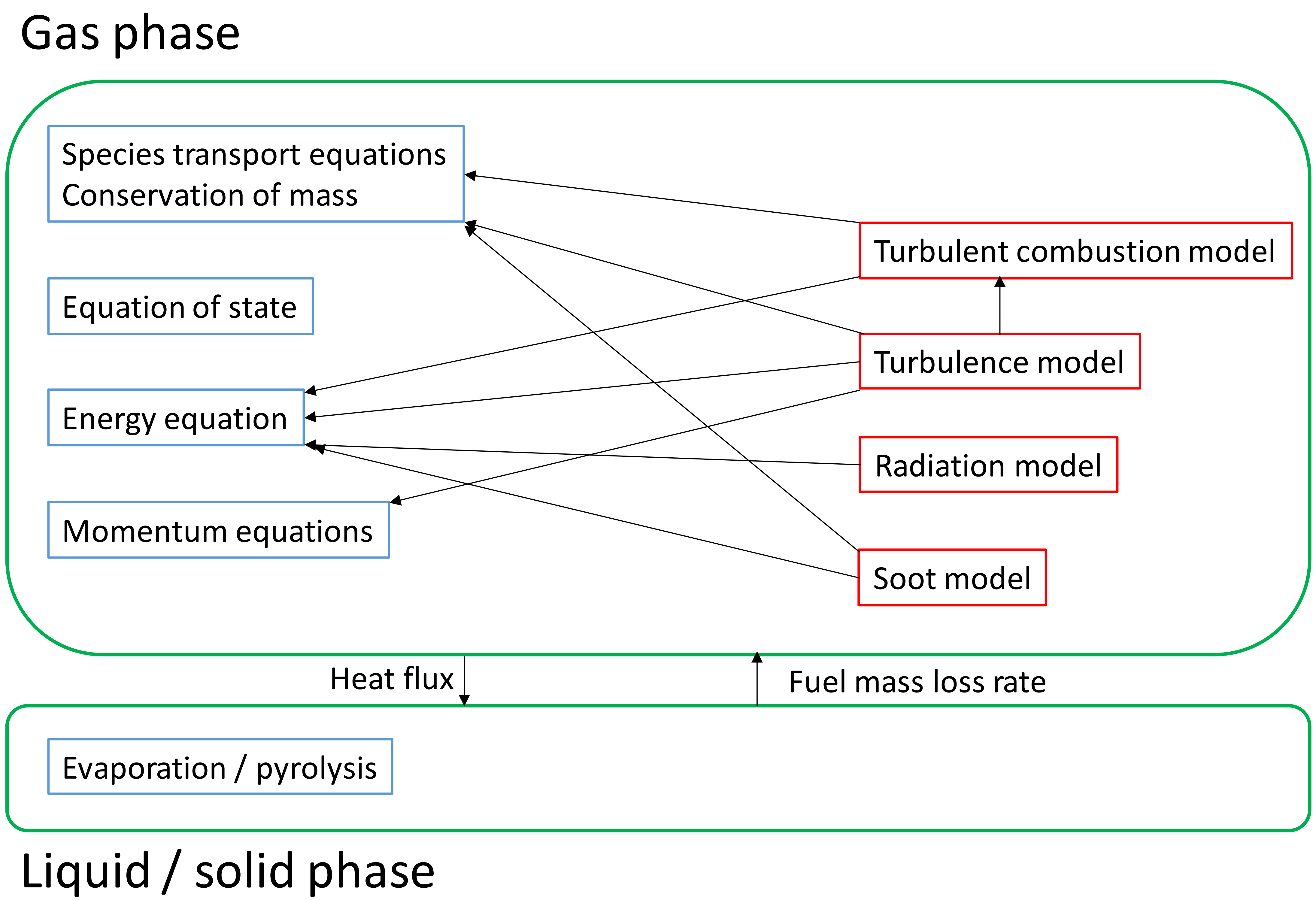
CFD – BRIEF INTRODUCTION

- CFD modelling is based on the (time-accurate and) three-dimensional solution of the fundamental conservation equations:
  - Conservation of mass;
  - Conservation of total momentum;
  - Conservation of energy;
  - Transport, generation and destruction of species.

CFD – BRIEF INTRODUCTION



CFD – RESOLUTION

- Sufficient resolution is required for CFD results to be reliable:
  - Computational mesh;
  - Radiation (e.g., number of angles).
- A sensitivity study is always necessary!

CFD – RESOLUTION (EX.: MESH)

- Always consider the important length scales for the problem at hand!
- Free fire / smoke plume:
  - (Hydraulic) diameter of the fire source. Rule of thumb: at least 10 cells across the (hydraulic) diameter.
  - D* criterion, based on heat release rate: $D^* = \left[\frac{\dot{Q}}{\rho_\infty C_\infty T_\infty \sqrt{g}} \right]^{2/5}$
  - Range cell size: $4 < \frac{D^*}{\delta x} < 16$

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CFD – RESOLUTION (EX.: MESH)

- Flow through openings:
  - (Hydraulic) diameter of the fire source. Rule of thumb: at least 10 cells across the (hydraulic) diameter.

$$\ell_2^* = D_h / \delta_x = (2W \cdot H / (W + H)) / \delta_x$$

  - Ventilation factor. Rule of thumb: at least 10 cells.

$$\ell_1^* = \ell_1 / \delta_x = (A\sqrt{H})^{2/5} / \delta_x$$

  - PhD Guoxiang Zhao (December 2017).

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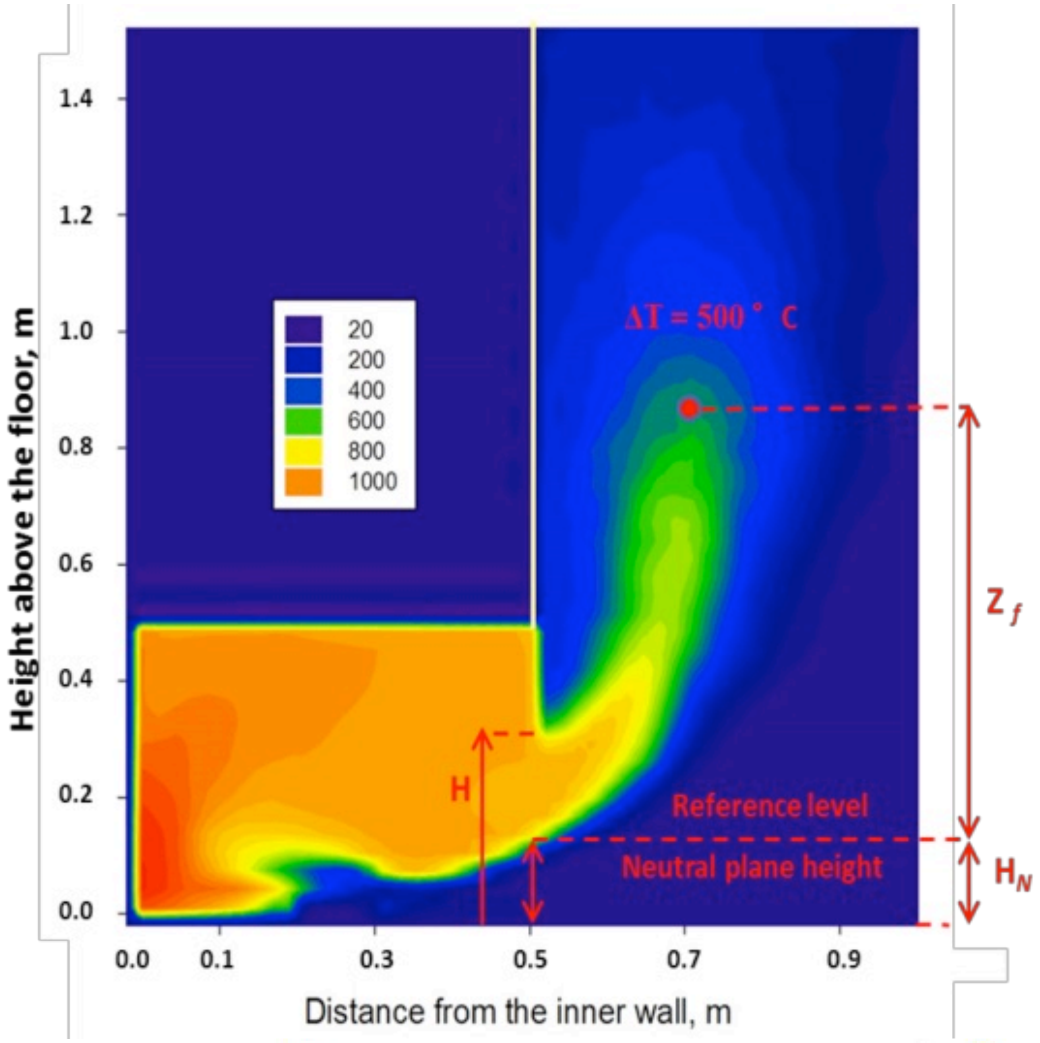
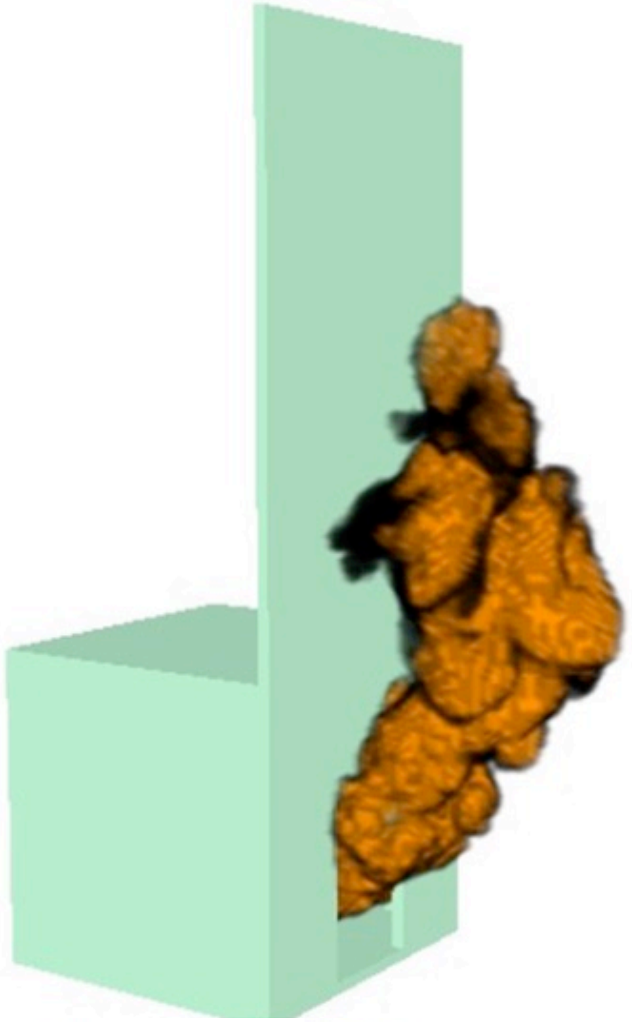
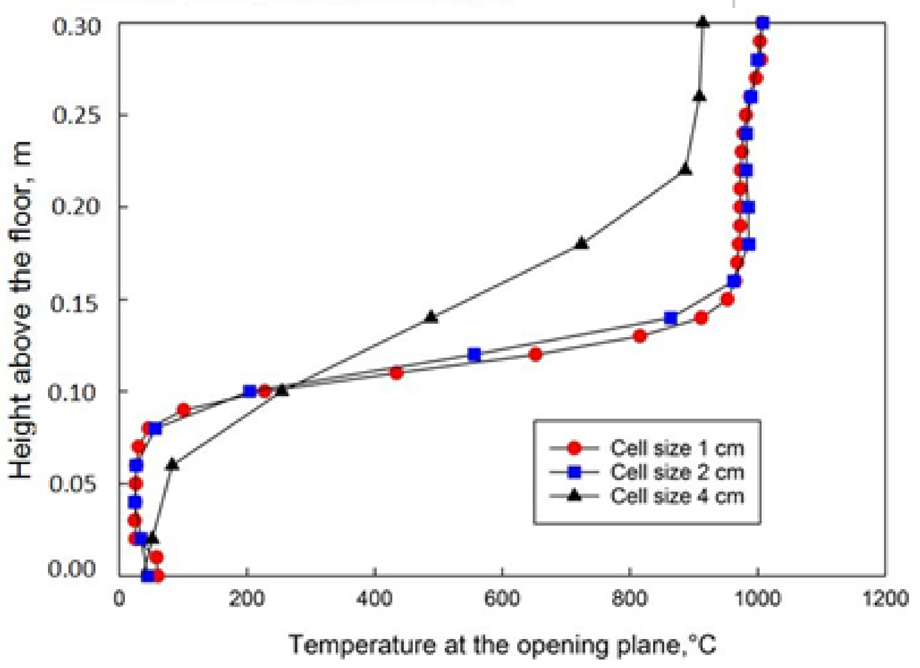
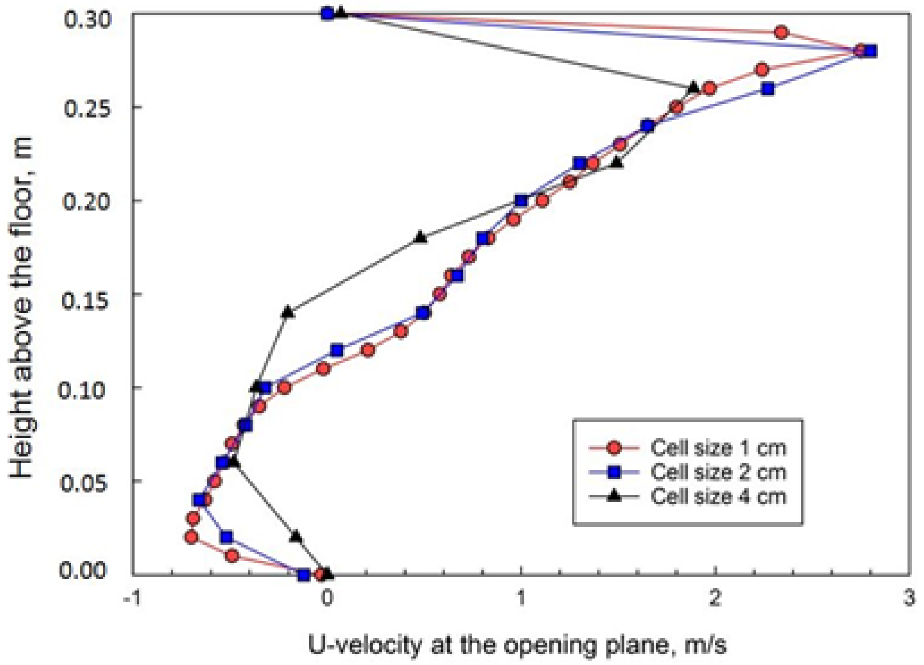
CFD – RESOLUTION (EX.: MESH)









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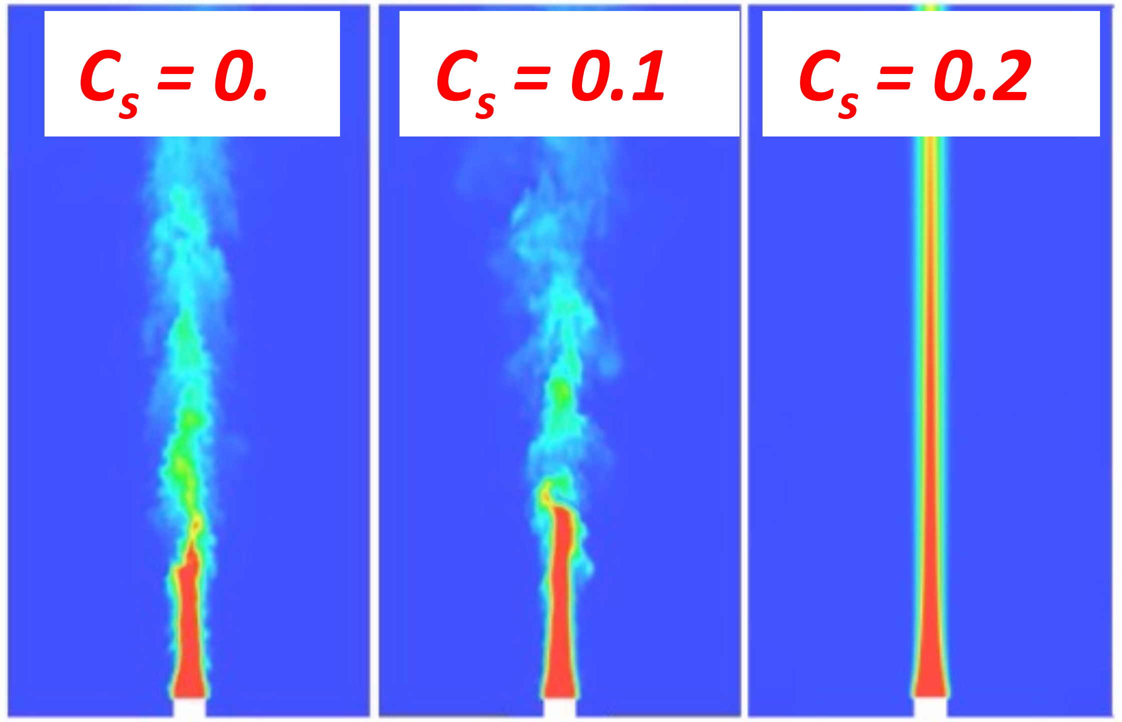
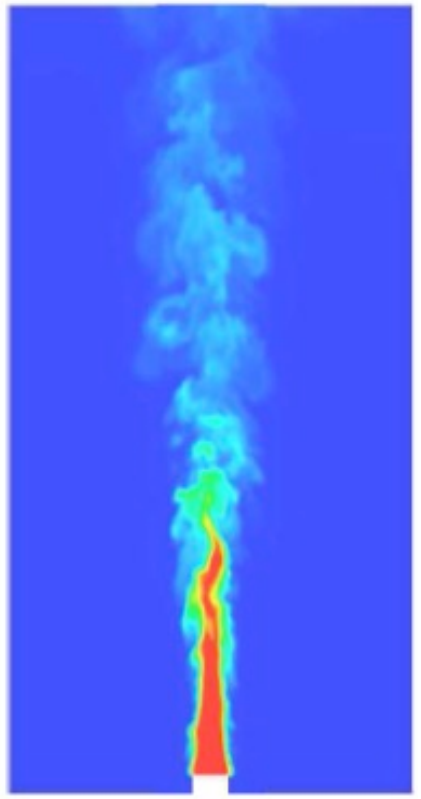
Temperature and horizontal velocity at centerline of the opening plane

CFD – MODELLING (EX.: TURBULENCE)

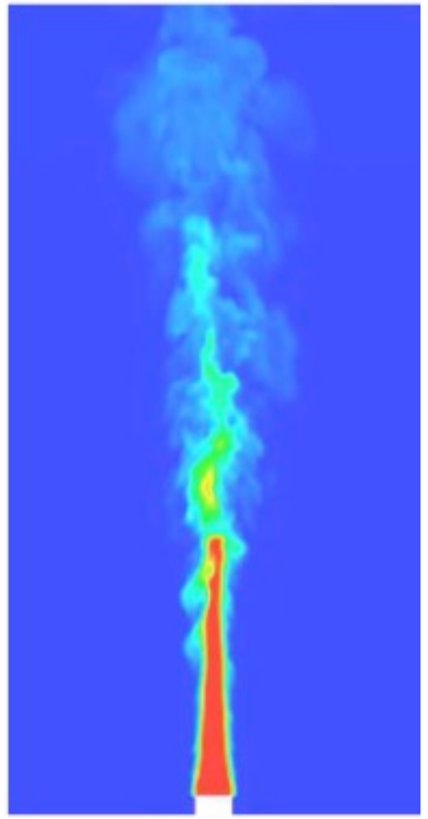
‘Static’ Smagorinsky



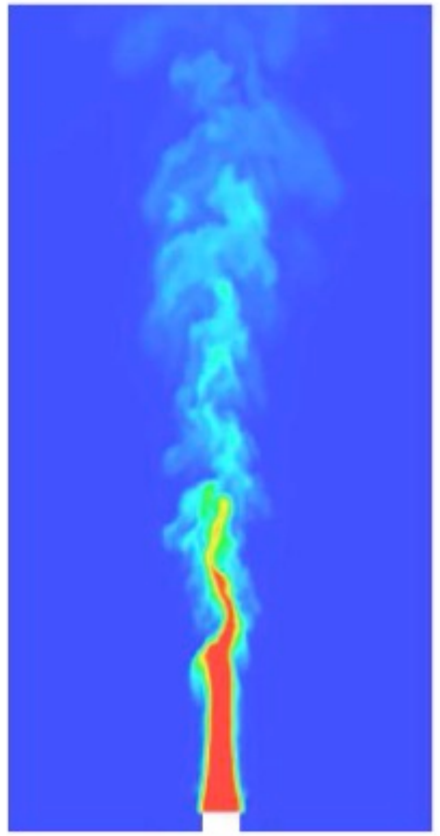
‘Dynamic’
Smagorinsky



‘Deardorff’
C =0.1



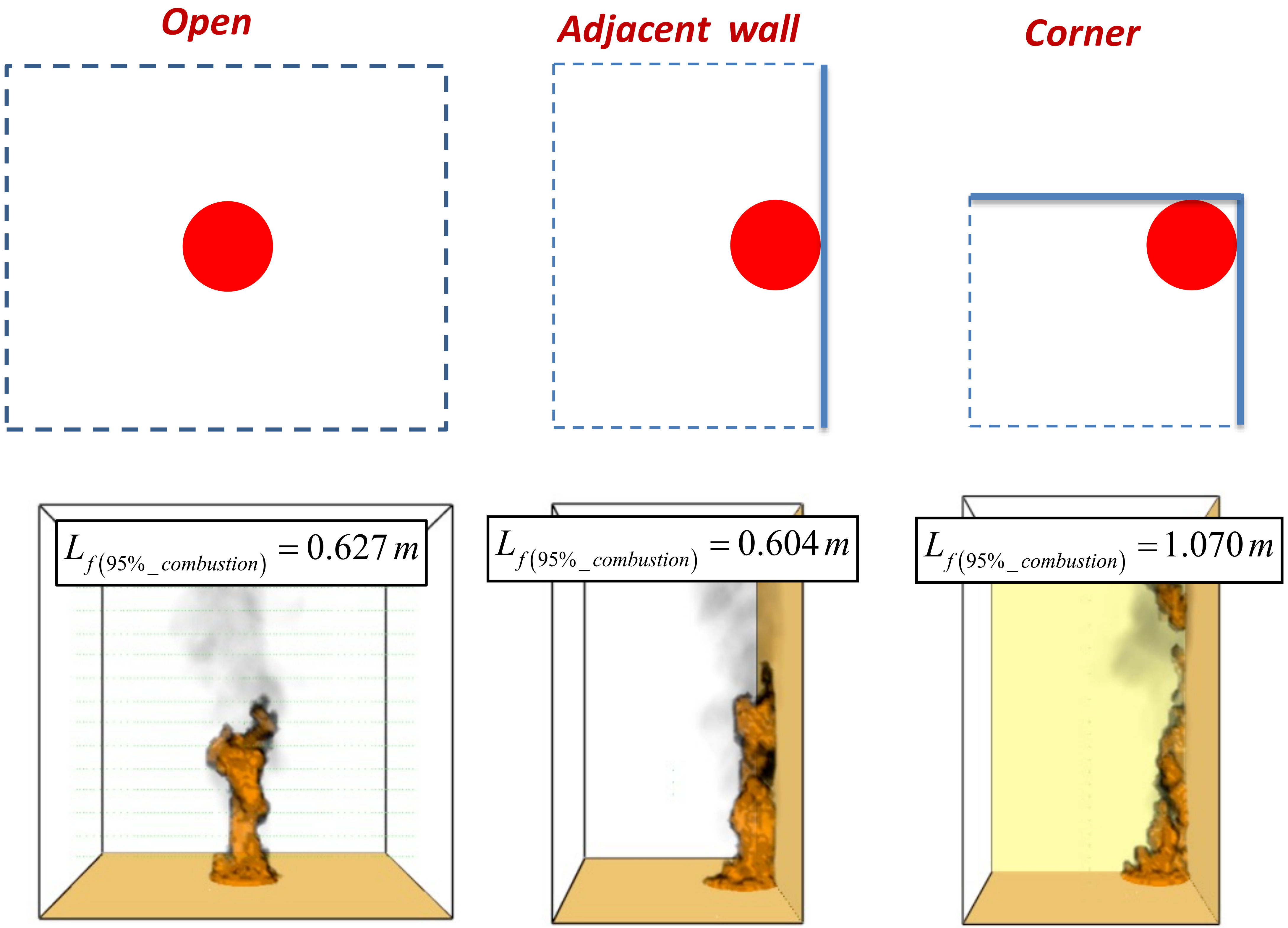
‘Vreman’
C =0.07



CFD – BOUNDARY CONDITIONS

- Boundary conditions (and initial conditions) determine the specific solution of the generic equations.
- Different types of boundary conditions:
  - Inlet BC (e.g., fire, forced air flow, fuel mass loss rate);
  - Outlet BC (e.g., extraction flow rate);
  - Wall BC;
  - Open BC.

CFD – BOUNDARY CONDITIONS



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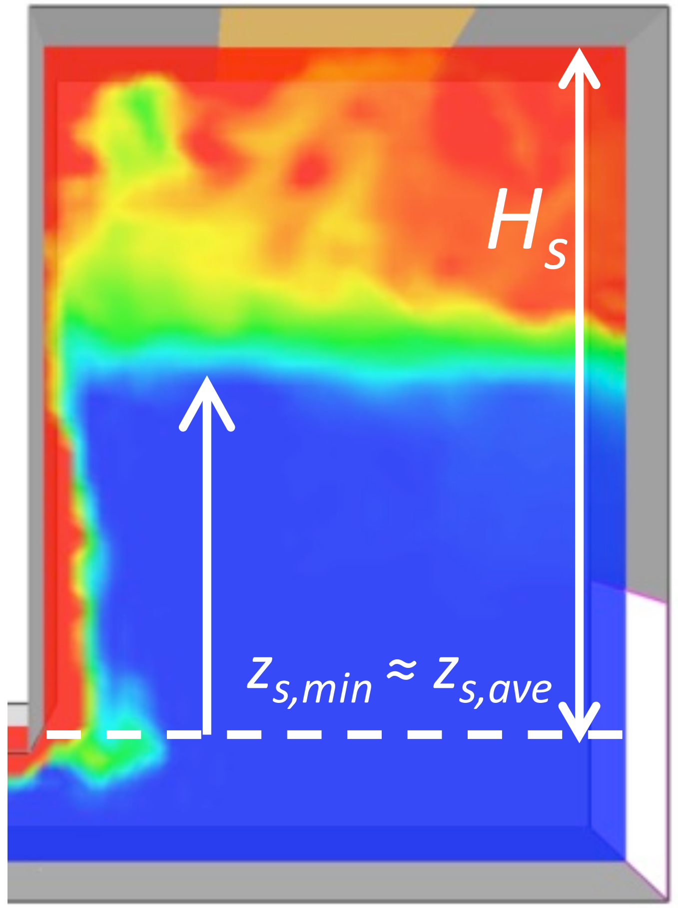
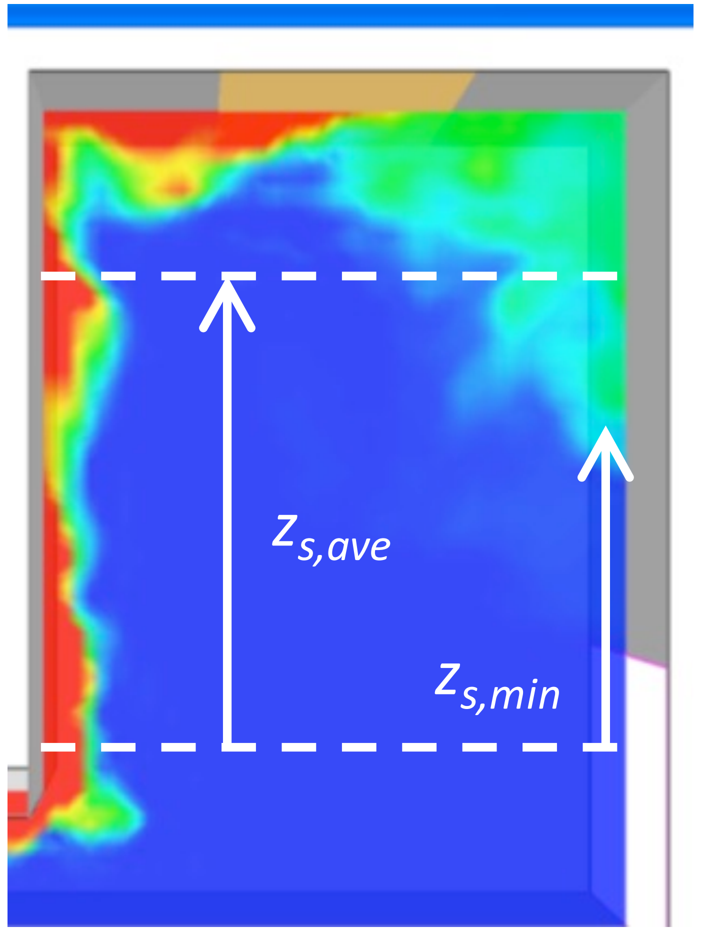
CFD – BOUNDARY CONDITIONS

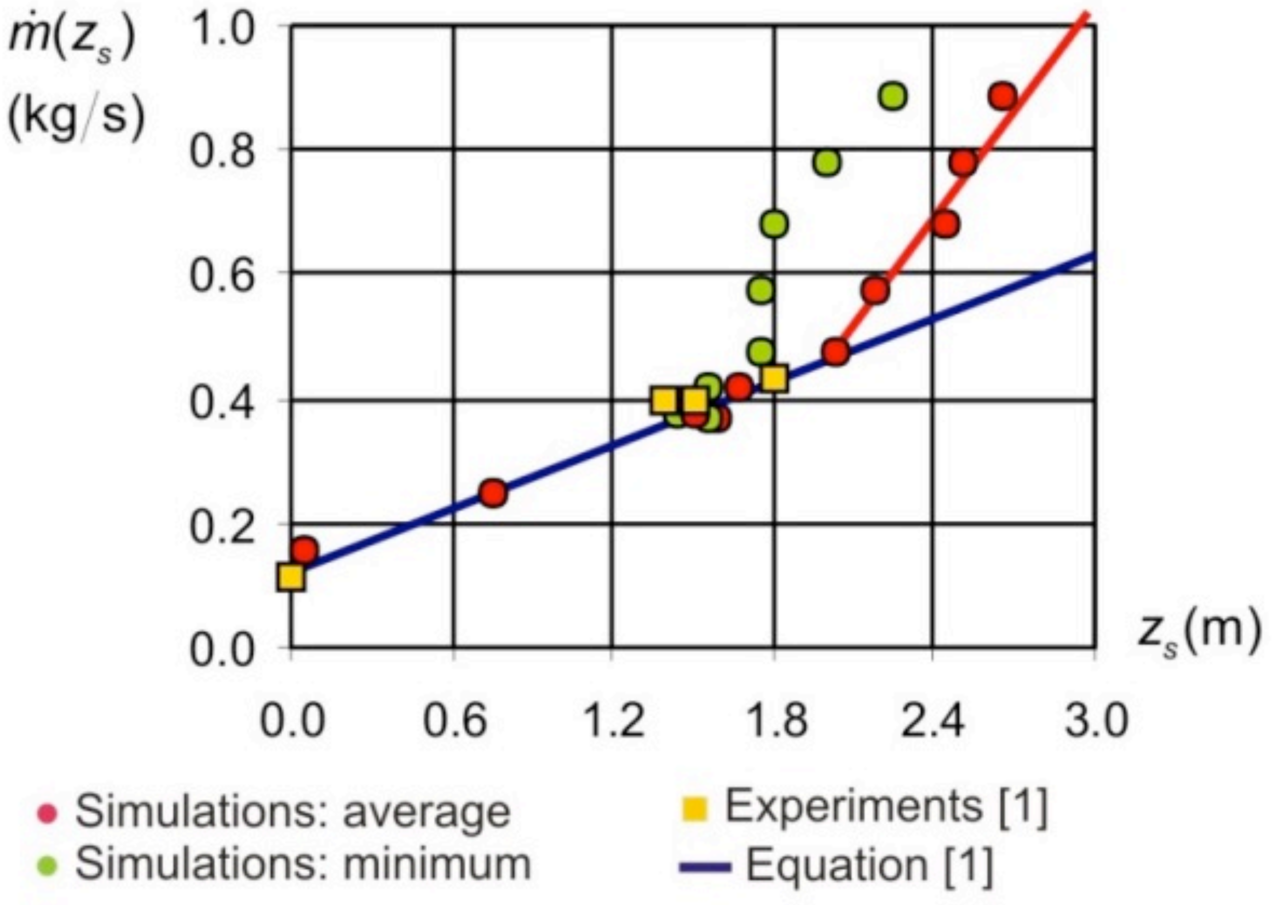
Impact of mechanical extraction rate (Tilley – Merci, Fire Safety Journal, Vol. 55: http://www.sciencedirect.com/science/article/pii/S0379711212001567)



1-D smoke layer



Multi-D smoke layer



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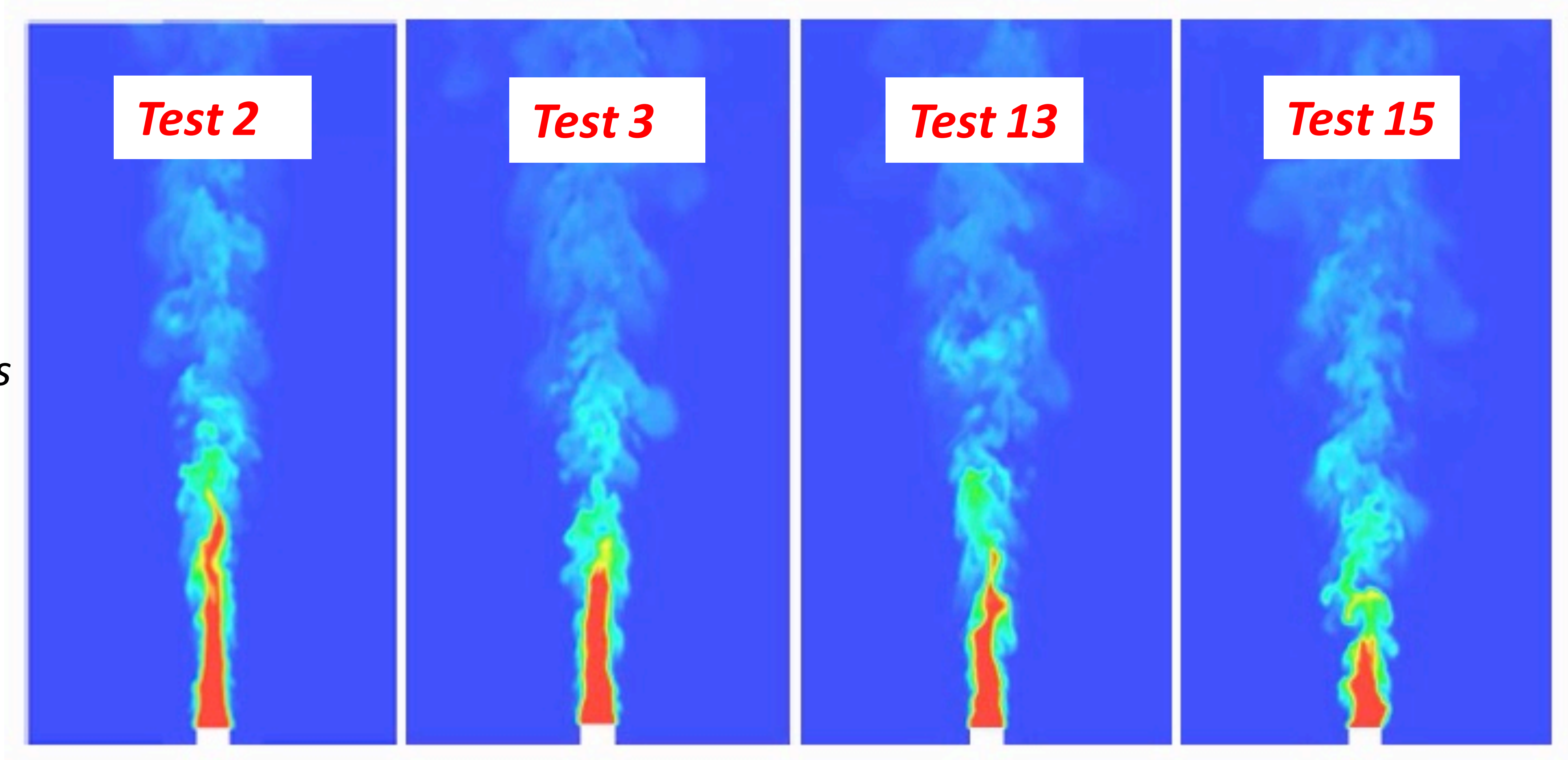
CFD – BOUNDARY CONDITIONS

Test ID	I	N_{eddy}	L_{eddy}	Isotropic or no
Test 2	0.	-	-	-
Test 3	30	196	0.004	isotropic
Test 13	30	1000	0.004	isotropic
Test 14	20	1000	0.004	anisotropic
Test 15	30	1000	0.010	isotropic

Instantaneous temperature fields



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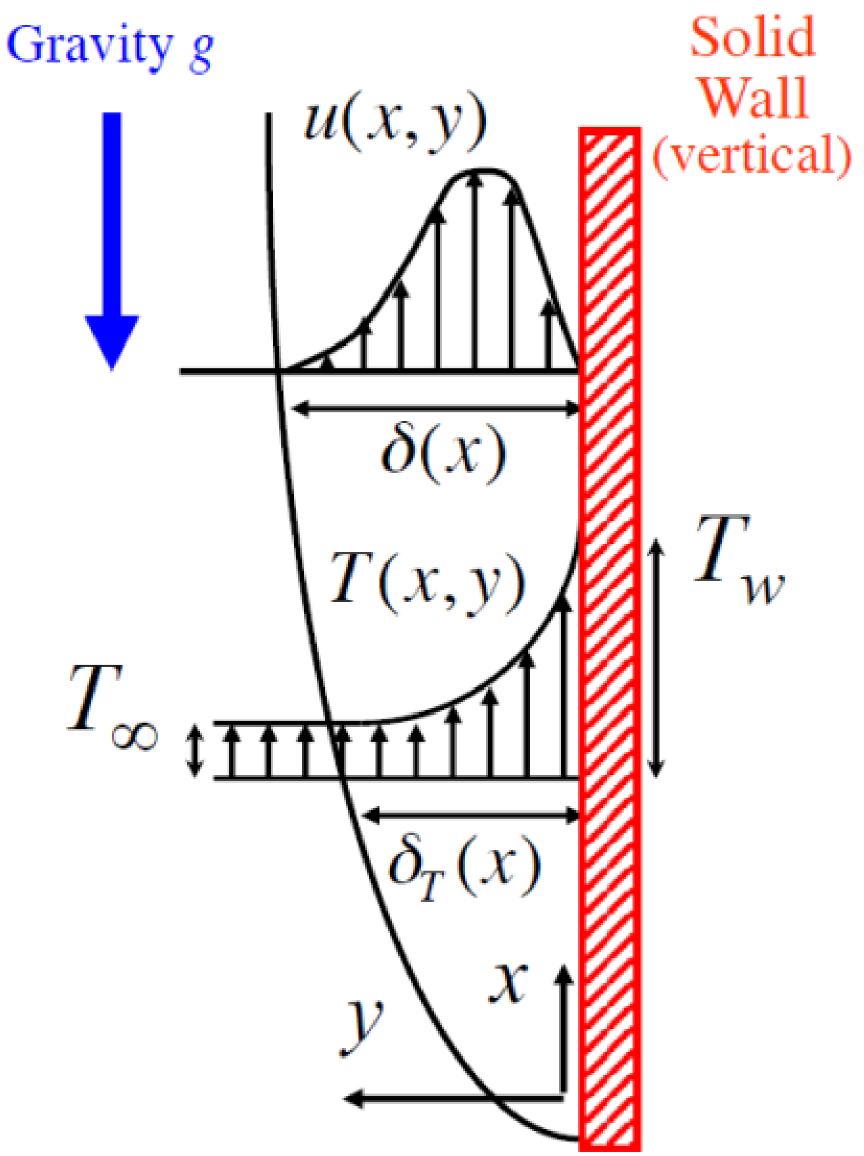
CFD – BOUNDARY CONDITIONS

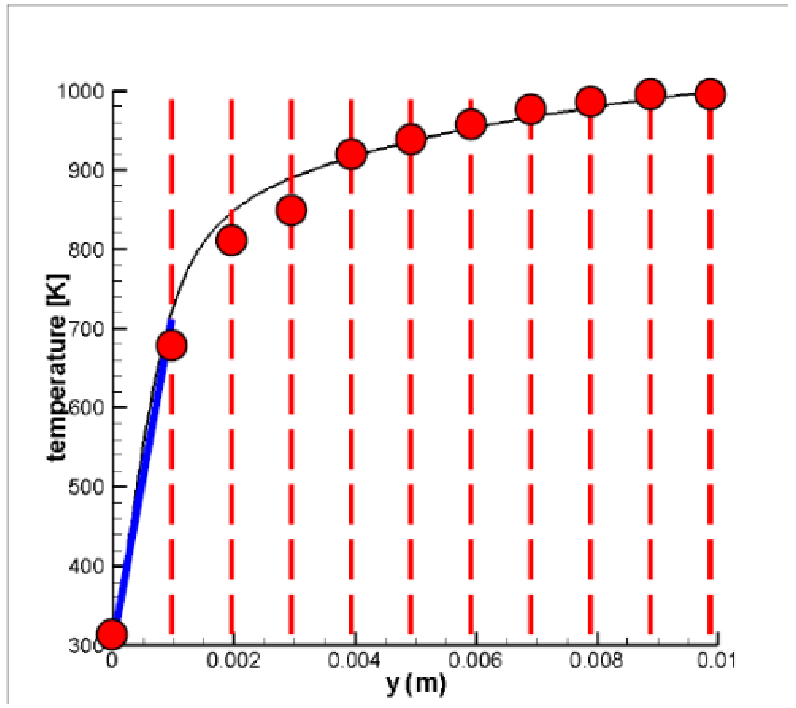
- Near walls:
  - Turbulent eddies become smaller (blocking effect);
  - Gradients become sharp.

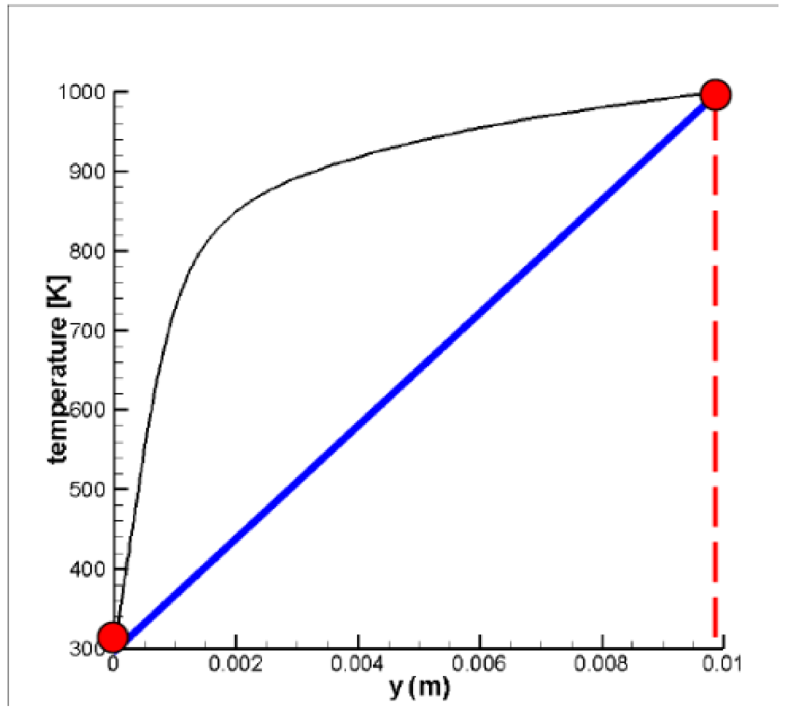


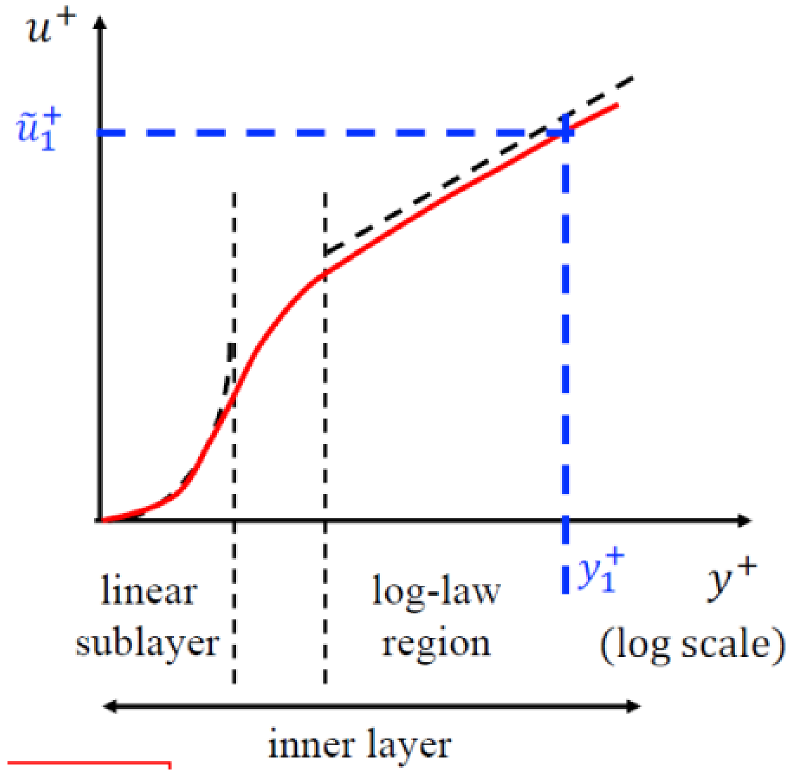
Courtesy Prof Arnaud Trouvé

CFD – BOUNDARY CONDITIONS

- Near walls:
  - Wall-resolved: gradients are captured, but the mesh must be very fine (O(mm)) and grid aspect ratios are an issue → often not affordable (except in research).
  - Wall functions: gradients are not captured, so the mesh need not be very fine, but modeling is required (e.g., log law assumption).



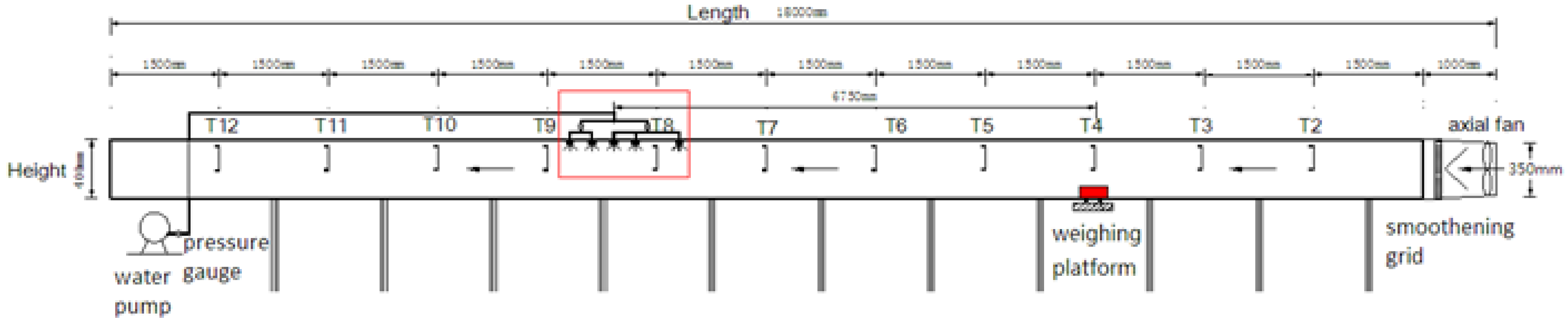


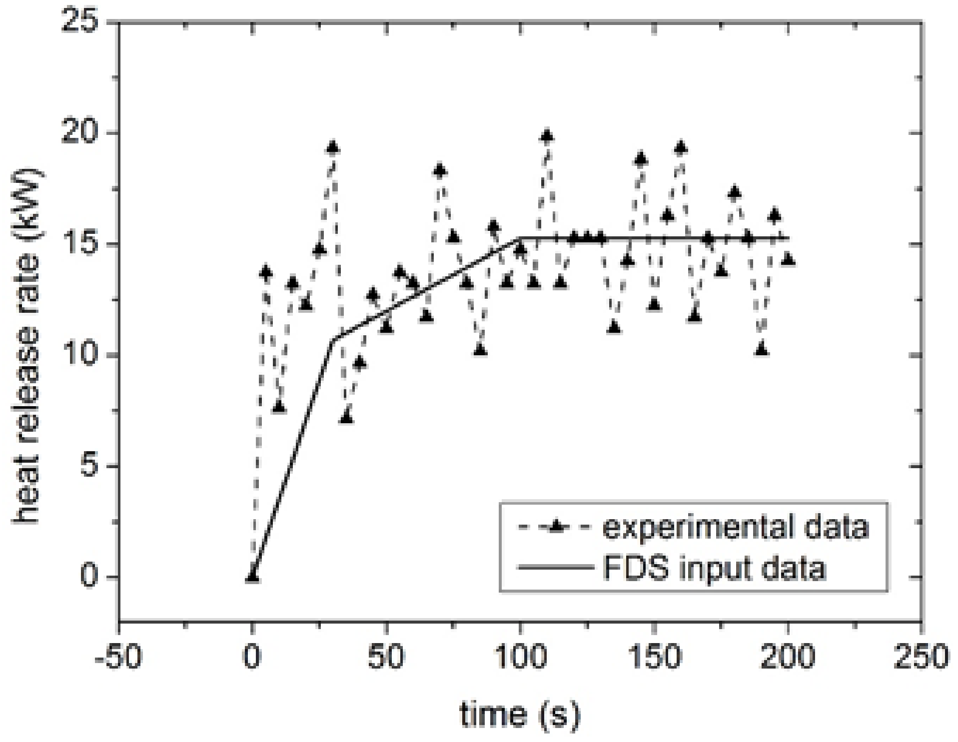


Courtesy Prof Arnaud Trouvé

CFD – EXAMPLE

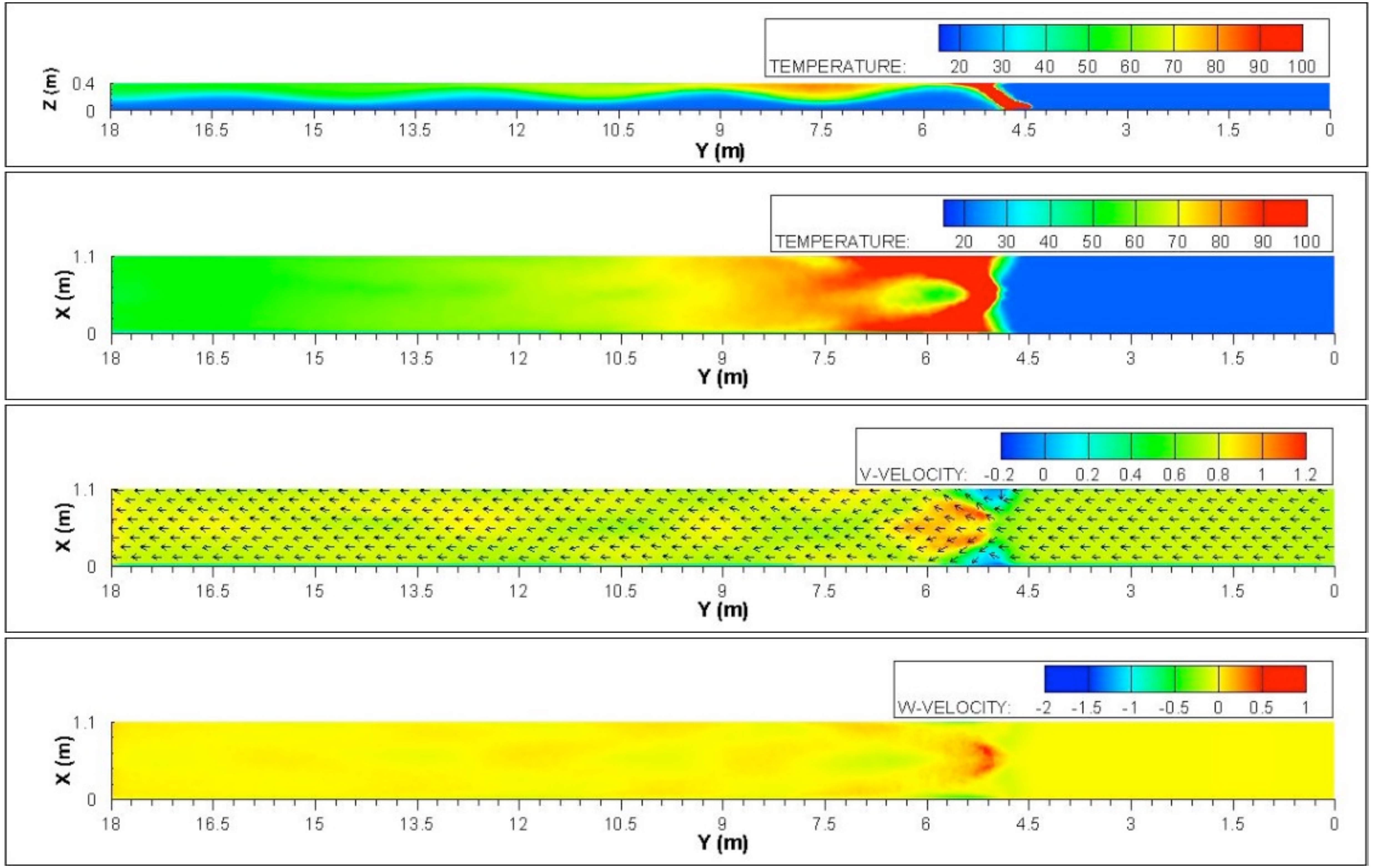
- J. Sun et al, TUST (2020): 10.1016/j.tust.2020.103543





CFD – EXAMPLE

No spray



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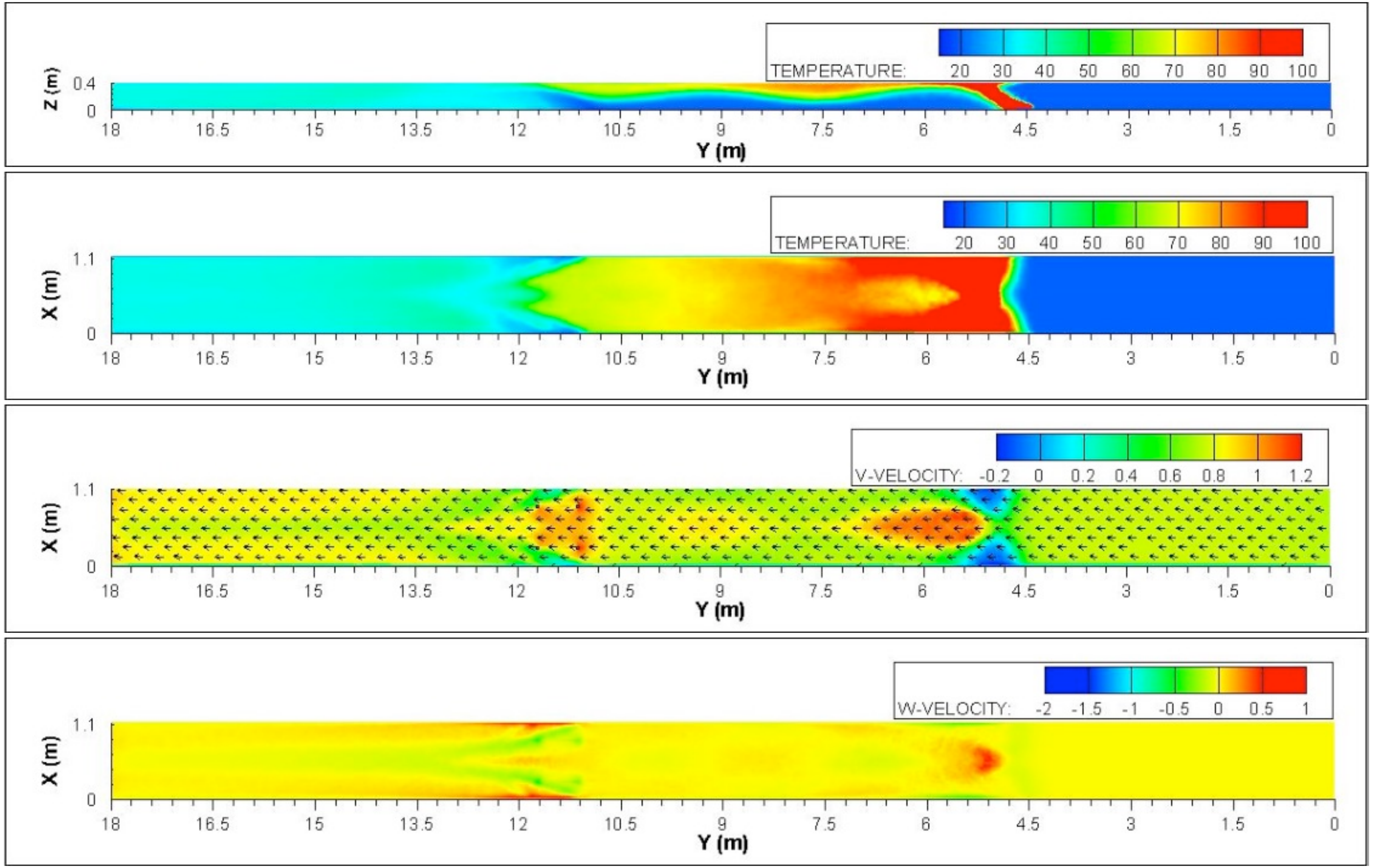
CFD – EXAMPLE

With spray



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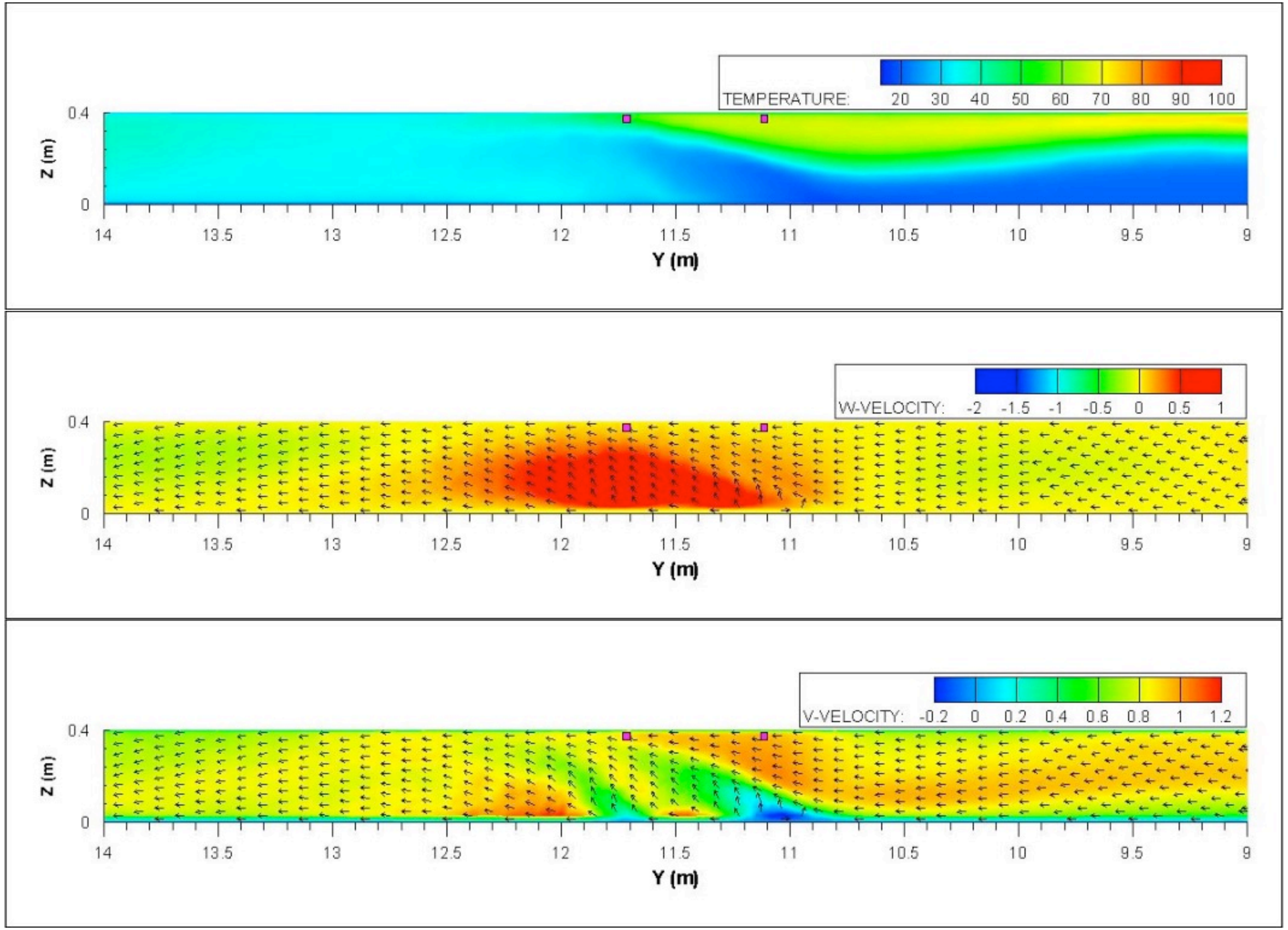
CFD – EXAMPLE

Close to spray

Mid-plane



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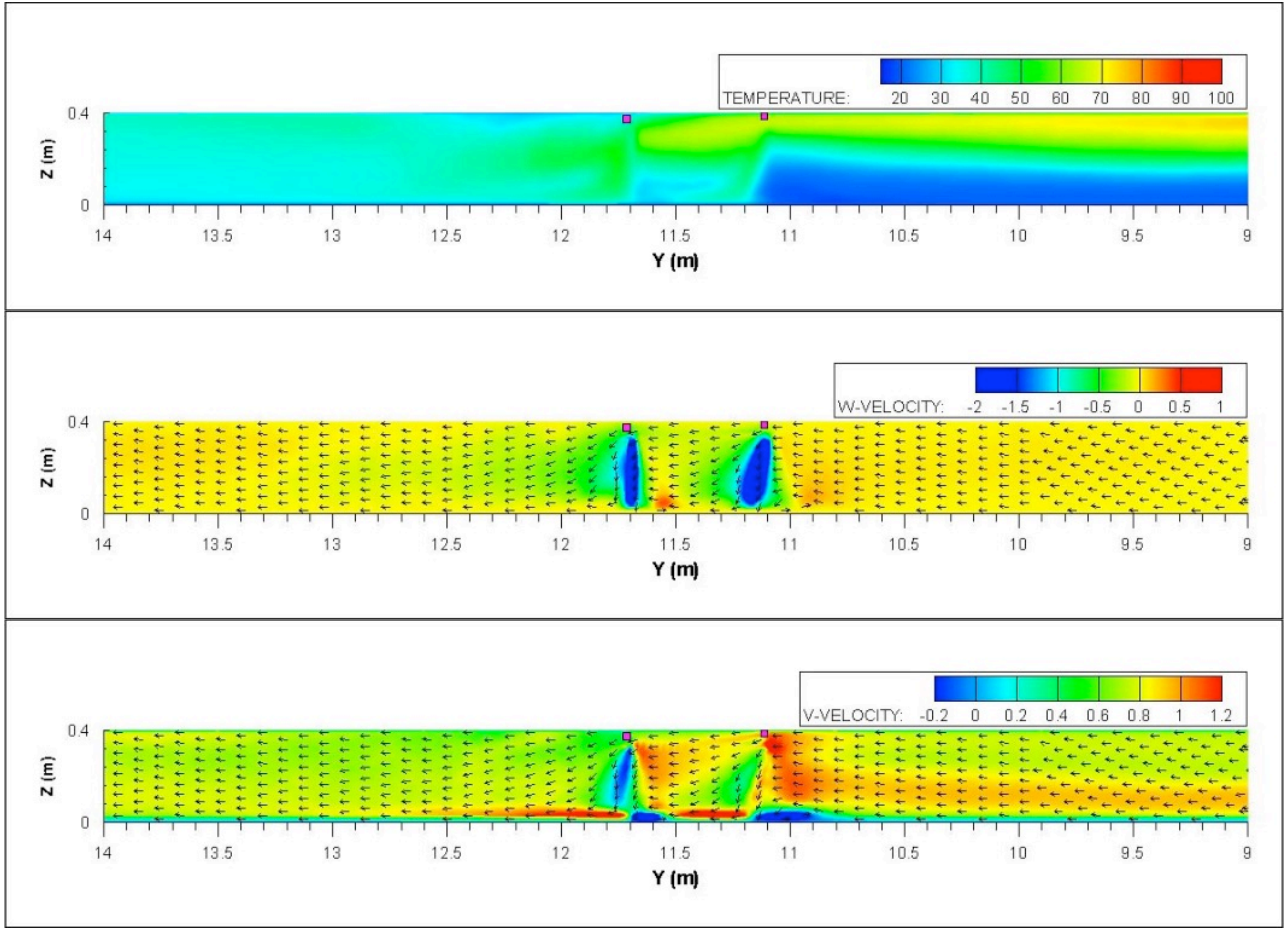
CFD – EXAMPLE

Close to spray

Plane through nozzles



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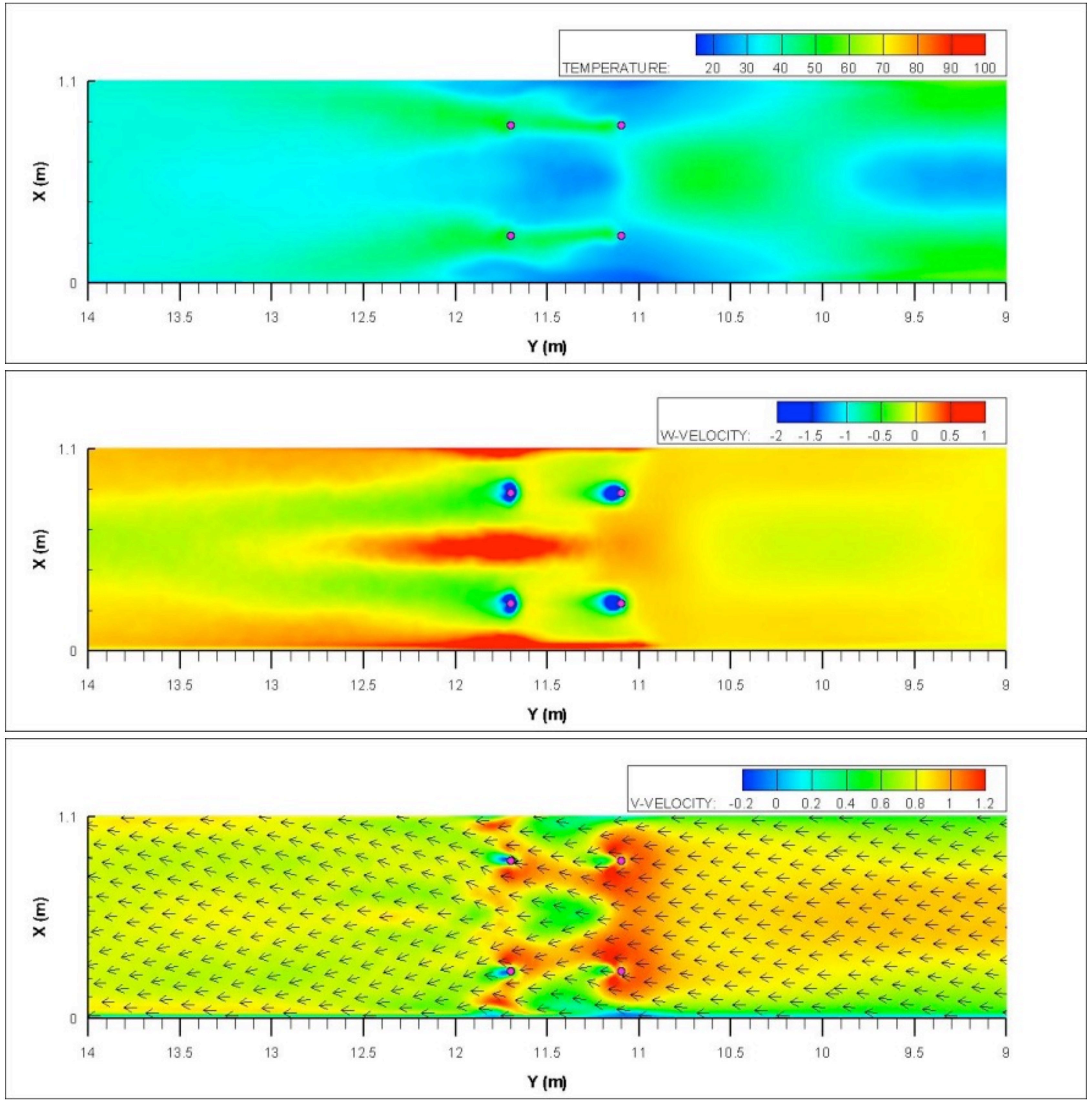
CFD – EXAMPLE

Close to spray

Horizontal Plane

Mid-height



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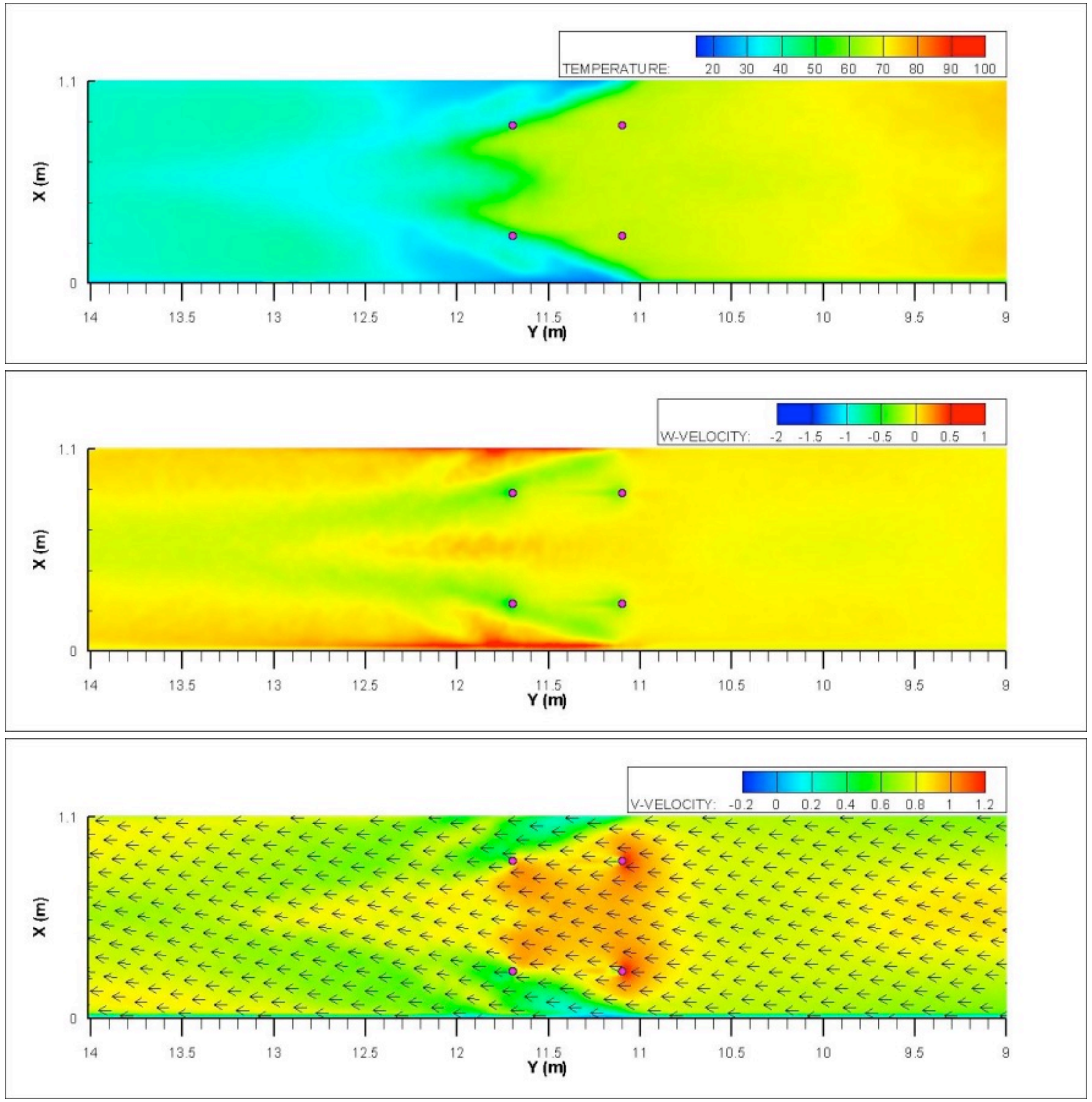
CFD – EXAMPLE

Close to spray

Horizontal Plane

Close to ceiling



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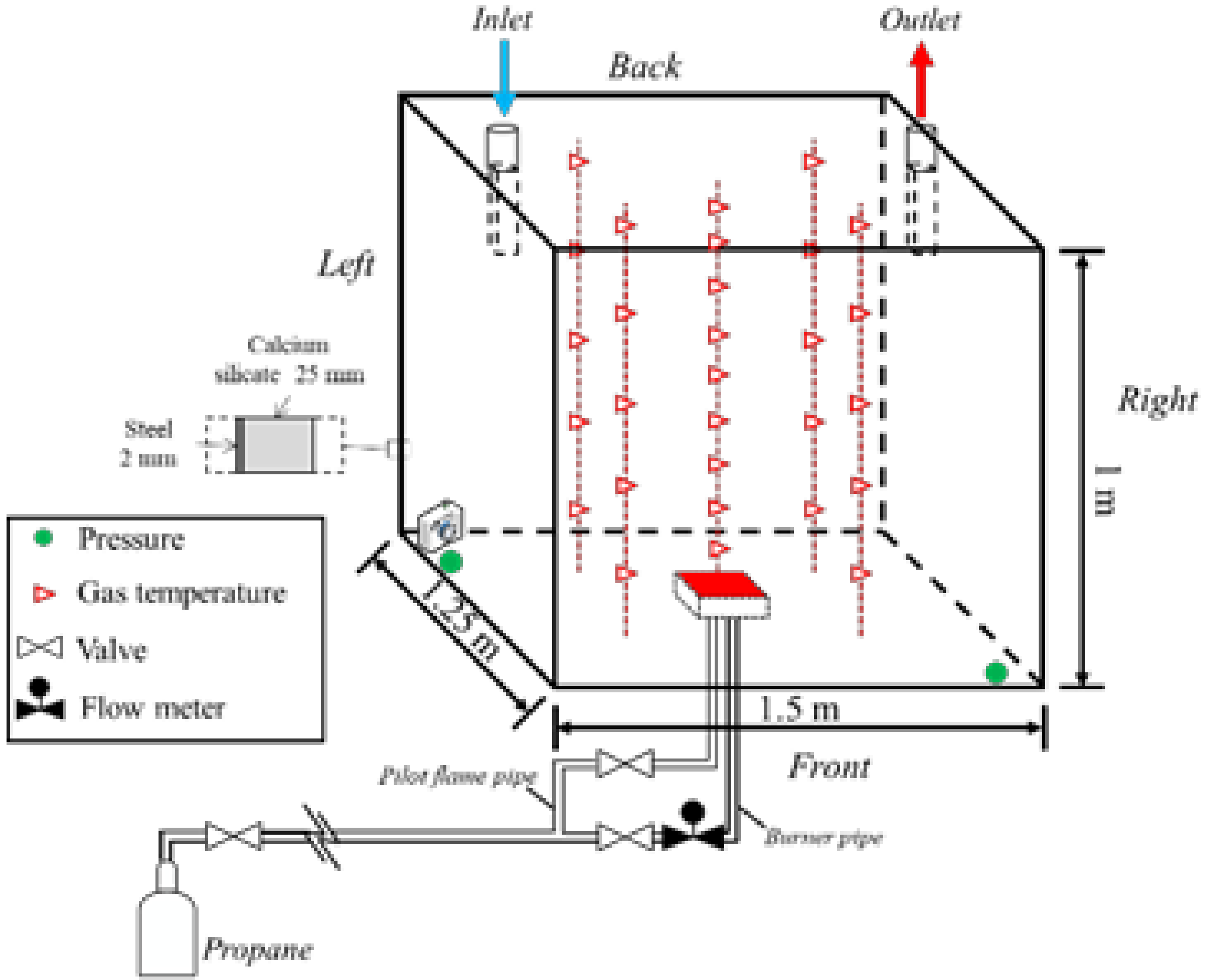
CFD – EXAMPLE

- CFD results are ‘validated’ by experimental data.
- CFD allows for in-depth and detailed discussion of the flow field, which would be very difficult to measure.
- CFD allows for further interpretation of observations in experiments.

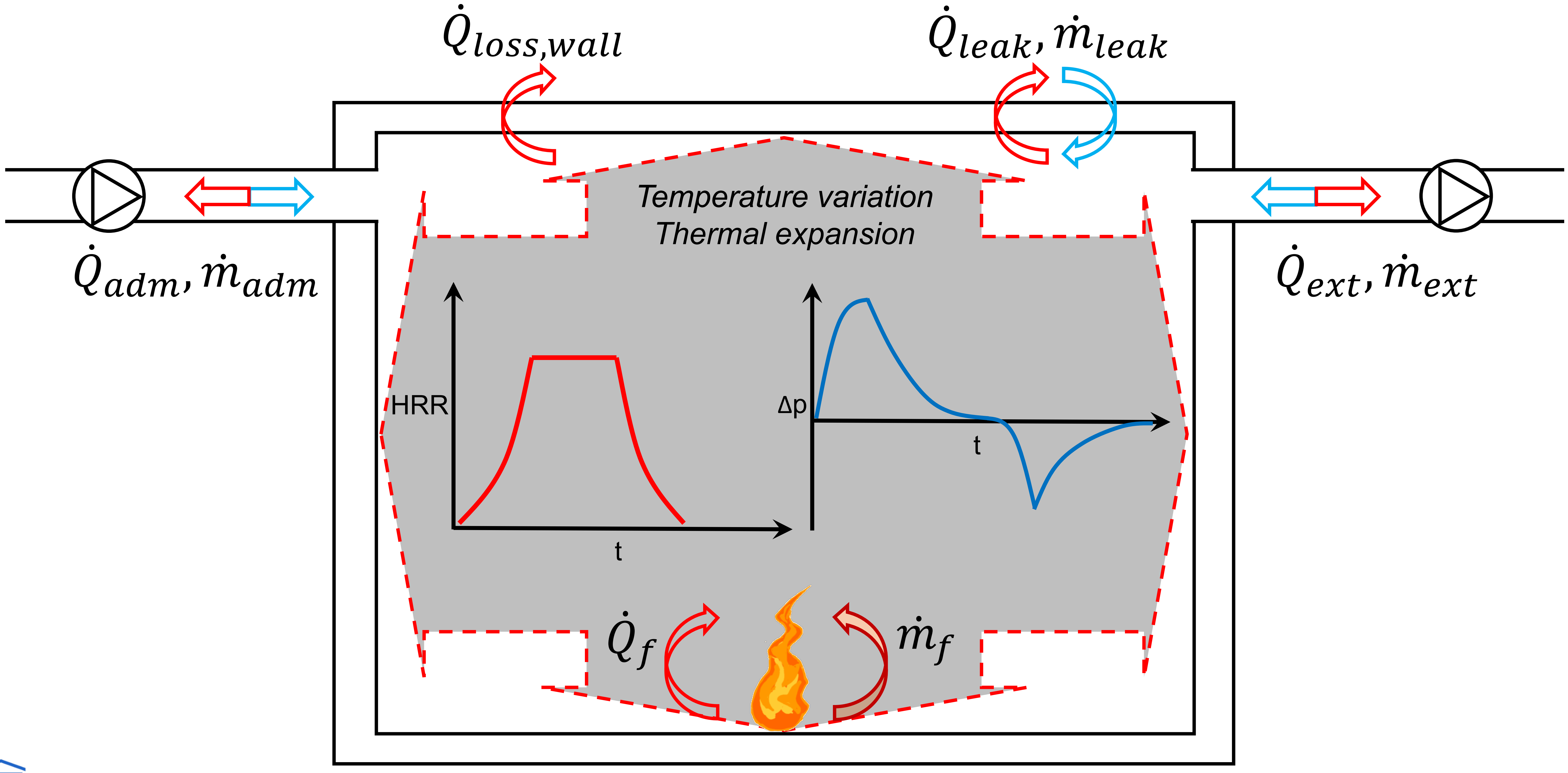
CFD – EXAMPLE

- PhD Junyi Li.
- Collaboration with IRSN.
- Experiments in NYX set-up.



Courtesy dr. Hugues Prétrel IRSN

Energy balance in air-tight compartments



$$\frac{V}{\gamma - 1}\frac{d}{dt}p = \dot{Q}_f - \dot{Q}_w + \dot{Q}_v$$

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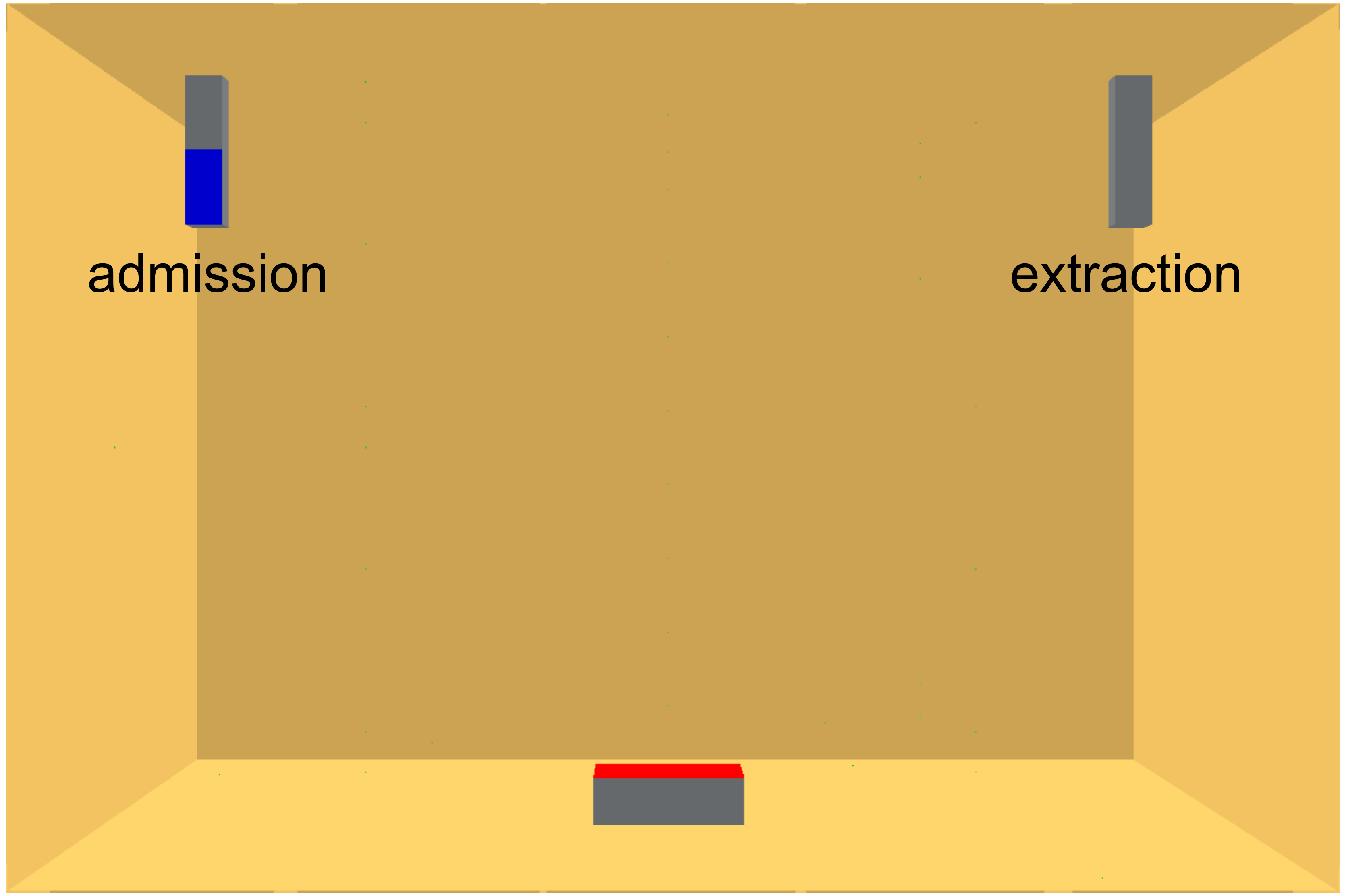
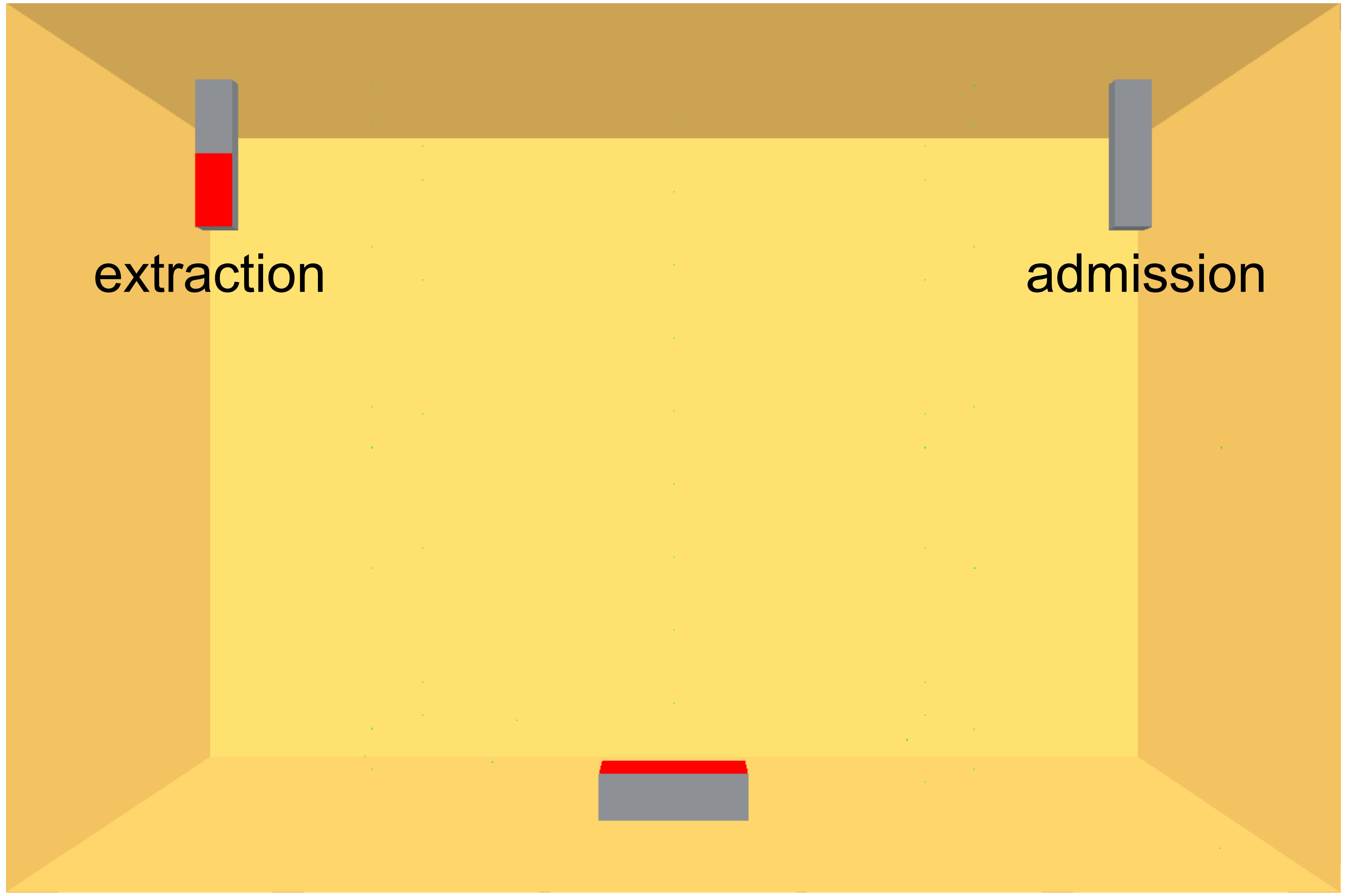
FDS model

FDS 6.7.5



Front view

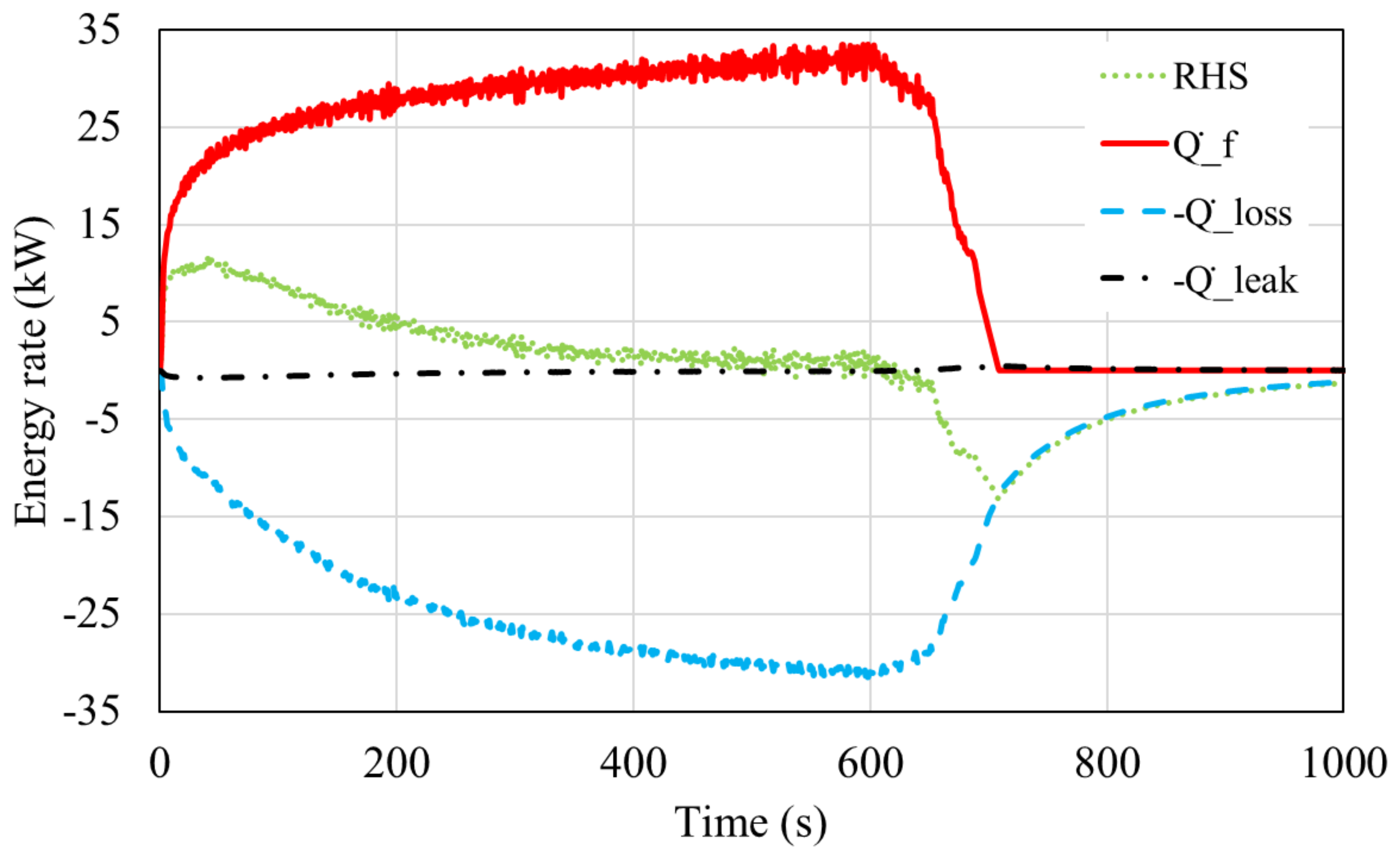


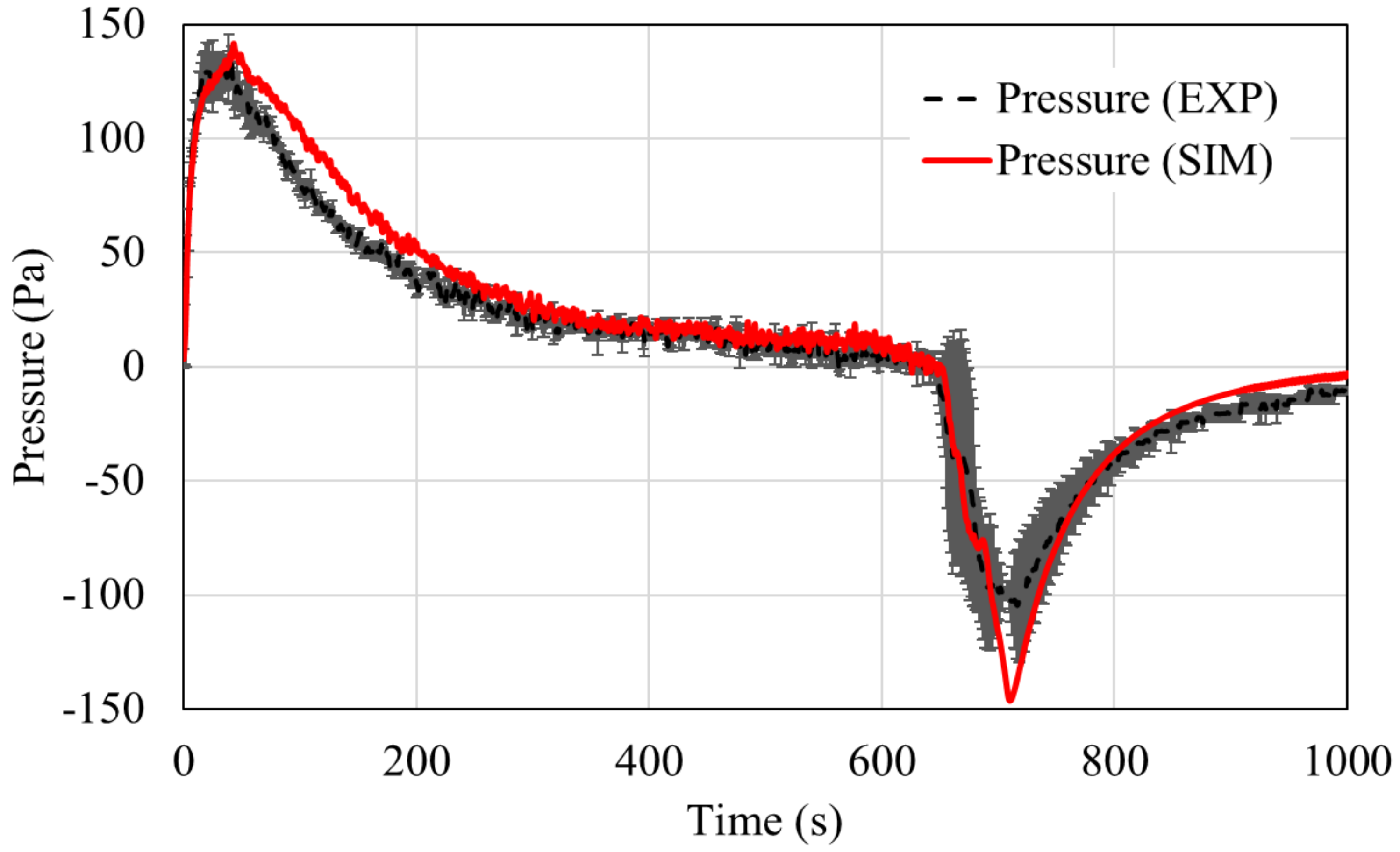
Back view

Energy balance in airtight compartments

$$\frac{V}{\gamma - 1}\frac{d}{dt}p = \dot{Q}_f - \dot{Q}_w + \dot{Q}_v$$

RHS>0 => $\frac{dp}{dt}$>0 => pressure increase ?





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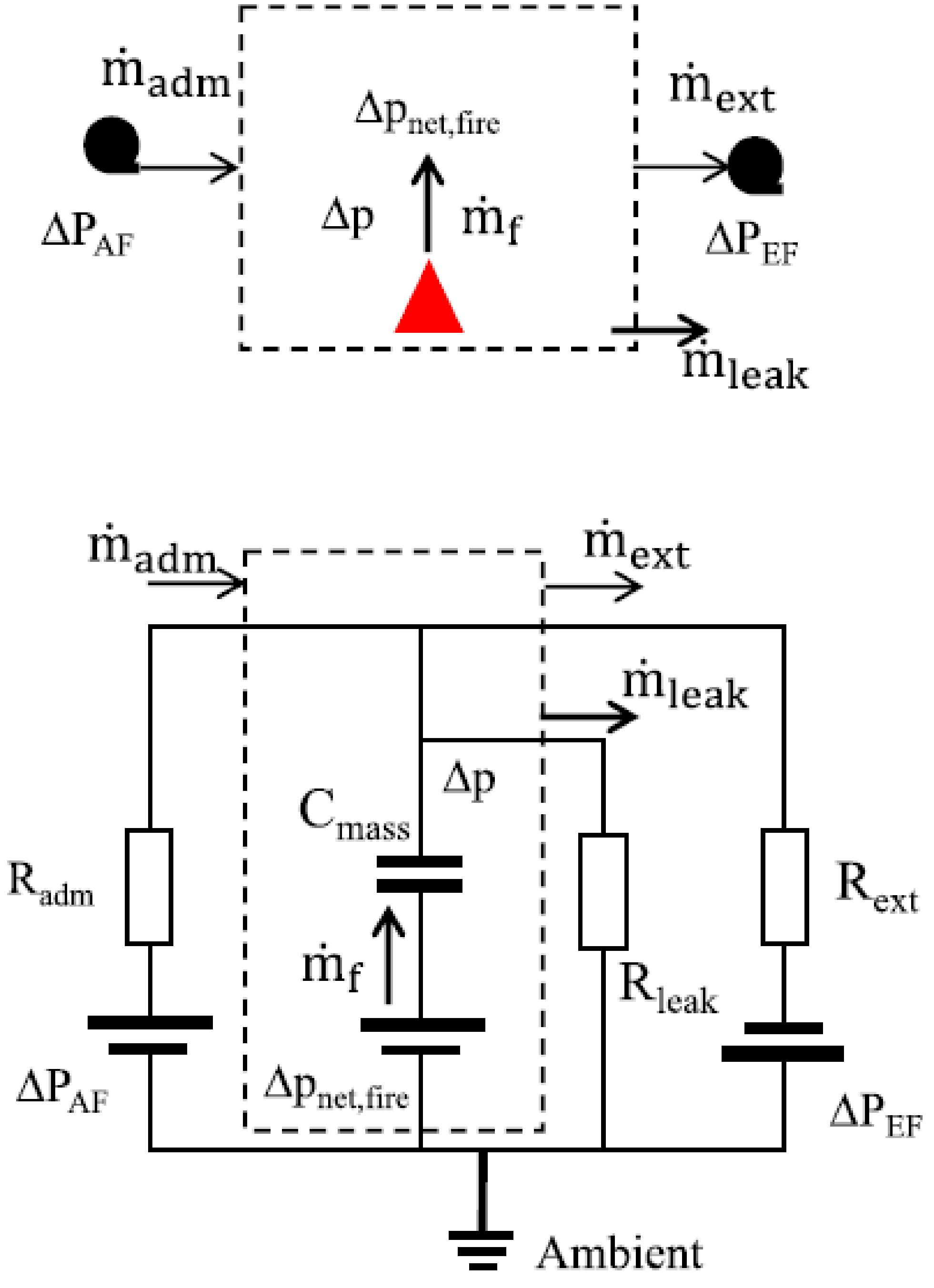
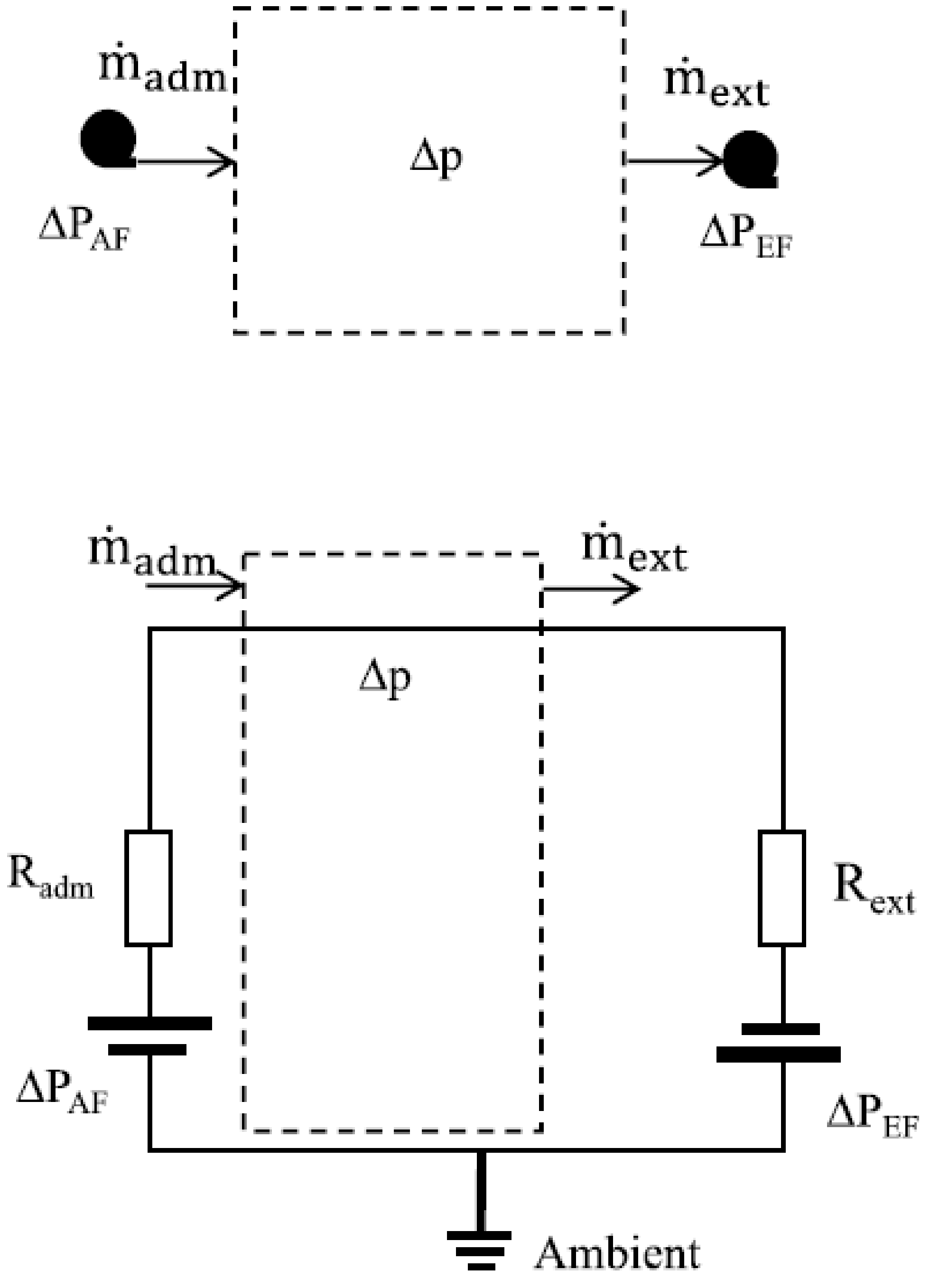
ENERGY EQUATION – IMPORTANCE OF HRR

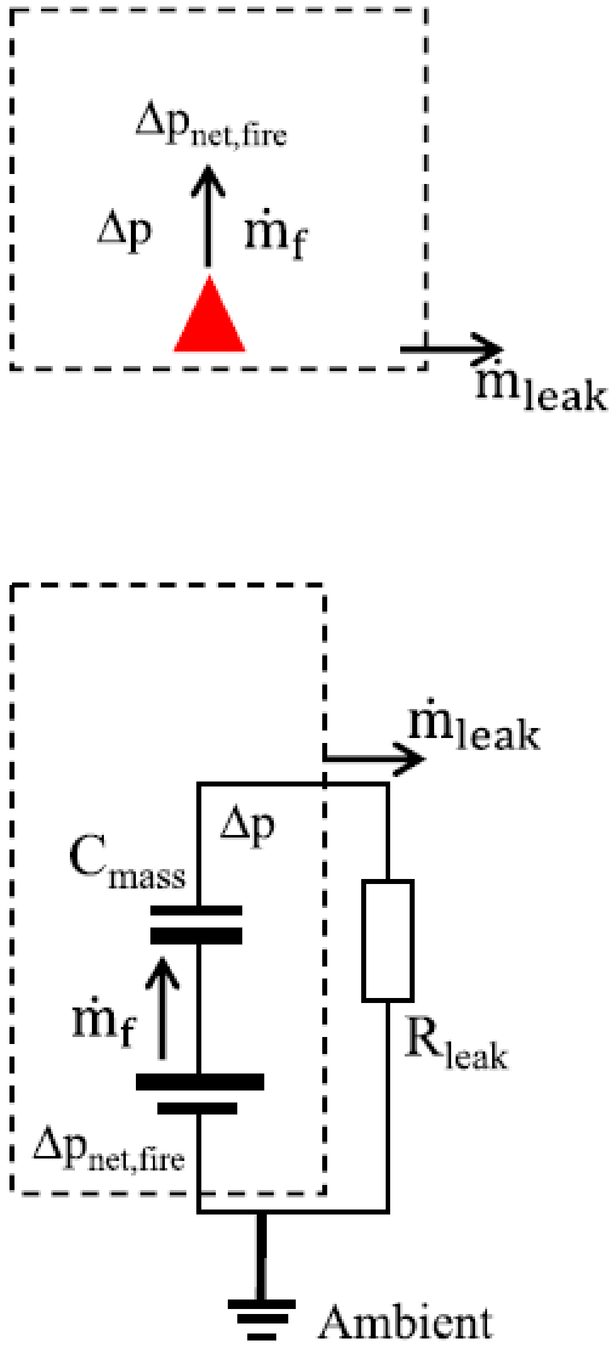
– Complex interaction:



Overall

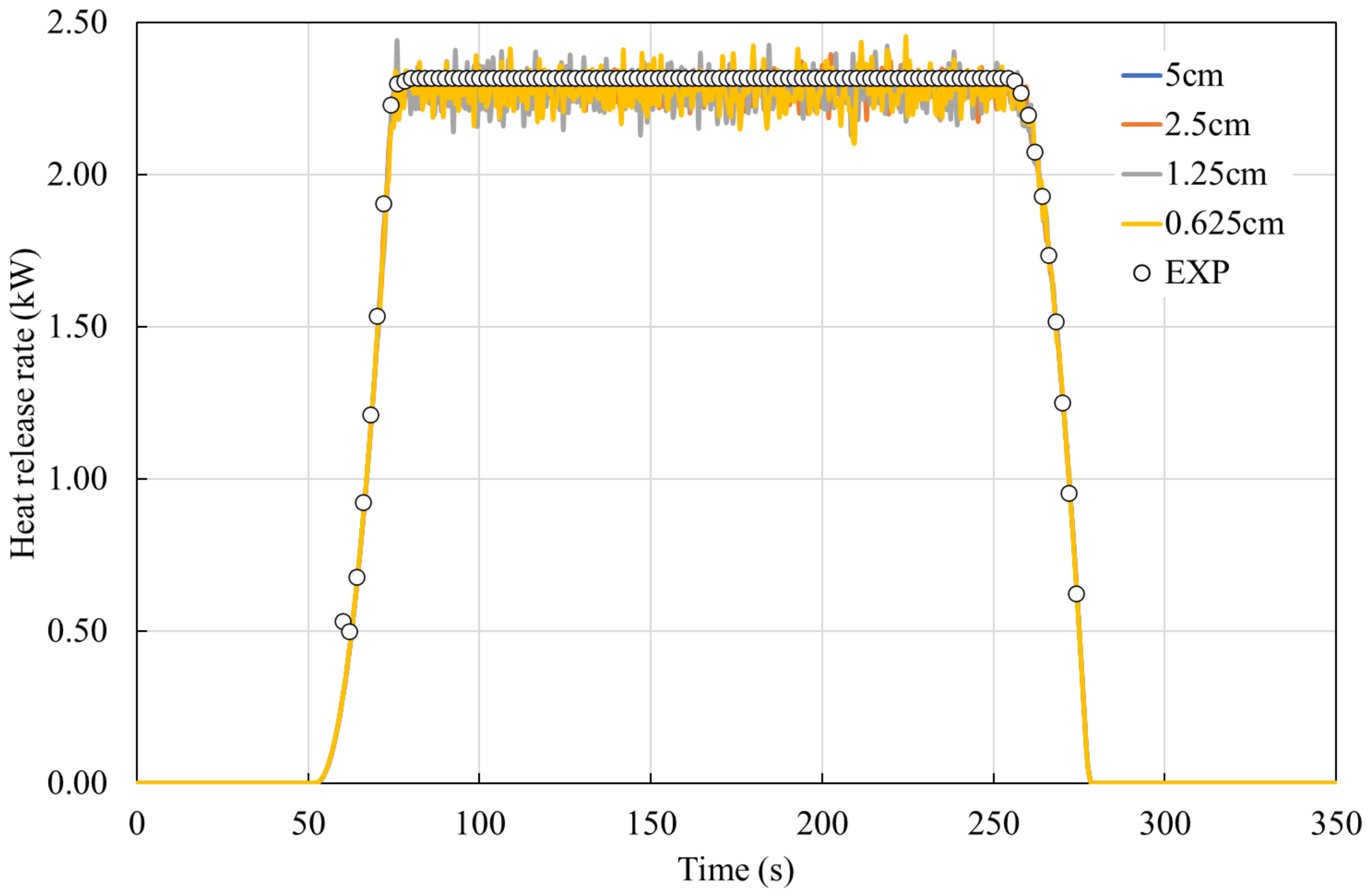


No fire



No ventilation

Mesh cell size



Heat release rates as function of time

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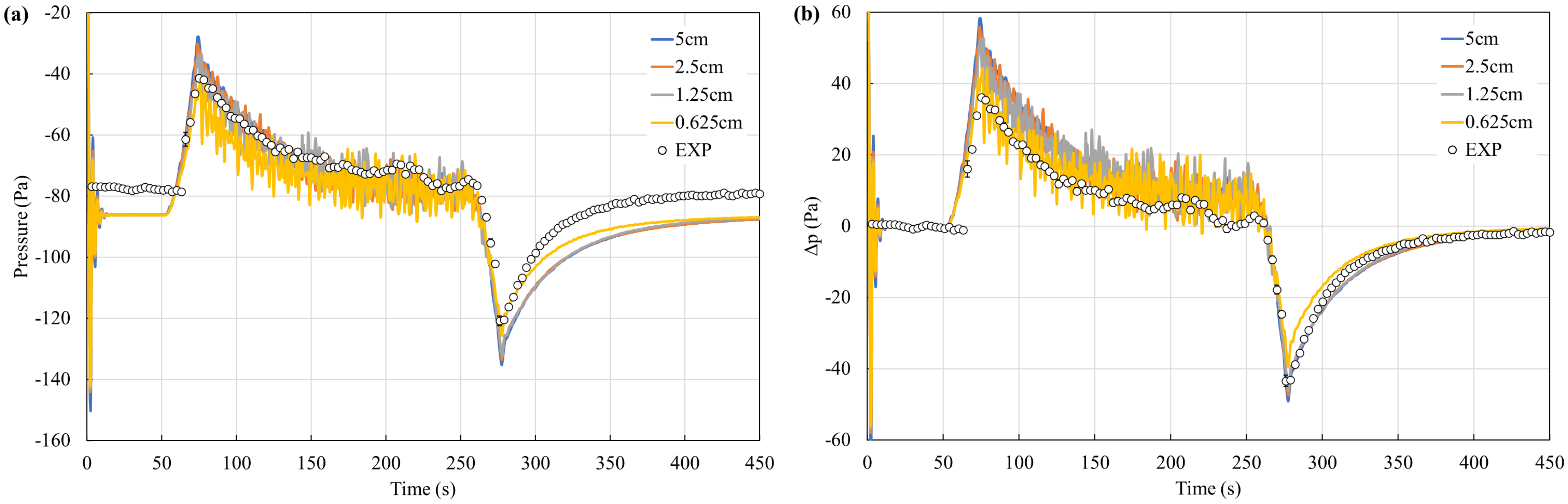
Mesh cell size



Pressure variations (left) and pressure change variations (right) as function of time

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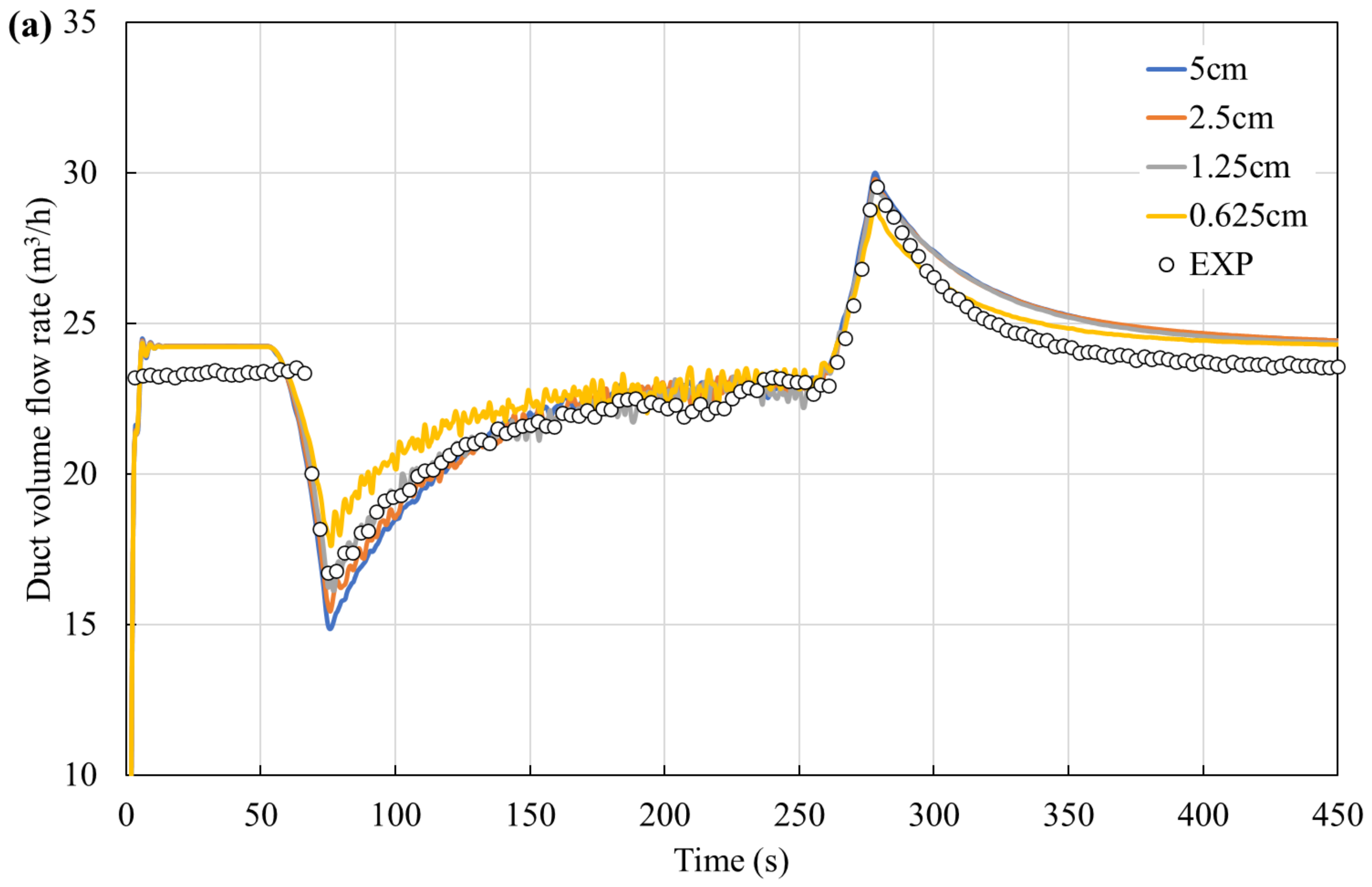
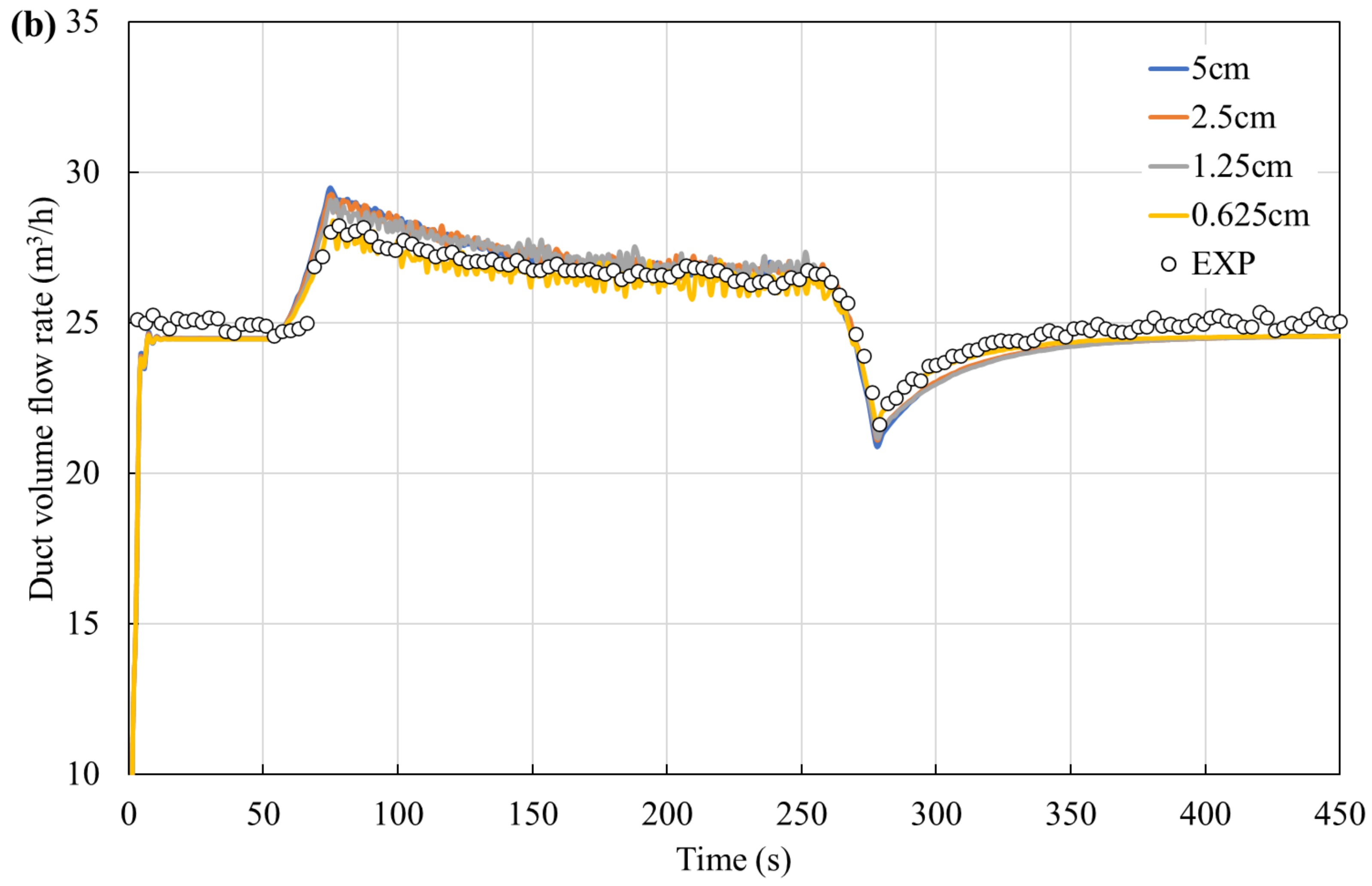
Mesh cell size





Mechanical ventilation flow rates as function of time: (a) admission; (b) extraction

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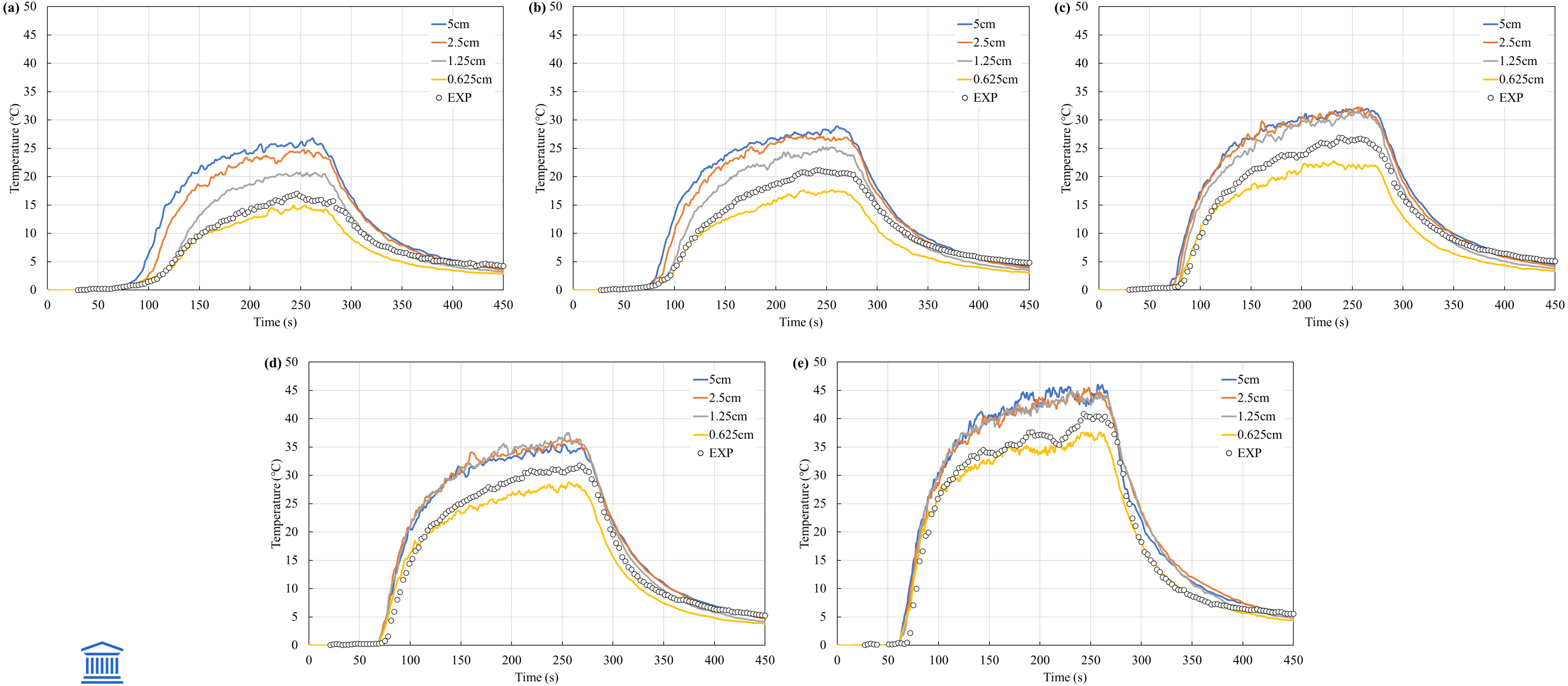
Mesh cell size



Temperature rise evolutions as function of time at different heights: (a) 0.15 m; (b) 0.35 m; (c) 0.55 m; (d) 0.75 m; (e) 0.95 m

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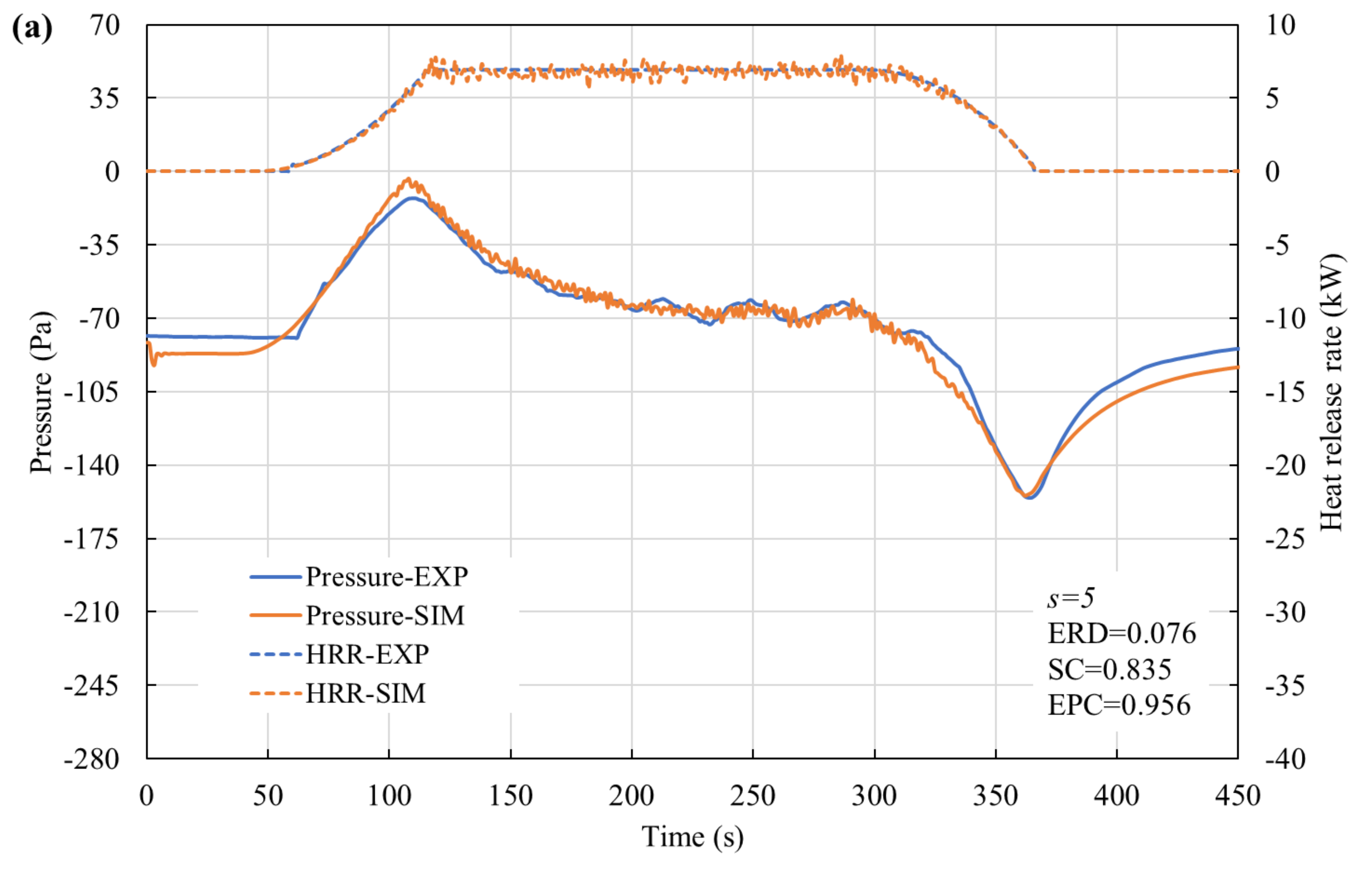
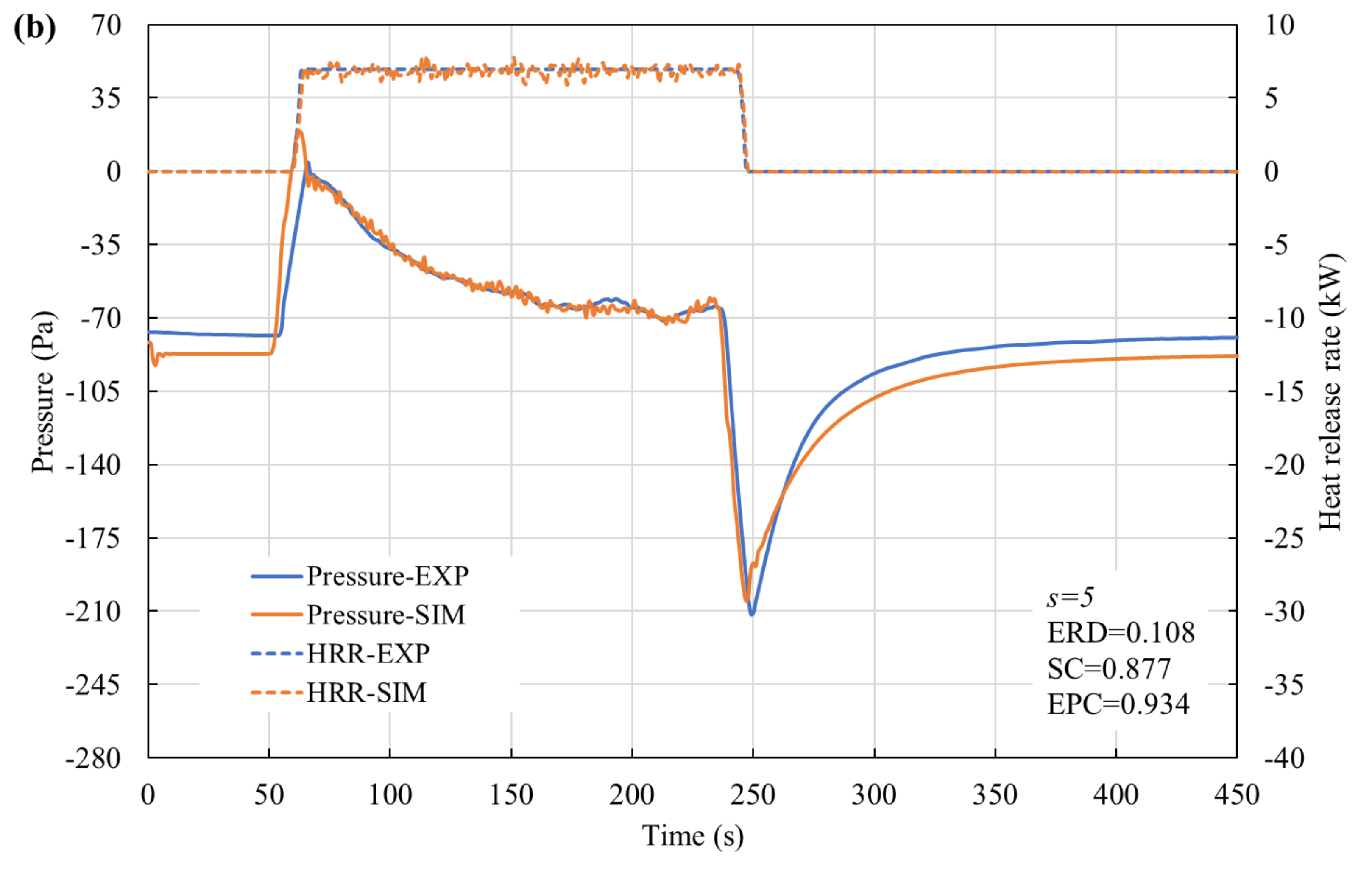
Pressure variations with different HRR evolutions





Pressure variations as function of time with different fuel mass flow rate growth rate coefficient: (a) α=0.00003 g/s^3; (b) α=0.01 g/s^3
10 points moving average for experimental curves and 20 points moving average for numerical curves

ERD: Euclidean Relative Difference, SC: Secant Cosine, EPC: Euclidean Projection Coefficient

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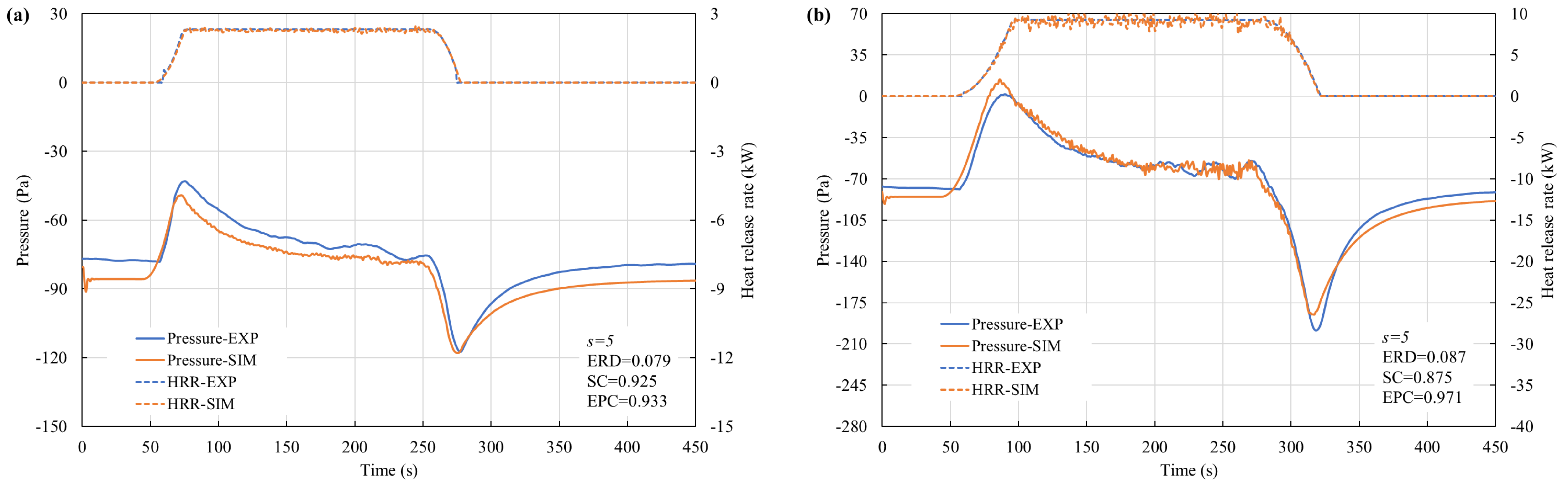
Pressure variations with different HRR evolutions



Pressure variations as function of time with different maximum fuel mass flow rate: (a) $\dot{m}_{f,max}$=0.05 g/s; (b) $\dot{m}_{f,max}$=0.2 g/s
10 points moving average for experimental curves and 20 points moving average for numerical curves

ERD: Euclidean Relative Difference, SC: Secant Cosine, EPC: Euclidean Projection Coefficient

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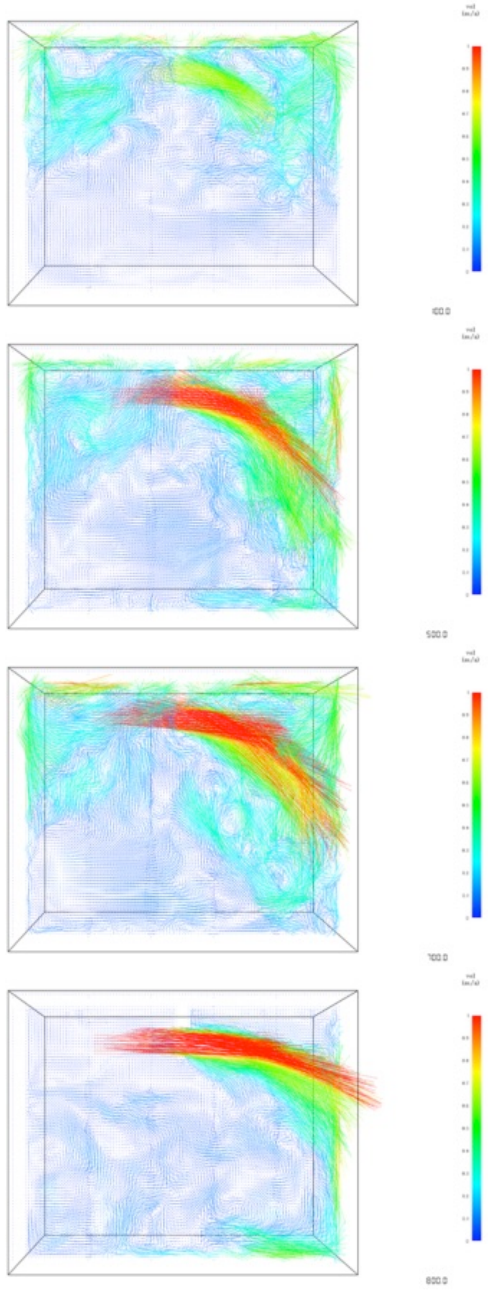
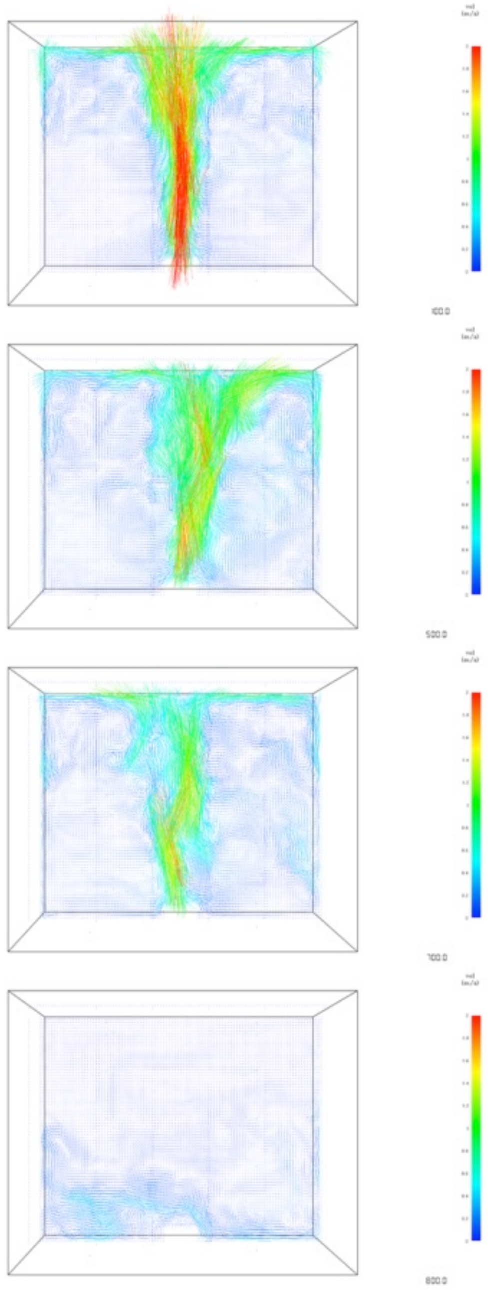
CFD – EXAMPLE

- Insight in flow fields:



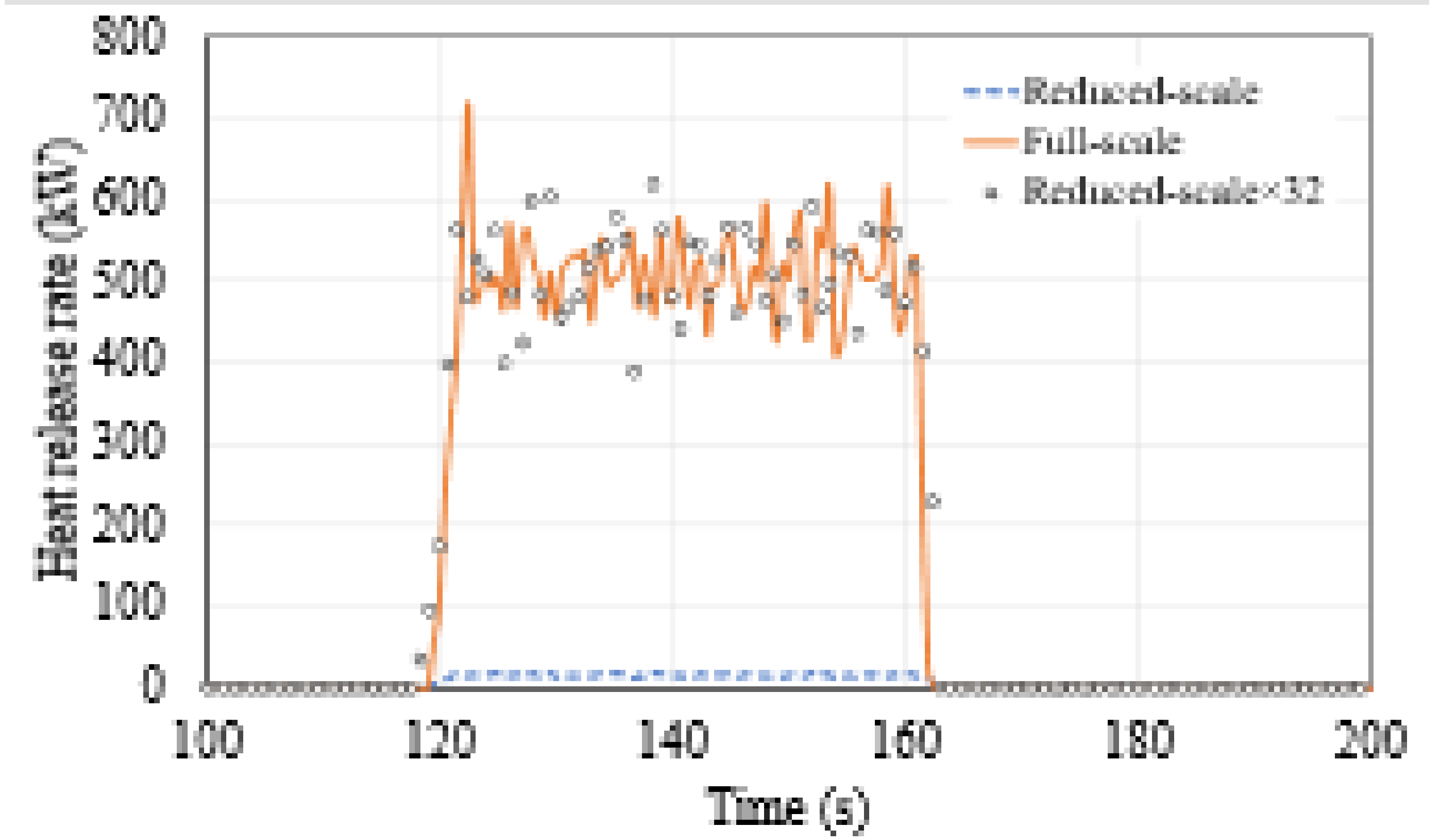
Instantaneous velocity vectors in the vertical plane through the admission duct at different times.

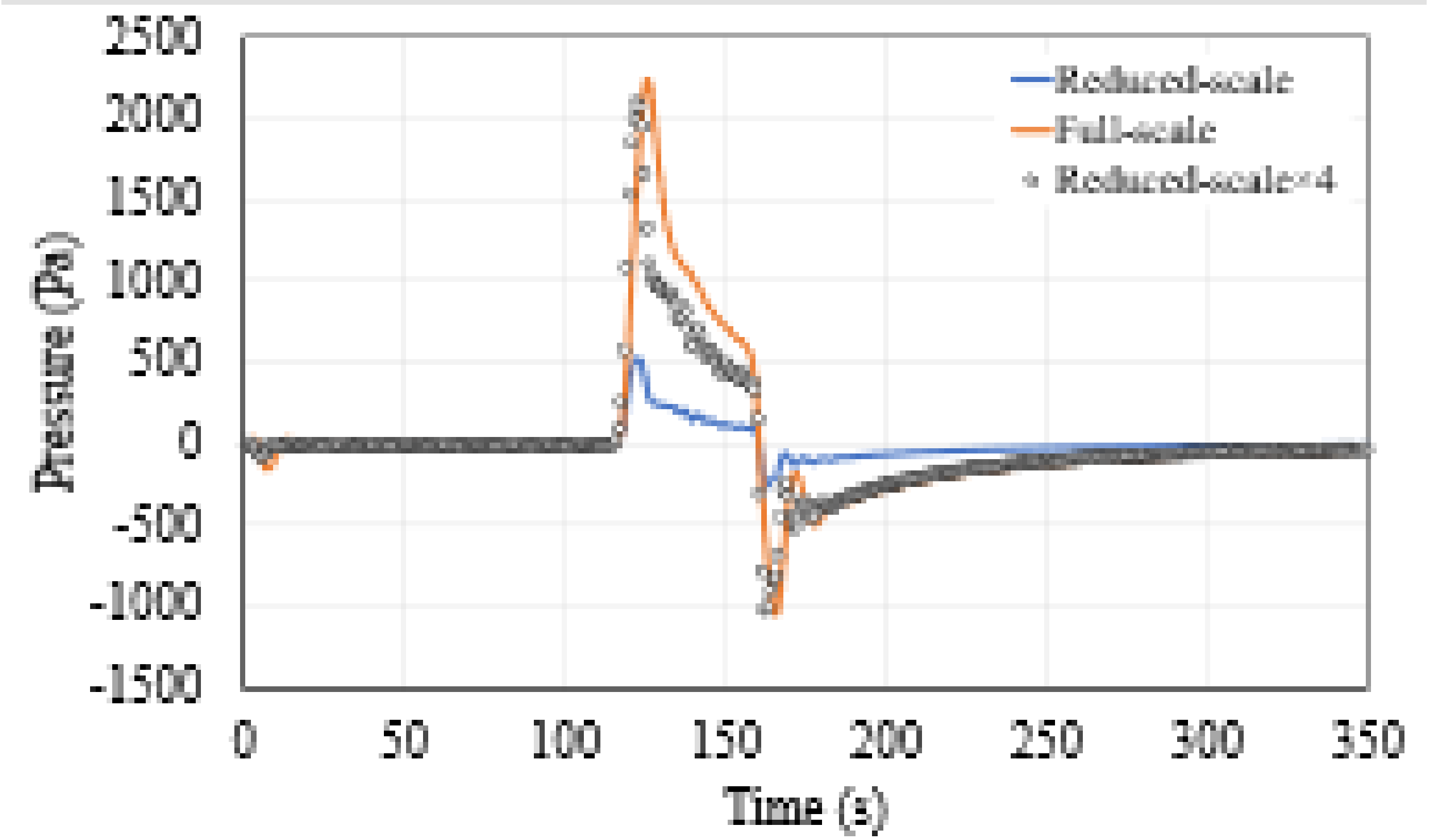


Instantaneous velocity vectors in the vertical plane through the burner at different times.

CFD – EXAMPLE

- Testing of scaling analysis:





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CFD – LIMITS OF VALIDITY

- CFD is a very powerful tool.
- CFD can lead to new insights.
- In principle, all physical (and chemical) phenomena can be captured.
- The use of CFD requires special care → quality assessment and deontology!
- Increasing computer power in favor of CFD, particularly for complex applications.

CFD – LIMITS OF VALIDITY

- Yet, things can go wrong:
  - Simplification of the geometry.
  - Generation of the computational mesh.
  - Determination of the boundary conditions.
  - Solution of the equations.
  - Choice of different sub-models.
  - Discretization.
  - Neglect of an important phenomenon.
- To summarize: the user can make mistakes!

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THERE'S (MUCH) MORE

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THERE'S (MUCH) MORE

- Wildfires
- WUI
- Human behaviour
- Artifical intelligence
- Automated digitization (e.g., BIM)
- Structural fire engineering
- New energy carriers
- Toxicity
- Material sciences
- Fire suppression