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INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

INVESTIGATION OF THE FIRE MASS LOSS RATE IN CONFINED AND MECHANICALLY VENTILATED ENCLOSURES BASED ON LARGE SCALE UNDER-VENTILATED FIRE TESTS

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MEMBRE DE ETSON

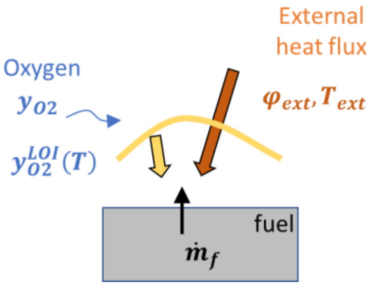
Introduction

Scenario of a Fire in forced ventilated compartment

- Nuclear facility application

Effect of the environment on the burning rate

- Oxygen concentration
- External heat fluxes



Use of the Well Stirred Reactor (WSR) approach to interpret the effect of environment

- Validated on simple configuration (dodecane, one room)

What about the performance of WSR approach for complex scenario ?

- Several rooms
- Specific ventilation set-up with several branches

Content

Methodology and tools

- The Well Stirred Reactor approach
- Large scale fire experiments from PRISME projects

Results

- Illustration of different effects of the environment on the MLR
- Identification of combustion regimes and analysis of time to extinction
- Discussion on modelling of burning rate in vitiated environment

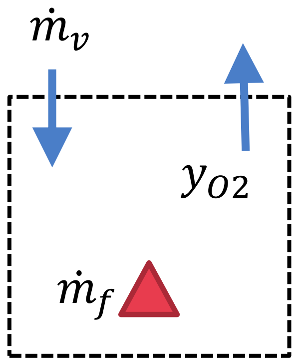
Well stirred reactor approach

Mass conservation

ventilation *fire*

(1)

$$\frac{\rho_o V}{y^o_{O2}\dot{m}_v}\frac{d}{dt}y_{O2} = \left(1-\frac{y_{O2}}{y^o_{O2}}\right) - \underbrace{\left(\frac{r.\dot{m}_f^o}{y^o_{O2}\dot{m}_v}\right)}_{\phi_o}\underbrace{\left(\frac{\dot{m}_f}{\dot{m}_f^o}\right)}_{M}\left(\frac{y_{O2}}{r}+1\right)$$



Law of burning rate dependency with oxygen (extinction mode)

(2)

$$\frac{\dot{m}_f - \dot{m}_f^e}{\dot{m}_f^o - \dot{m}_f^e} = \frac{y_{O2} - y^e_{O2}}{y^o_{O2} - y^e_{O2}}$$

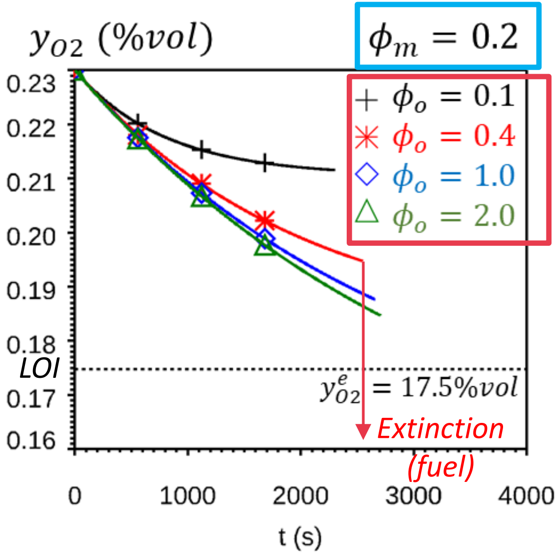
ϕ_o : ventilation factor (GER) $= \dfrac{r.\dot{m}_f^o}{y^o_{O2}\dot{m}_v} = \dfrac{\textit{fire}}{\textit{ventilation}}$

ϕ_m : mass factor $= \dfrac{r.m_f^{init}}{\rho_o V y^o_{O2}} = \dfrac{\textit{Mass of fuel}}{\textit{compartment volume}}$

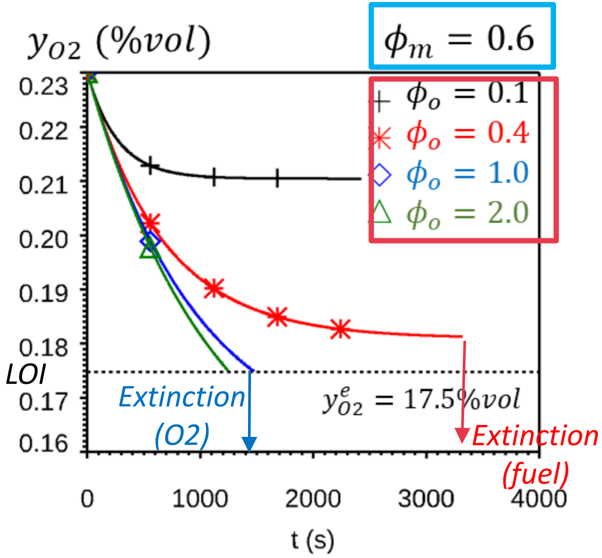
$$\left.\begin{array}{l} y_{O2}(t) \\ M(t) \end{array}\right\} = f(\phi_o, \phi_m, extinction)$$

Well stirred reactor approach

Time variation of oxygen concentration and extinction mode



$$\phi_m = \frac{r.m_f^{init}}{\rho_o V y^o_{O2}}$$



Small ϕ_m
Transient only
Only extinction by lack of fuel

Larger ϕ_m
Stationary (low ϕ_o) / transient (large ϕ_o)
Two regimes of extinction (Fuel/O2)

Well stirred reactor approach

Time to extinction

$$t^*_{ext} = t_{ext} \frac{\dot{m}_f^o}{m_f^{init}}$$

Two regimes

- Increase of t_{ext} - extinction by lack of fuel
- Decrease of t_{ext} - extinction by lack of O2

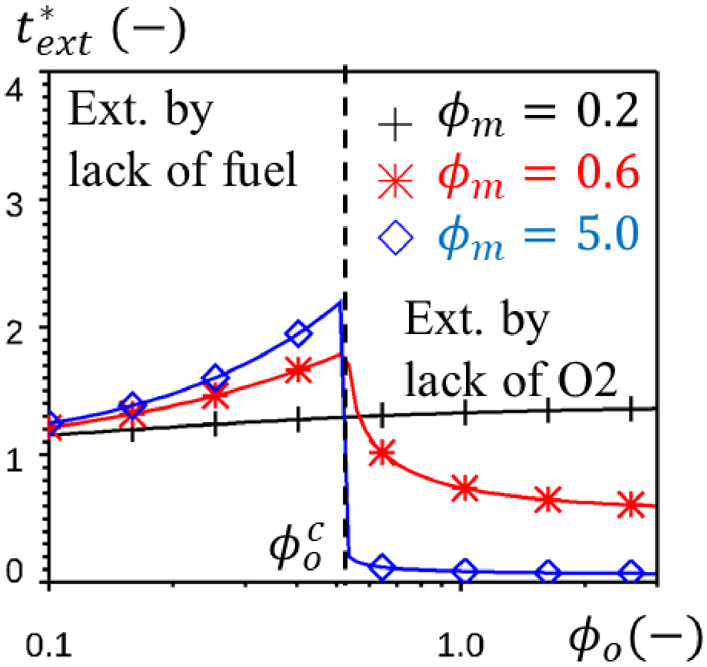
Transition -> Critical ventilation factor

$$\phi_o^c = \frac{\dot{m}_f^o}{\dot{m}_f^e} \frac{(y_{O2}^o - y_{O2}^e)/y_{O2}^o}{(1 + y_{O2}^e/r)}$$

- Depends on the extinction conditions

Special feature : two regimes only if

- $\dot{m}_f^e \neq 0$
- $\phi_m > 0.2$

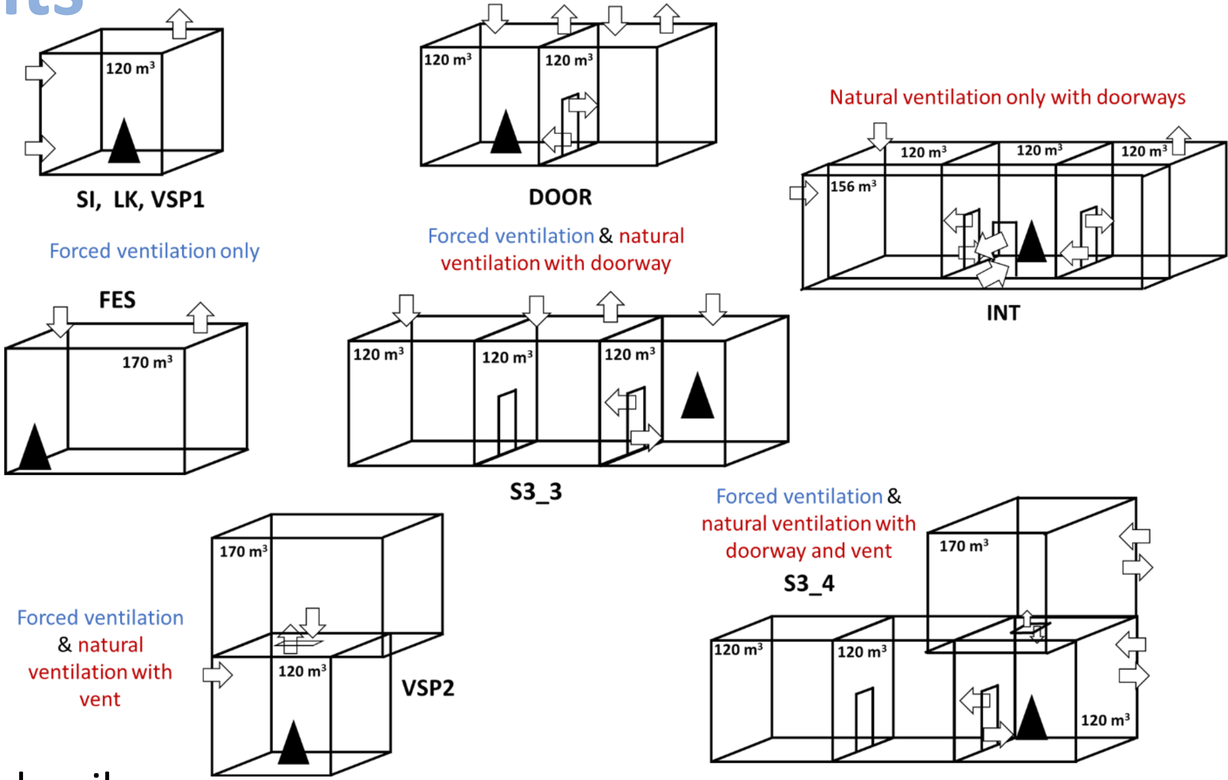


H. Prétrel, N. Chaaraoui, B. Lafdal, and S. Suard, "Effect of environmental conditions on fire combustion regimes in mechanically-ventilated compartments," *Fire Saf. J.*, vol. 127, no. June 2021, 2022, doi: 10.1016/j.firesaf.2021.103493.

Fire experiments

PRISME projects (2005-2021)

- *Various geometries*
  - 1-> 4 rooms
  - 120-170m^3
- *Various ventilation*
  - Inlet/outlet
  - Flow rate
- *Openings*
  - Doorways
  - vent
- *Pool fires*
  - 0,2-1,0 m2
  - Dodecane/Heptane/HTP/Lub. oil



Fire experiments

Test features

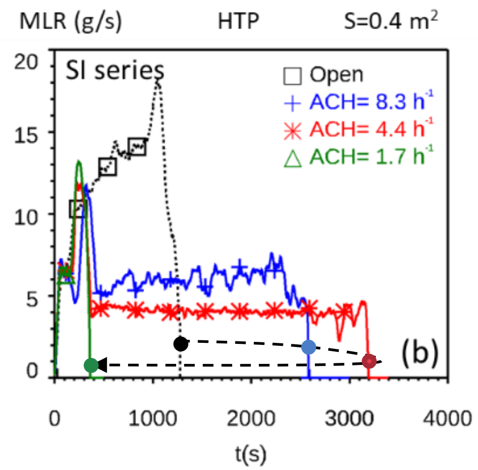
- **24 large scale fire tests**
- **Parameters**
  - Scenario (-> V)
  - Mass of fuel (-> ϕ_m)
  - Ventilation flow rate (-> ϕ_o)
- **Ouputs**
  - MLR (t) (steady/transient)
  - Extinction time t_{ext}
  - Extinction mode (02/fuel)

Serie	Name	Pool area	Fuel type	Number of room	Number of Doorway	Number of vent	Fire room volume	Total Volume	Ventilation flow rate	Admission position	ACH	Extinction mode	Regime	$\dot{m}_f^o$	ϕ_o	ϕ_m	t_{ext}	$\dot{m}_f$
		(m^2)		(#)	(#)	(#)	m^3	m^3	m^3/h	(-)	(h^{-1})	(-)	(-)	(g/s)	(-)	(-)	(s)	(g/s)
SI	SI_D1	0.4	T	1	-	-	120	120	560	Top	4,67	O2	R2	13,2	1,10	1,67	3190	4,04
	SI_D2	0.4	T	1	-	-	120	120	1000	Top	8,33	F	R1	13,2	0,59	1,64	2580	6,02
	SI_D3	0.4	T	1	-	-	120	120	180	Top	1,50	O2	R3	13,2	2,84	1,67	360	12,25
	SI_D4	0.4	T	1	-	-	120	120	560	Top	4,67	O2	R2	13,2	1,03	1,65	2895	4,18
	SI_D5	0.2	T	1	-	-	120	120	560	Top	4,67	F	R1	5,3	0,43	0,75	2550	3,12
	SI_D5a	0.2	T	1	-	-	120	120	180	Top	1,50	O2	R2	5,3	1,15	0,82	1980	1,07
	SI_D6	0.4	T	1	-	-	120	120	560	Bot.	4,67	O2	R2	13,2	1,06	1,67	2500	6,40
	SI_D6a	0.4	T	1	-	-	120	120	180	Bot.	1,50	O2	R3	13,2	6,80	1,65	560	8,18
DOOR	DOOR1	0.4	T	2	1	-	120	240	50	Top	0,42	O2	R3	13,2	11,90	1,55	885	3,74
	DOOR2	0.4	T	2	1	-	120	240	180	Top	1,50	O2	R2	13,2	3,35	1,85	1410	4,83
	DOOR3	0.4	T	2	1	-	120	240	570	Top	4,75	F	R1	13,2	1,05	1,70	1910	7,88
	DOOR4	0.4	T	2	1	-	120	240	1000	Top	8,33	F	R1	13,2	0,61	1,57	1160	13,48
	DOOR5	1	T	2	1	-	120	240	570	Top	4,75	F	R1	40,8	3,26	1,66	1310	7,34
LK	LK_3	0.6	T	1	-	-	120	120	1850	Top	15,42	F	R1	21,9	0,59	1,84	1120	19,25
INT	INT_4	1	T	4	3	-	120	516	3100	-	25,83	F	R1	40,8	0,59	5,44	1610	30,09
VSP1	VSP_1A	0.3	H	1	-		120	120	2000	Top	16,67	F	R1	16,2	0,38	2,17	1555	13,08
VSP2	VSP_2	0.4	H	2	-	1	120	290	2320	Top	19,33	F	R1	23,7	0,46	2,88	1310	22,16
	VSP_3	0.4	H	2	-	1	120	290	960	Top	8,00	O2	R2	23,7	1,10	2,87	755	15,31
	VSP_4	0.4	H	2	-	1	120	290	960	Top	8,00	O2	R3	23,7	1,14	2,90	335	20,11
FES	FES_1	0.7	O	1	-	-	170	170	2550	Top	15,00	F	R1	16,3	0,29	1,86	2650	11,65
S3_3	S3_B0	0.56	D	3	1	-	120	360	1200	Top	10,00	F	R1	16,8	0,62	3,90	2650	14,05
	S3_C1	0.56	D	3	1	-	120	360	1200	Top	10,00	F	R1	16,8	0,65	3,89	3470	11,22
S3_4	S3_A1	0.4	O	4	1	1	120	530	10	-	0,08	F	R1	8,4	0,75	1,76	3620	5,33
	S3_A2	1	O	4	1	1	120	530	2400	Top	20,00	F	R1	24,5	0,49	8,85	6250	16,09

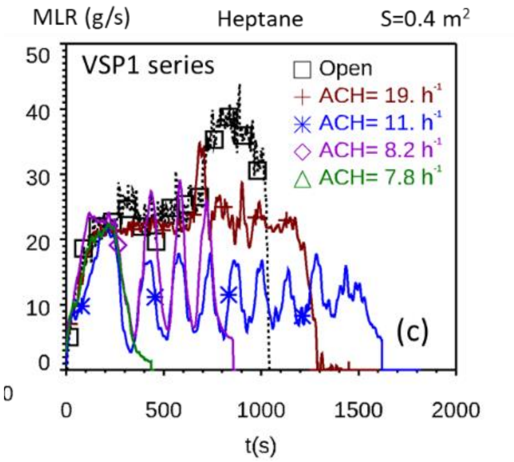
T=TPH ; H=Heptane - O=Lub.oil - D=Dodecane - O2= lack of oxygen - F=lack of fuel

Results

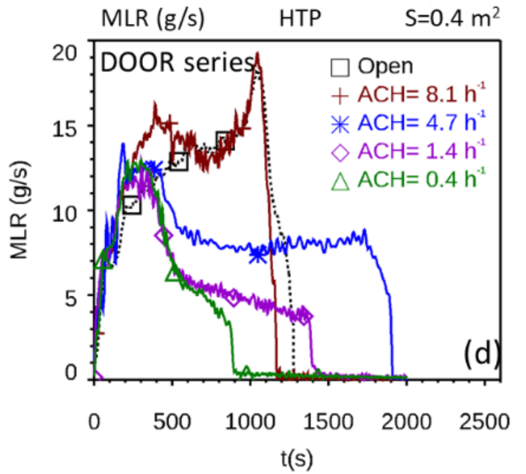
Different effects of the environment : effect of the ventilation flow rate (or ACH)



One room / HTP
Decrease of the MLR
Increase & decrease of the fire duration



One room /heptane
Decrease of the MLR
Increase & decrease of the fire duration
Oscillatory behaviour (near ϕ_o^c)



Two rooms / HTP
Decrease of the MLR
Increase & decrease of the fire duration

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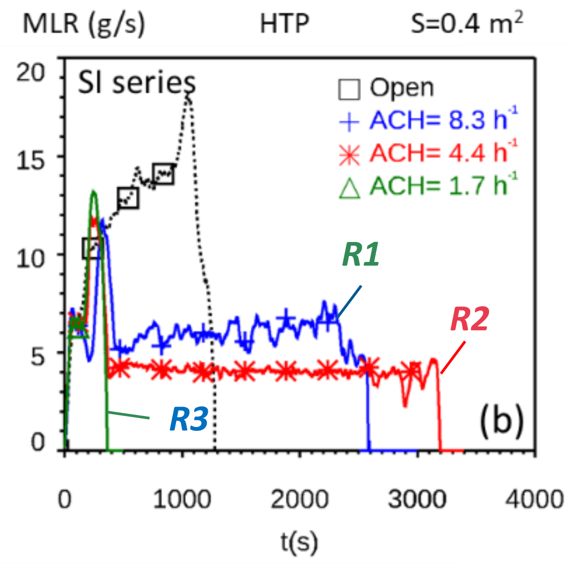
Results

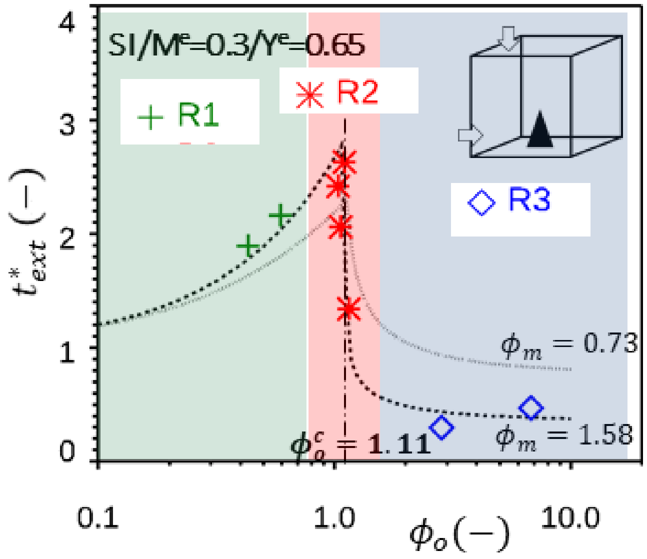
Three combustion regimes



R1 : Stationary – extinction by lack of fuel

R2 : Stationary – extinction by lack of O2

R3 : Transient – extinction by lack of O2



Agreement with the WSR model

Regime 2 = transition between R1 and R3

Calculation of the critical ventilation factor

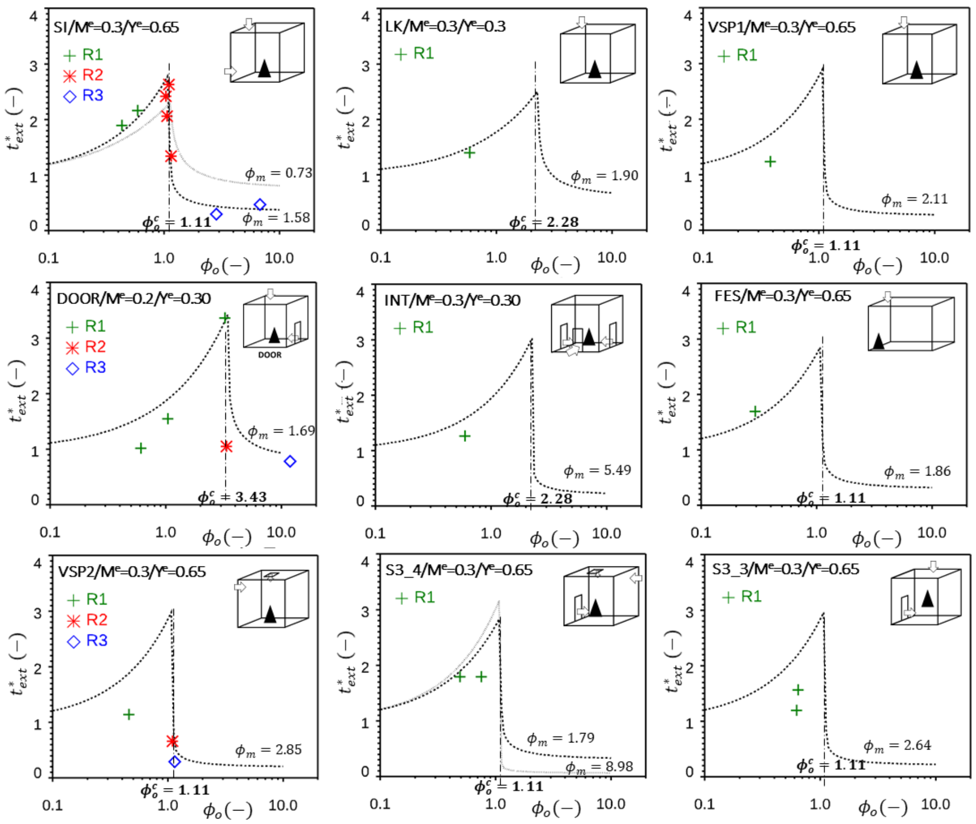
$$\phi_o^c = \frac{\dot{m}_f^o}{\dot{m}_f^e} \frac{(y_{O2}^o - y_{O2}^e)/y_{O2}^o}{(1 + y_{O2}^e/r)}$$

Results

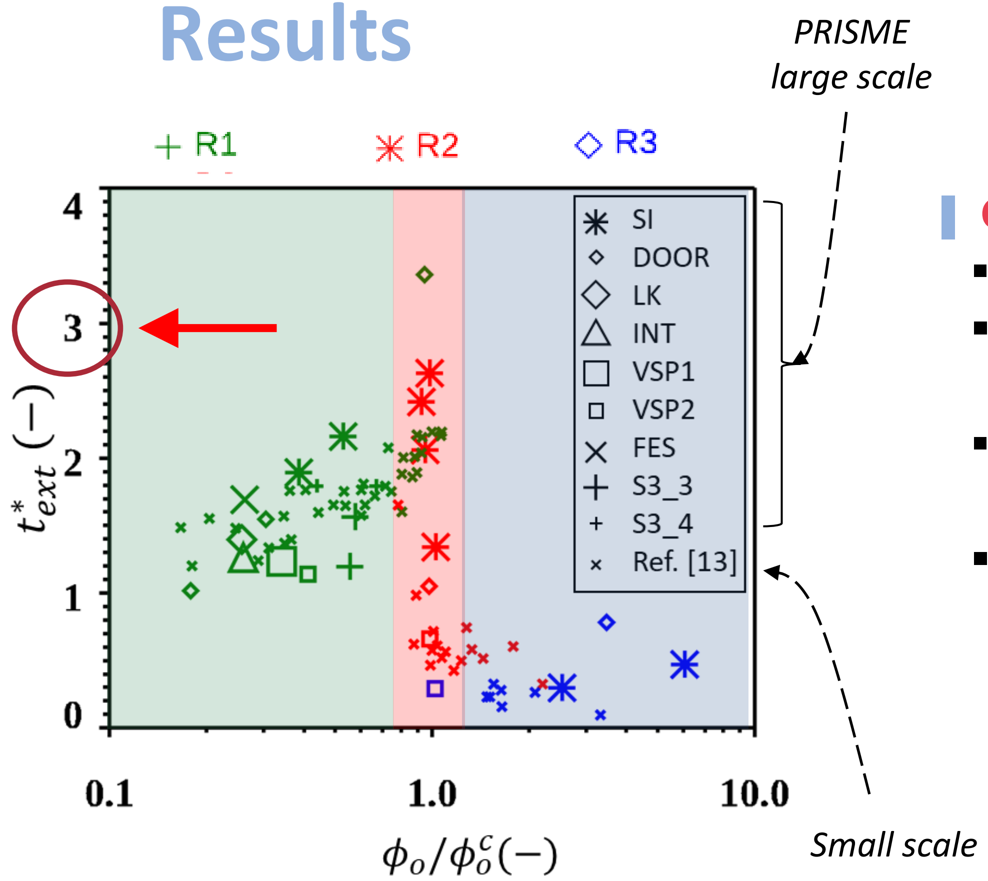
Combustion regime

- Application to all campaigns
  - –Specific (m_f^{init} , V)-> ϕ_m
- the critical ventilation factor may vary between scenarios
  - –Specific ($\dot{m}_f^e, y_{O2}^e$)

	SI	FES	LK	INT	VSP1	VSP2	FES	S3_3	S3_4	NYX
M^e	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.44
Y^e	0.65	0.3	0.3	0.3	0.65	0.65	0.65	0.65	0.65	0.76
ϕ_o^c	1.11	3.43	2.28	2.28	1.11	1.11	1.11	1.11	1.11	0.51



Results



Generalized behavior of time to extinction

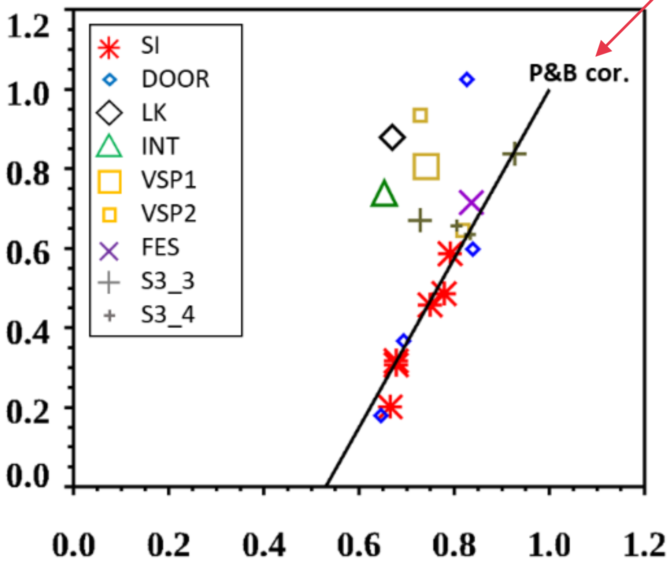
- Three regimes
- Validation of the WSR model for very different large-scale experiments
- Fire duration can reach about 3 times the duration in open atmosphere
- Critical ventilation factor is a good indicator

Ref [13] - H. Prétrel, N. Chaaraoui, B. Lafdal, and S. Suard, "Effect of environmental…," *Fire Saf. J.*, vol. 127, 2022.

Results

$$\frac{\dot{m}_f^e}{\dot{m}_f^o} = 0\,;\frac{y_{O2}^e}{y_{O2}^o} = 0{,}53$$

$M = \dot{\boldsymbol{m}}_{\boldsymbol{f}}/\dot{m}_f^o$



$Y = \boldsymbol{y}_{\boldsymbol{O2}}/y_{O2}^o$

- **Burning rate versus oxygen**
- **Effect of the environment**

$$\frac{\dot{m}_f - \dot{m}_f^e}{\dot{m}_f^o - \dot{m}_f^e} = \frac{y_{O2} - y_{O2}^e}{y_{O2}^o - y_{O2}^e}$$

- **Include the effect of external heat fluxes**

$$\dot{\boldsymbol{m}}_{\boldsymbol{f}} = \underbrace{\mathrm{f}(\boldsymbol{y}_{\boldsymbol{O2}})}_{O2\ vitiation} + \underbrace{g(\varphi_{ext})}_{External\ heat\ fluxes}$$

Results

Classification of fire scenarios

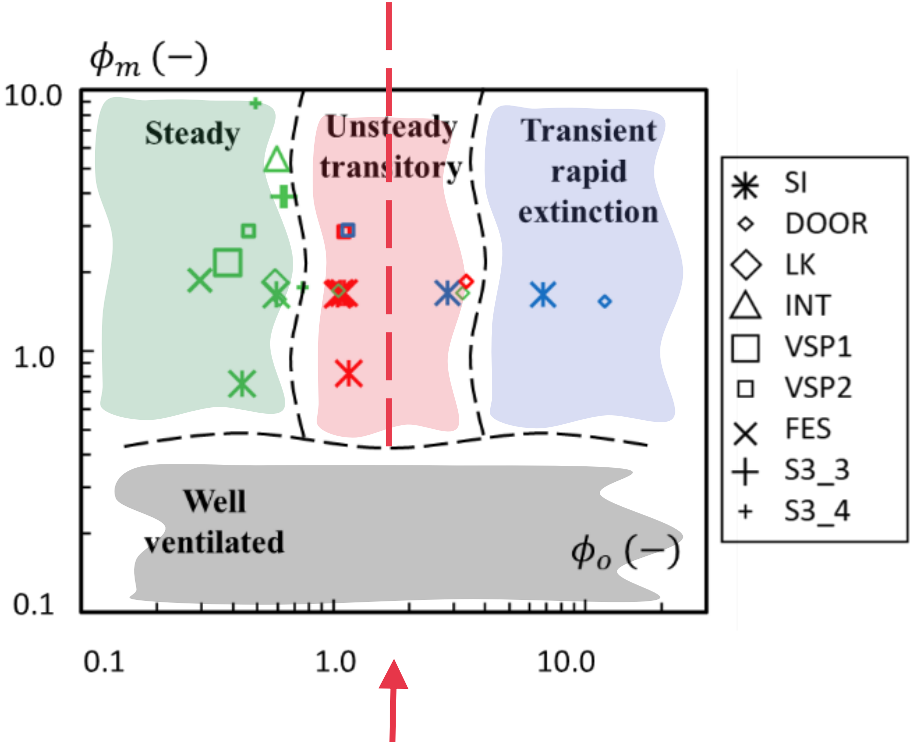
- *3 parameters*
  - Mass factor

$$\phi_m = \frac{r.m_f^{init}}{\rho_o V y_{O2}^o}$$

  - Ventilation factor

$$\phi_o = \frac{r.\dot{m}_f^o}{y_{O2}^o \dot{m}_v}$$

  - Extinction features
- *4 regions*
  - ϕ_m weak: little effect of the ventilation
  - ϕ_m significant
    - $\phi_o < 1$ -> steady
    - $\phi_o = \phi_o^c$ -> unsteady
    - $\phi_o > 1$ -> rapid extinction



$\phi_o^c = [0.7, 3]$

Extinction features

Conclusion

- Effect of the environmental conditions on the burning rate from large scale PRISME project fire tests data base

- Well stirred reactor (WSR) approach suited for interpreting large scale fire scenario
  - Identification of the main parameters
  - Dimensionless variables

- Three regimes
  - Steady / unsteady and extinction mode

- Ventilation factor is a robust parameter to interpret the fire scenario and the regime of combustion for forced ventilated compartment scenario

- O_2 vitiation has a strong effect on the burning rate, but external heat flux may have to be considered for some specific scenario