Investigation of the fire mass loss rate in confined and mechanically ventilated enclosures on the basis of a large-scale under-ventilated fire test

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Highlights:

- Under-ventilated combustion regimes in mechanically ventilated enclosures
- Effect of oxygen vitiation on the burning rate
- Summary analysis from a large-scale fire test database
- Application to complex scenarios representative of real fires event

Abstract:

This study concerns the under-ventilated combustion regimes of a fire scenario in mechanically ventilated enclosures. Using the theoretical approach of the well-stirred reactor model and the data-base of large-scale pool fire tests, the study analyses the mass loss rate as a function of the environmental conditions. The novelties lie in the analysis of a large set of realistic scenarios involving complex geometries (several compartment connected) and new ventilation configurations and the applicability of the well-stirred reactor model to interpret these scenarios. The variables of interest are the combustion regimes (stationary, transient or with rapid quenching), the duration of the combustion phase and the mass loss rate. The results show a satisfactory prediction of the well-stirred reactor model to interpret the experimental results of complex and realistic fire scenario and the robustness of this model to deal with the under-ventilated regimes. The analysis also highlights the interest of two new parameters rarely used in the literature, the ventilation factor and the mass factor, to characterise under-ventilated scenarios. The analysis points out the importance of the relationship expressing the burning rate as a function of environmental conditions (oxygen level and external flux) and extinction conditions.

Keywords: compartment fires; burning rate; under-ventilated, combustion regimes

1 Introduction

Compartment fires remain an important safety issue for the assessment of fire risk in nuclear facilities. These events, often encountered in nuclear installations and more generally in the industrial area, presents the particular feature of a strong coupling between the fire heat release rate and the environment. The physical understanding and the numerical simulation of these scenarios require appropriate modelling of the fire heat release rate, and the induced flows generated such as the thermal plume, ceiling jet and smoke filling. In terms of modelling, a

scientific bottleneck of these fire scenarios lies in the quantification of the coupling between the burning rate and the environment, which is rapidly vitiated by gaseous combustion products and soot and characterized by high temperature. The coupling between the fire and the environment leads to different combustion regimes such as stationary, oscillatory, or transient to rapid extinction. The nature of these different regimes depends on the thermodynamic conditions surrounding the fire, in particular the oxygen concentration and the temperature of the gases as well as the presence of combustion products (CO and soot). The literature on compartment fires is very extensive and a large proportion of it concerns natural ventilation with openings to the outside (i.e. façade fire applications). The configuration of an enclosure ventilated only by mechanical ventilation has been less extensively addressed but remains a configuration of interest especially for applications in the nuclear industry.

One of the first studies for mechanically ventilated configurations was that of Peatross & al. showing from a medium-scale 34 m^3 single compartment tests with pool fires and solid fuel (PMMA) that there is a linear dependence of the mass loss rate (MLR) and the oxygen concentration in the vicinity of the fire [1]. This work was continued during the three PRISME research programs (PRISME, PRISME2 and PRISME3) led by the French "Institut de Radioprotection et de Sûreté Nucléaire" in the framework of the Organisation for Economic Co-operation and Development (OECD/NEA) on more complex configurations involving several compartments of 120 m^3 and 170 m^3 connected together with openings [2],[3] [4]. Among other conclusions, these projects showed that the fire heat release rate is often lower than that in an open environment due to a change in the environment, particularly the decrease of the oxygen content. Other studies highlighted the specific feature of fires in a mechanically ventilated enclosure that can lead to unstable or oscillatory regimes [5], [6], [7], [8]. These large-scale observations were confirmed by academic studies carried out on a smaller scale, allowing a wider range of parameters and more detailed metrology[9] (8 m^3 compartment), [10] (1.9 m^3 compartment), [11] (1 m^3 compartment), and [7] (0.2 m^3 compartment). The influence of the position of the air vents on the fire heat release rate was also addressed by [12], [13] (8 m^3 compartment), [14] (25 m^3 compartment). Oscillatory regimes were further demonstrated for different configurations [15] [16]. Studies with controlled atmosphere cone calorimeter were also able to show the dependence of the MLR on the oxygen concentration for liquid pool fires and PMMA plates [17]. More recently, attempts to reproduce a given one compartment large-scale fire scenario (120 m^3 compartment) at small-scale (1.9 m^3 compartment) were performed successfully and demonstrated the performance of down-scaling mechanical ventilated fire scenario [18]. This reduced scale approach was also considered to demonstrate the relevance of the well-stirred reactor (WSR) approach in ranking and characterizing the combustion regimes for dodecane pool fire in a single mechanically ventilated compartment [10].

The purpose of the present study is to consider the analysis developed in [10] for a simple configuration (single compartment of 1.9 m^3) to interpret a wide spectrum of more realistic and complex fire scenario and to discuss how the behaviour reported at reduced scale remains applicable for real situations. These scenarios are those investigated experimentally in the framework of the three PRISME projects that include several compartments of various dimensions (120 m^3 to 170 m^3) connected to each other by doorways or vents and representative of scenarios encountered in nuclear facilities. Some of these tests have already been analysed

separately, focusing on a particular aspect of the scenario, influence of doorway [19], vent [20] or ventilation flow rate [21]. The novelty of this work lies in highlighting the applicability of the WSR model for interpreting the behaviour of fire scenarios in complex configurations such as those encountered in real-life situations. It highlights the generic nature of analyses developed on a reduced scale or on simplified configurations. This work also makes it possible to bring together in a review study a very varied set of large-scale and representative tests. First, the analytical means implemented for this study are recapped. This concerns the basis of the WSR approach as well as the fire test data-base. The analysis of the results is then presented by focusing on the evolution of the MLR in time, the duration of the combustion phase and the dependence of the environmental conditions on the MLR.

2 Material and methods

2.1 Summary of the well stirred reactor (WSR) model

The following is a recap of the WSR approach, often considered for compartment fire analysis [22] [23], [24], and applied in the present work to analyse the change in MLR. This approach, revisited recently in [10], considers the fire compartment as a homogeneous reactor in which oxygen and gaseous fuel interact, leading to an exothermic reaction. As previously derived in [10], the oxygen mass conservation in its raw form is

$$\frac{d}{dt}(\rho_o V y_{O2}) = (y_{O2}^o - y_{O2})\dot{m}_v - \mathrm{r}.\dot{m}_f \qquad (1)$$

ρ_o and V are the gas density in the compartment assumed to be constant and the compartment's volume respectively. y_{O2}^o and y_{O2} are the average mass fraction in the air (0.23) and in the compartment respectively, $\dot{m}_v$ is the ventilation flow rate assumed to be constant, r is the stoichiometric ratio and $\dot{m}_f$ the MLR that may vary with time. This balance states that the variation in oxygen in the compartment depends the oxygen supply through ventilation and the oxygen consumption by the fire. A dimensionless form is expressed in order to identify the ventilation factor as :

$$\frac{d}{d\tau}\mathrm{Y} = (1 - \mathrm{Y}) - \phi_o M(\frac{Y_{O2}^o}{r}Y + 1) \qquad (2)$$

where $\mathrm{Y} = y_{O2}/y_{O2}^o$ is the dimensionless average mass fraction of oxygen, $\tau = \dot{m}_v/(\rho_o V).t$ the dimensionless time. This approach highlights the importance of the MLR and the ventilation flow rate integrated through a single parameter, the ventilation factor, $\phi_o = r\dot{m}_f^o/y_{O2}^o\dot{m}_v$. This parameter, similar to the global equivalence ratio (GER), expresses a ratio of oxygen mass flow rates: one required to burn the fuel in open atmosphere and one injected into the compartment by the ventilation. One feature of this definition is to only consider variables known before the experiment ($\dot{m}_f^o$ and $\dot{m}_v$). The ventilation factor allows the type of combustion to be ranked as well-ventilated ($\phi_o \ll 1$) or under-ventilated ($\phi_o \gg 1$). A value of one corresponds to a balance between the oxygen demand through combustion and the oxygen supply through ventilation. The model also introduces the dimensionless MLR as $M = \dot{m}_f/\dot{m}_f^o$ where $\dot{m}_f^o$ is the reference one in open atmosphere. It is worth noting that this approach of the WSR model is limited in the present

analysis to the mass balance and does not include the energy balance, which allows the temporal evolution of temperature to be expressed. This choice simplifies the presentation but has no influence on the conclusions that can be drawn from the model. The WSR approach may also highlights the influence of the gas conditions in the compartment (oxygen concentration and temperature) on the MLR. In this case, the MLR is no more a fixed input parameter but varies with time as the oxygen concentration and the gas temperature. They are many laws that can be considered and one of these is the following one used in [10]:

$$M = (1 - \mathrm{M}^e)[(Y - Y^e)/(1 - Y^e)] + \mathrm{M}^e \quad (3)$$

where M^e and Y^e are the dimensionless MLR and oxygen mass fraction at extinction (equivalent to the low oxygen index, LOI). Relation (3) expresses a linear relationship between the MLR and the oxygen concentration. It states that the reduction of the oxygen concentration will proportionally reduce the radiation from the flame towards the combustible and thus the MLR. The parameters M^e and Y^e express the boundary conditions at extinction. The relations (2) and (3) are solved numerically to obtain the dimensionless time evolution $M(\tau)$ and $Y(\tau)$, for which ϕ_o, r, M^e and Y^e are parameters. A variable of interest for ranking the combustion regimes is the time to extinction (or the duration of the combustion period), ending either through lack of fuel or lack of oxygen. Its determination is therefore based on two cases: (1) the dimensionless oxygen fraction reaches the LOI, $Y(\tau) = Y^e$ or (2) the time integral of the dimensionless MLR is equal to a dimensionless mass m^*, $\int_0^\tau M d\tau = m^*$ and extinction occurs through lack of fuel. For the second case, the parameter $m^* = \left[\left(r m_f^{init}\right)/(y_{O2}^o \rho_o V)\right]/\phi_o$ includes the initial mass of fuel, m_f^{init}. A dimensionless time to extinction is defined as $t_{ext}^* = t_{ext}\, \dot{m}_f^o / m_f^{init}$ to get rid of the initial mass of fuel. It is worth noting that the dimensionless mass m^* contains a second important ratio, the mass factor $\phi_m = \left(r m_f^{init}\right)/(y_{O2}^o \rho_o V)$: the mass of oxygen required to oxidize the total mass of fuel divided by the mass of oxygen initially in the compartment's volume. This parameter is an important characteristic of the fire scenario. For a low value of ϕ_m (low fuel mass in a large volume for instance), all the fuel is consumed before reaching the conditions of extinction through lack of oxygen and the scenario is therefore not affected by extinction conditions, whatever the ventilation flow rate.

An example calculation is given in Fig. 1 to illustrate the influence of the model parameters. The evolution with time of the oxygen concentration (Fig. 1 a and b) is presented for several values of the ventilation factor ϕ_o and for two given values of ϕ_m (0.2 and 0.6). For a low value of ϕ_m (here 0.2, Fig. 1-a), the conditions for extinction through lack of oxygen are never met and the extinction always occurs through lack of fuel. For a higher value of ϕ_m (here 0.6 Fig. 1-b), both extinction modes are encountered, depending on the value of the ventilation factor. In the latter case, the duration of the combustion phase first increases with ϕ_o for low values of ϕ_o (0.1 and 0.4) and extinction occurs here through lack of fuel. Then, for higher values of ϕ_o, (1 and 2), the opposite behaviour is observed: the duration of the combustion phase decreases with ϕ_o (extinction occurs by reaching the LOI).

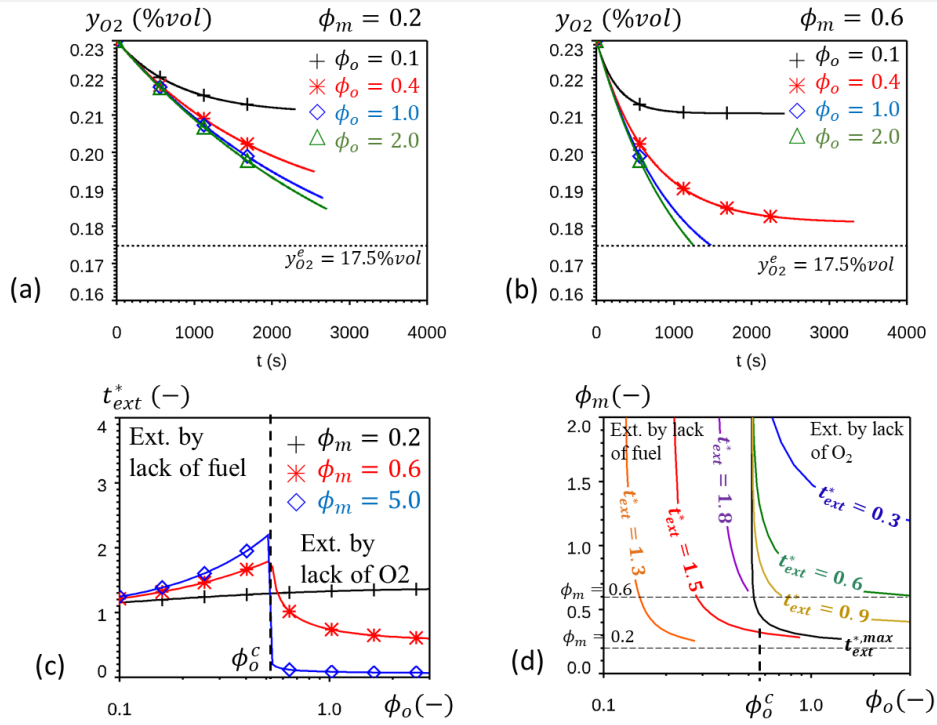

Fig. 1. Examples of simulation with the WSR model (where M^e=0.44 and Y^e=0.76) (top) time variation of O_2 concentration with $\phi_m = 0.2$ (a) and with $\phi_m = 0.6$ (b)- (Bottom) t^*_{ext} versus the ventilation factor ϕ_o for three values of ϕ_m (c), Iso-contours of t^*_{ext} in the (ϕ_m, ϕ_o) domain (d).

The evolution of t^*_{ext} as a function of ϕ_o is summarized in Fig. 1-c for three values of ϕ_m. For values of ϕ_m above or equal to 0.6, the two opposite behaviours mentioned previously are observed: t^*_{ext} first increases with ϕ_o due to a decrease in the MLR (under the effect of oxygen reduction) and an oxygen concentration still above the LOI due to a high ventilation rate in comparison to the MLR (low ϕ_o). At ϕ_o above a critical value, the reverse behaviour is evidenced: t^*_{ext} decreases because the LOI is reached faster with a ventilation rate too low compared to the MLR. Fig. 1-c and Fig. 1-d also illustrate the behaviour for scenarios with low ϕ_m (here 0.2) for which only one regime is observed. Extinction occurs only due to lack of fuel (the conditions for extinction through lack of oxygen are never encountered) because of too little fuel mass in a very large volume. As previously derived in [10], the critical ventilation factor $\phi_o^c = (1 - Y^e)/M^e(1 + y_{O2}^o/r\,Y^e)$ that characterizes the change of behaviour (only for scenarios with ϕ_m large enough) only depends on the extinction conditions specified here with the parameters M^e and Y^e. The WSR model gives the basis to characterize the combustion regimes based on the fire duration, the extinction mode, the ventilation factor and the mass factor ϕ_m. These parameters will be considered to analyse the burning rate in large-scale fire experiments.

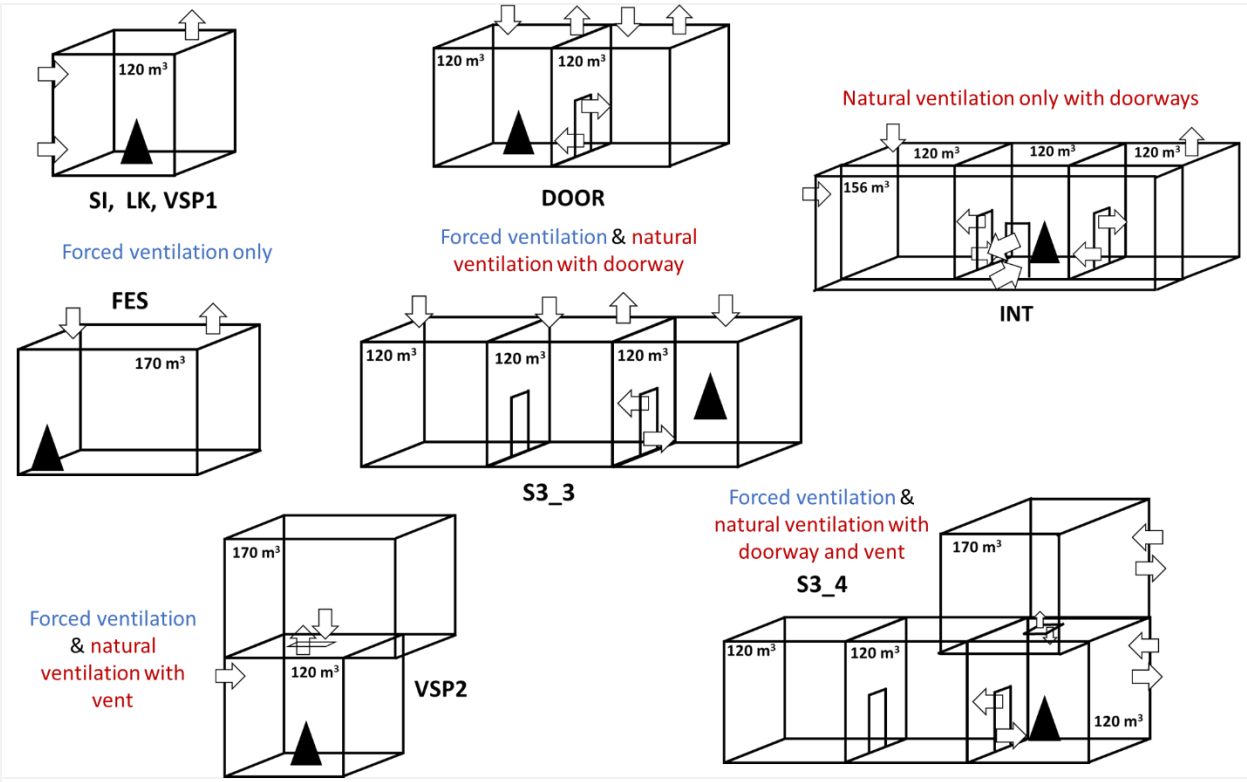

Fig. 2. Illustration of the configurations with various types of ventilation considered in the data-base (arrows indicate the air flows).

2.2 Fire experiments

The fire experiments considered in this study concern scenarios involving an hydrocarbon pool fire in various configurations of mechanically ventilated compartments. These tests were carried out at IRSN's DIVA facility as part of the OECD/NEA PRISME projects. The special feature of these tests is that they produce a wide variety of ventilation configurations that are barely discussed in the literature. They were carried out during several experimental campaigns (named SI, DOOR, LK, INT, VSP1, VSP2, FES, S3_3 and S3_4, acronyms used in the project and the related publications), each with a specific configuration of the experimental set-up as shown in Fig. 2. The first configuration concerns a ventilated, single compartment 120 m^3 by volume (SI, LK and VSP1 series), or 170m^3 by volume (FES series). The second configuration involves two compartments connected via a doorway (DOOR series), or by a vent (VSP2 series). The third configuration involves three compartments connected via doorways (S3_3 series). Finally, a fourth configuration involves four compartments connected via doorways (INT) or via doorways and a vent (S3_4 series). For all tests, the fire compartment's volume is 120 m^3 or 170 m^3. The fire compartment had various ventilation configurations: (i) only mechanical ventilation (SI, LK, FES and VSP1), (ii) only natural ventilation via doorways (INT), (iii)) mechanical and natural ventilation via doorways and/or vents (DOOR, VSP2, S3_3 and S3_4). The mechanical ventilation is provided through an inlet positioned at the top of the compartment except for the SI series in which two tests had inlets at the bottom of the compartment. The natural ventilation is provided by the incoming air through an opening: (i) a vertical doorway (INT, DOOR), (ii) an

horizontal vent (VSP2) or both (S3_3 and S3_4). The ventilation rate (or air change per hour ACH) is calculated based on the air flow rate supplied by the mechanical ventilation duct only and the volume of the fire compartment (120 m^3 or 170 m^3).

In all fire tests, the fire is a circular pool fire with various pool diameters from 0.2 m^2 to 1 m^2. Two liquid fuels commonly found in nuclear facilities are considered: Hydrogenated Tetra-propylene (HTP) used for reprocessing processes and lubricating oil used for gas turbines. Dodecane (has a similar chemical formulation to HTP), and heptane were also used for comparison with other results in the literature [31].

Table 1. List of experiments and main results

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	$\dot{m}_f^{\circ}$	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

The test parameters are given in Table 1. These are the pool size (from 0.2 m^2 to 1 m^2), the fuel type (HTP, heptane, dodecane and lubricant oil), the number of rooms, the size of the fire room, the presence of openings in the fire room (doorway or vent), the ventilation flow rate or ACH induced by the mechanical ventilation only and the position of the air intake (Bottom or Top).

One of the aims of this study is to show the influence of the ventilation on the MLR for a wide variety of ventilation configurations that are representative of real-life situations.

All the tests were carried out in the same facility and the instrumentation used was identical. The mass loss was measured by a SARTORIUS balance located under the pan. The measurement range was 300 kg with an accuracy of 2 g. Ventilation flow rates were measured by ANNUBAR type averaged Pitot probes inserted in the ventilation ducts and connected to pressure transducers. The volume flow rate was obtained by considering the ANNUBAR probe coefficient and the gas temperature. The uncertainty on the volume flow rate was assessed to 10%. Oxygen concentrations were measured by SERVOMEX XANTRA 4100 gas analysers fitted with paramagnetic cells. These analysers were connected to a sampling case that takes gas samples at three points in the fire compartment (at the top at 0.85 m from the ceiling, at the bottom at 1 m from the ground and near the fire at the pan level on its side). The uncertainty on oxygen concentration was assessed as less than 1%. The MLR is obtained as the time derivative of the mass loss signal. The extinction time is determined visually and consolidated with the mass loss measurement. The mode of extinction (through lack of oxygen or lack of fuel) is determined based on the fuel mass. More detailed information for each campaign can be found in the references dedicated to modelling (SI, [25]-[26], DOOR, [27], LK, [28], INT ,[29], VSP1 and VSP2, [20], FES,[30]).

All the tests are shown in the domain (pool area, ACH) illustrating the ranges considered for the two parameters (Fig. 3-a). As suggested by the WSR model, the tests can be represented in the (ϕ_m, ϕ_o) domain (see Fig. 3-b). The ϕ_m factor is greater than 0.7 which indicate that the mass of fuel was large enough to investigate the effect of the ventilation and the ventilation factor ϕ_o is well-distributed over a wide range including well- and under-ventilated regimes.

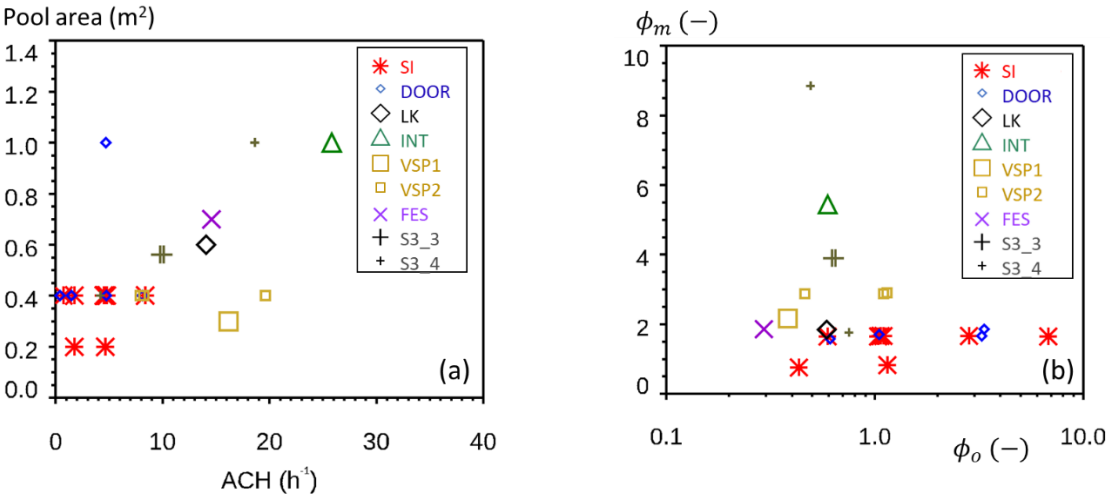

Fig. 3. Representation of the data set (a) in the (pool area, ACH) domain and (b) in the (ϕ_m, ϕ_o) domain.

3 Results

3.1 Behaviour in open atmosphere

Fuels were characterized in an open environment under a calorimetric hood in order to determine the evolution of MLR per unit of area ($\dot{m}''$) in open environment with the pool diameter *D*. This quantity is needed to determine the MLR in an open environment $\dot{m}_f^o = \pi D^2/4 \times \dot{m}''$ used in the evaluation of the ventilation factor ϕ_o introduced in the section 2.1. The MLR per unit of area can be theoretically expressed with Babrauskas's relationship, $\dot{m}''(D) = \dot{m}''_\infty\left(1 - exp(-k\beta D)\right)$ where $\dot{m}''_\infty$ and $k\beta$ are the two parameters characterizing the constant MLR per unit area for large diameters and the propensity to produce soot. For the four fuels, experiments are carried out with several diameters to obtain the parameters $\dot{m}''_\infty$ and $k\beta$ from fitting. The results given in Fig. 4, agree with the theoretical prediction and the parameters agree with those found in the literature [32]. The variability of the results also observed in the literature [33] is due to the influence of initial and boundary conditions such as ambient temperature, initial fuel height or pan height. The results also show that heptane is, among the four, the fuel that leads to the highest MLR for a given diameter while HTP and Dodecane have similar results, and lubricant oil has the lowest MLR. Both HTP and Dodecane fuel give similar results. Lubricant oil is the fuel giving the lowest MLR.

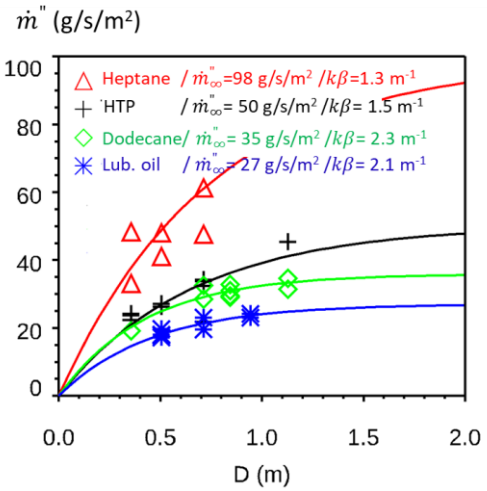

Fig. 4. MLR per unit area versus the pool diameter for the Heptane, HTP, Dodecane and lubricant oil.

3.2 Influence of environmental conditions

The wide variety of configurations studied during the PRISME projects highlights the influence of environmental conditions on the MLR. Three parameters have been studied: the ventilation rate, the presence of an opening (in this case a doorway) and the position of the inlet. The aim here is to study whether the influence of these parameters, highlighted on a reduced or intermediate scale, can be found on a large scale in real configurations. Firstly, configurations involving a single mechanically ventilated compartment (SI and VSP1 campaigns) are

considered. The major effect of the ventilation flow rate decrease is a reduction of the MLR in comparison to the level in open atmosphere. As shown in Fig. 5-(a) and (b), after a transitory phase during which a behaviour like that in open environment is observed, a stationary behaviour is evidenced, for which the average MLR is lower than the one in open environment. Lower the ventilation flow rate and lower the MLR. This result is reported whatever the pool area (0.2 m^2 or 0.4 m^2 Fig. 5 (a) and (b)) or the nature of the fuel (HTP or Heptane Fig. 5 (c)). This result agree with literature as for example the work of Peatross & al. [1]. One consequence is a longer fire duration in comparison to that in open atmosphere if extinction occurs through lack of fuel. In case of a low, and potentially limited ventilation rate, extinction occurs rapidly when the LOI is reached, and the fire duration becomes very short (ACH=1.7 h^{-1} in Fig. 5 (b) or ACH=7.8 h^{-1} in Fig. 5 (c)). The test series with heptane also show oscillatory behaviour of the MLR that may appear for low values of the ventilation rate (Fig. 5 (c)). The results obtained on a large scale also confirm the observation made on a reduced scale [7], [16]. The oscillations appear for conditions leading to oxygen concentrations close to the extinguishing conditions. Modulations of the MLR are associated with those of the air intake into the compartment, induced by a coupling between the fire heat release rate and the ventilation network. The effect of the ventilation flow rate is also observed on more complex configurations with two rooms. The fire room is ventilated mechanically but also naturally with the doorway. Similar results as those obtained with one room are reported Fig. 5-(d)). The main difference is that a steady state is no longer achieved. The MLR decreases progressively until extinction.

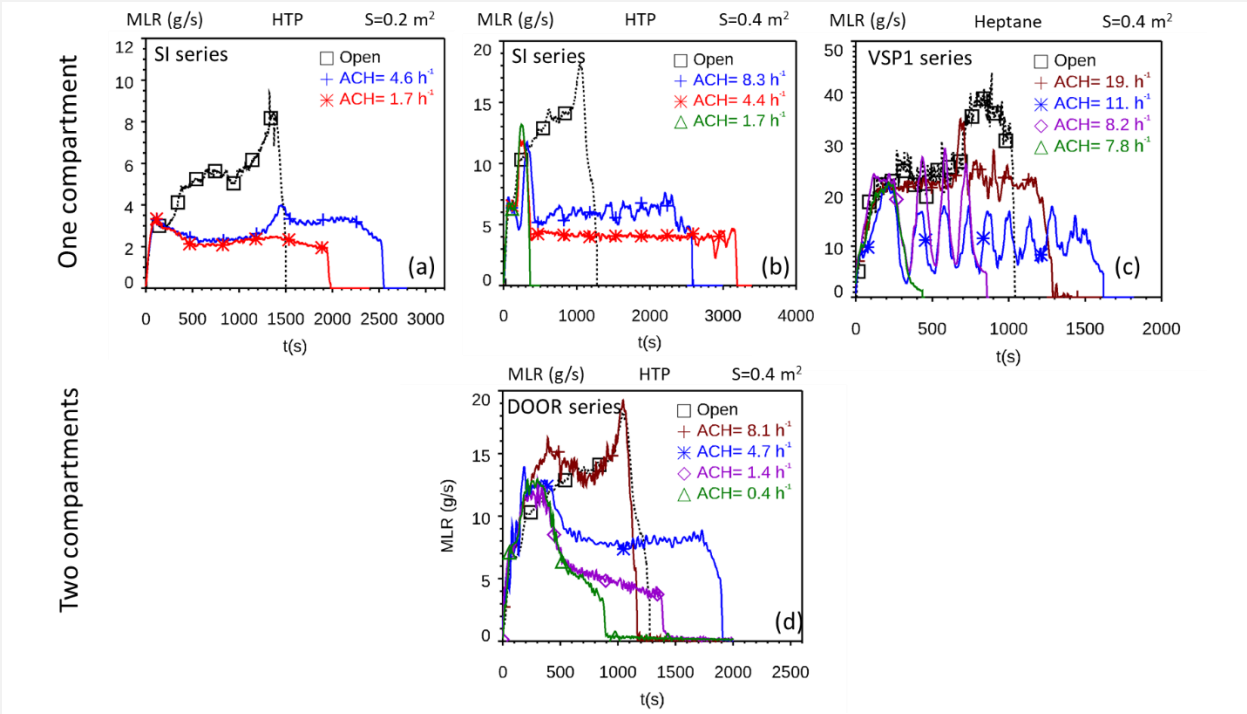

Fig. 5. Effect of the ventilation flow rate on the MLR time variation for two configurations: one compartment (first line) (a) with 0.2 m^2 HTP pool fires (b) with 0.4 m^2 HTP pool fires (c) with 0.4 m^2 heptane pool fire; and two compartments (second line) (d) with 0.4 m^2 HTP pool fires

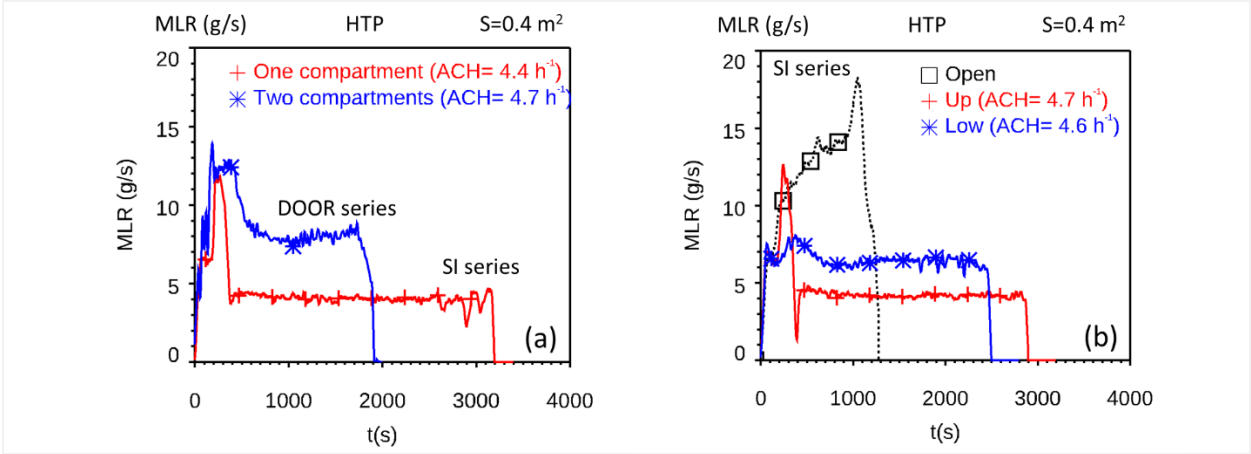

Fig. 6. (a) Effect of the number of compartments with 0.4 m^2 HTP pool fires and for a given ventilation flow rate (SI and DOOR series) (b) Effect of the air intake position location with 0.4 m^2 HTP pool fires (SI series)

It is important to note that different behaviours are observed for the same ventilation rate. Indeed, the ventilation rate is not the only parameter influencing the classification of the tests (and in the following section, the ventilation factor is introduced for this purpose), the nature of the fuel (stoichiometric coefficient in particular), the type of ventilation (forced only or forced with an open door) and the position of the air supply also have an influence. This is the reason why different behaviours can be observed for the same ventilation flow rate value.

The effect of the presence of a doorway is isolated by comparing two similar tests (same fuel, same mechanical ventilation rate and same fire compartment size) (Fig. 5-(e)). The results show a greater MLR with a doorway compared to the same configuration without a doorway. The doorway induced a significant incoming air flow which can be assessed with the relation $0.5 \times A\sqrt{H}$ (where A and H are the section and the height of the opening). For standard dimensions (H=2.1 m and w=0.8 m), this air flow rate is in the range from 2,000 to 3,000 m^3/h which corresponds to an ACH greater than 15 h^{-1} for a fire compartment of 120 m^3. Although this result is expected, it is new and has received little attention in the literature.

The tests of these data-base were also able to highlight the influence of the position of the air intake on the MLR. For a given configuration with only the air inlet as a variable parameter, the MLR is higher for a low position, which is favourable for maintaining a high oxygen concentration near the fire location (Fig. 5-(f)). The high position of the air intake is less efficient for feeding the fire. These result agrees with a medium scale study that discussed this effect in a 25 m^3 compartment [14]. The present tests confirm the significant effect of the position of the air intake on the MLR. The tests at a large scale and for complex scenarios validate the results on the influence of the fire scenario on the MLR, which to date have mainly been carried out on a reduced or intermediate scale.

3.3 Combustion regimes and time to extinction

Based on the MLR temporal variation, three combustion regimes reported at small-scale in [10] are also considered here: regime 1 (R1), where the MLR experiences a stationary period with an amplitude lower than the level in open atmosphere but extinction occurs through lack of fuel, regime 2 (R2), where the MLR also shows a stationary period with an amplitude lower than the level in open atmosphere but extinction occurs through lack of oxygen (there is still fuel in the pan after extinction), and regime 3 (R3), where the MLR shows a transient period and extinction rapidly occurs through lack of oxygen (the limit oxygen index, LOI, is reached). For a given scenario, these three regimes are correlated to the value of the ventilation factor, ϕ_o as predicted by the WSR model. Regimes R1, R2 and R3 are respectively observed successively when ϕ_o increases.

A second parameter of interest is the duration of the combustion phase. As observed for the MLR temporal variation, the vitiation of the surrounding environment can lead to different behaviours of the duration versus the ventilation flow rate; either an increase due to the decrease of the MLR or a decrease due to a rapid extinction through lack of oxygen. This behaviour, also highlighted with the WSR model, is analysed from these large scale data-base. For each test, the duration of the combustion phase, the mode of extinction (through lack of fuel, F or lack of oxygen O) as well as the combustion regime (R1, R2 and R3) are identified and the ventilation factor ϕ_o and a dimensionless time t^*_{ext} determined (Table 1). As defined previously, the ventilation factor is computed from the MLR in open atmosphere and only from the mechanical ventilation flow rate in the fire compartment before ignition.

The dimensionless time versus the ventilation factor is presented in Fig. 7 for each scenario indicating also and the type of combustion regime (R1, R2 and R3). On each plot, the data and the WSR predictions are compared. For the three scenarios corresponding to series SI, DOOR and VSP2, enough tests have been performed to visualize the three regimes and to observe similar behaviour to that predicted theoretically. The increase of the dimensionless fire duration with the ventilation factor corresponds to regime 1. Regime 3 corresponds to the opposite behaviour for higher values of ϕ_o. Regime R2 corresponds to the transitional regime between the two behaviours. A critical ventilation factor can be experimentally determined, respectively about 1.11, 3.43 and 1.11 for the series SI, DOOR and VSP2. A comparison with the WSR model is proposed, considering the experimental parameter ϕ_m and adjusting realistic values for M^e and Y^e to obtain the value of the critical ventilation factor that enables the model to reproduce the data as well as possible. The values of M^e and Y^e are summarized in Table 2. Results show very similar trends, highlighting the suitability of the WSR approach for reproducing the test results. It is worth noting that for the scenario including doorway (DOOR), the parameters (M^e, Y^e) need to be modified to move the critical ventilation factor, ϕ_o^c, toward a larger value (about 3) and to fit the data. For the other configurations, for which only one regime R1 is evidenced, the critical ventilation is only assessed by fitting the WSR predictions.

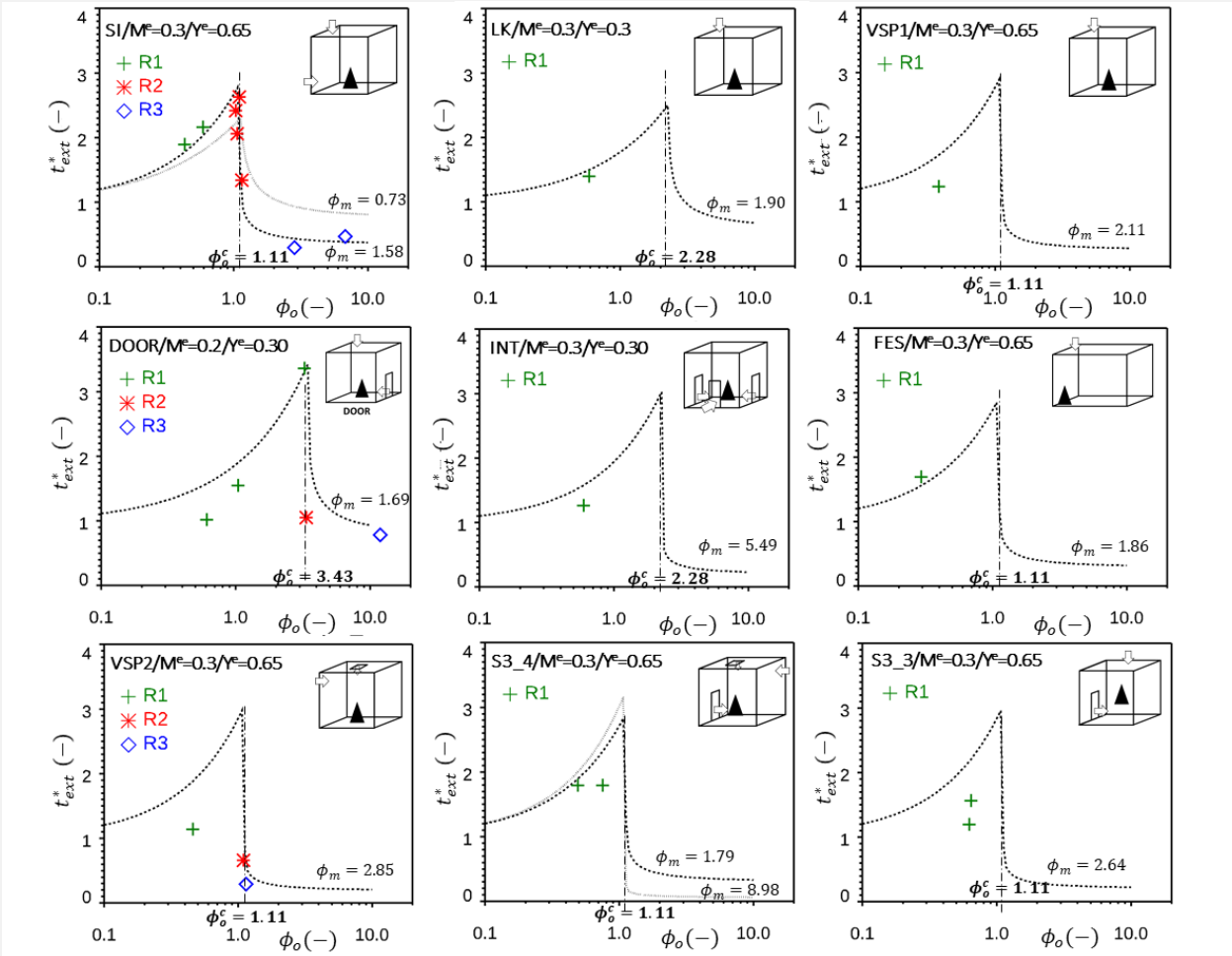

Fig. 7. Dimensionless time to extinction versus the ventilation factor for each configuration (first line) mechanical ventilation only (second and third lines) mechanical ventilation and natural ventilation with doorway and vent

Table 2. Values of M^e and Y^e and the corresponding critical ventilation factor used for the prediction with the WSR model.

	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

Despite the optimisation of the critical ventilation factor, in some cases there are discrepancies between the experimental points and the model. These discrepancies are attributed more to the simplicity of the model than to experimental uncertainties. The experimental variables, in this case the duration of the combustion phase and the initial fuel mass, have a fairly low uncertainty.

The fact that there are different ϕ_o^c values between the configurations is explained by the contribution of the openings (doorway or vent) to the global effect of the ventilation. The presence of openings in addition to mechanical ventilation leads to a shift in the observed trend towards higher values of the ventilation factor. The ventilation factor as it is defined in the WSR model is a global parameter that does not include the specific nature of each configuration and in particular the additional effects of openings to the oxygenation of the fire.

Nevertheless, a generic behaviour can be proposed by scaling the ventilation factor by its critical value (Fig. 8). Despite the different configurations, the combustion regimes can be classified according to the value of the ventilation factor. For values below the critical value, the duration of the fire increases with the normalised ventilation factor due to the decrease in MLR; the duration of the combustion phase can increase up to three times the duration in an open environment (tests from all campaigns). For ventilation factor values higher than a critical value, the duration of the fire is lower than in open environment because of anticipated extinction through lack of oxygen (tests from SI and DOOR campaigns). Between these two regimes, there is a transition stage, during which the duration can take very variable values for the same ventilation factor corresponding to the critical value (tests from SI, DOOR and VSP2). A comparison with tests carried out on a reduced scale single compartment without opening ([10]) shows very similar behaviour, illustrating the generic nature of this representation. For this test series, the critical ventilation factor was 0.52 [10]. This evolution of the dimensionless time versus the ventilation factor scaled by the critical ventilation factor is generic to fire scenarios of different scales, various types of ventilation and various hydrocarbon fuels. It also allows ranking of the three combustion regimes. The critical ventilation factor is therefore a good indicator for characterising a fire scenario. The higher it is, the more the scenario favours oxygenation of the fire.

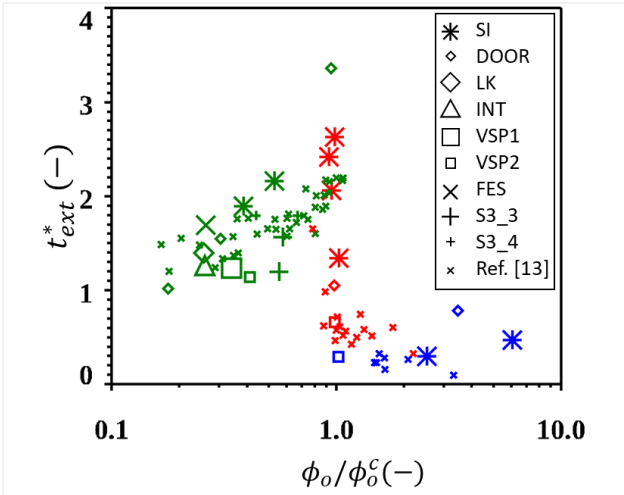

Fig. 8. Dimensionless time to extinction versus the ventilation factor scaled by its critical value (Regime R1 in green, regime R2 in red and regime R3 in blue)

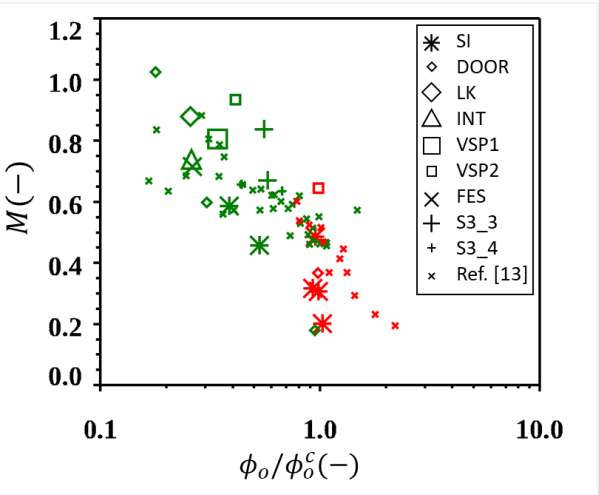

Fig. 9. Dimensionless MLR versus the ventilation factor scaled by its critical value (Regime R1 in green and regime R2 in red)

It is worth noting a non-negligeable spread of the points around a common trend. This dispersion is explained by the fact that the ventilation factor is a global parameter, which does not allow the specific features of each scenario (shape of the enclosure, position of the air inlets, position of the fire location, etc.) to be considered. For the same ventilation factor and the same initial mass of fuel, the duration of the fire can be slightly different.

Theoretical analysis shows that the critical ventilation factor depends on the extinction conditions (minimum MLR at extinction and LOI). The prediction of these scenarios in regime R2 is most complex because it requires satisfactory modelling of the extinction conditions that may be different for each test. On the other hand, for scenarios with a small or very large ventilation factor, any inaccuracy in the extinction conditions will have no (regime R1) or little (regime R3) influence on the prediction.

3.4 Burning rate in vitiated environment

The WSR model also highlights that the decrease in MLR is correlated with the ventilation factor. This analysis is conducted on tests with a R1 or R2 combustion regime for which a stationary phase is identified. The results, presented in Fig. 9, show indeed a decrease in MLR as a function of ventilation factor. This result demonstrates the influence of the oxygen concentration on the MLR. As the ventilation factor increases and consequently the oxygen concentration decreases, the MLR decreases. This result is evidence that there is a need in the model of a relationship between the MLR and the oxygen concentration. A general trend is observed for all the large-scale tests as well as for the reduced-scale experiments, indicating the generic character of this result. Nevertheless, as with the study of the fire duration, dispersion of the experimental data is evidenced (Fig. 9). It is also explained by the global character of the ventilation factor but also by the uncertainty in the identification of the stationary phase for which the MLR is assessed.

One relationship of interest is that between the MLR and the characteristics of the surrounding environment. To identify this relation and to validate the relationship introduced in the WSR model with relation (3), these quantities measured during the tests are evaluated for a stationary phase and only for the tests on regime R1 or R2. The correlation between MLR and oxygen concentration is presented in Fig. 10. The results show a decrease in MLR with oxygen concentration, as expected. A comparison with the specific Peatross & Beyler law, relation (3) with $M^e=0$ and $Y^e=0.53$, shows good agreement for some tests. For other tests, the experimental points are far from the theoretical prediction. This can be explained in two ways. The first concerns the experimental difficulty in obtaining a concentration representative of the average concentration of the flows used to oxidize the combustible. Defining the control volume over which the oxygen concentration should be assessed is difficult for some scenarios. In these cases, the global approach reaches its limits and a detailed CFD approach (with adapted combustion and pyrolysis models) seems to be necessary. The second point concerns the influence of induced flows as well as external heat fluxes, which will contribute to increasing the MLR despite low oxygen concentration. This is the case for the LK and INT tests where the fire compartment was highly thermally insulated, resulting in a high temperature overall. The VSP2 and INT tests concern scenarios with the presence of openings, reinforcing the MLR. For these

tests, relationship (3) including only the effect of oxygen is incomplete. The influence of additional effects such as heat flux and induced flows must be integrated.

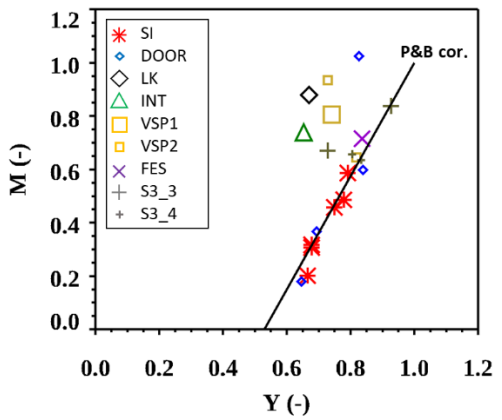

Fig. 10. Relationship between the dimensionless MLR and oxygen concentration near the fire location at steady state

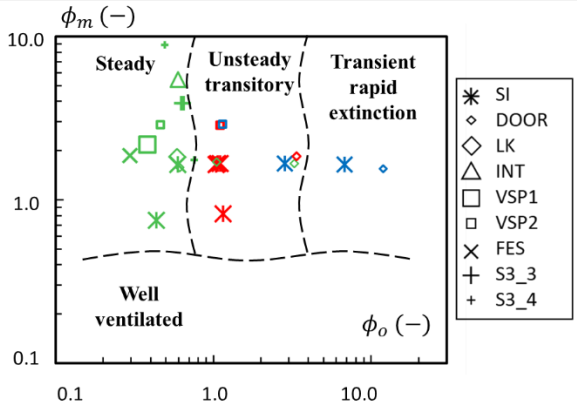

Fig. 11. Classification of fire scenario in a (ϕ_o, ϕ_m) map with the PRISME project tests as examples (Regime R1 in green, regime R2 in red and regime R3 in blue)

Nevertheless, the good agreement in average of the relation (3) correlation explains why this relationship, widely used in simulation tools, may give satisfactory results for some scenarios. However, the results also show that for scenarios close to the extinction conditions and in the presence of additional effects to that of oxygen (external flow, temperature, flow), this relation needs to be improved.

3.5 Classification of the fire scenario

By analysing the large-scale fire test data-base with the theoretical support of the WSR model, a classification of the fire scenarios can be made based on two parameters, the ventilation factor ϕ_o and the mass factor ϕ_m. Depending on the values taken by these two parameters, the fire scenarios can be sorted according to their behaviour (Fig. 11). For ϕ_m values below a limit estimated from the simulations to be about 0.6, the fire scenarios are not very sensitive to the ventilation rate (and thus to the ventilation factor) due to a small amount of fuel in a large volume; these scenarios can be similar to those in an open environment. For values of ϕ_m greater than the above-mentioned limit, the ventilation and in particular the ventilation flow rate (expressed through ϕ_o) influences the fire scenario by reducing the burning rate compared to its value in open atmosphere. For low values of ϕ_o, the MLR is reduced by the vitiation of the surrounding environment, the duration of the combustion phase is longer than in an open environment and extinction occurs due to lack of fuel. The LOI limit is never reached. On the other hand, for large values of ϕ_o, the MLR is also reduced but extinction occurs quickly due to lack of oxygen (the LOI is reached) and the duration of the combustion phase is shorter than that obtained in open environment. Between these two regimes, an intermediate regime is observed in which the MLR also decreases, and the oxygen concentration stabilises at values close to the

LOI. These regimes correspond to unstable situations during which oscillatory regimes can be observed. This mapping was obtained from both large- and small-scale tests and for a wide variety of vessel geometry configurations and four fuel types. It is important to mention that it is the area of unstable and transient behaviour that is the most difficult to predict and which requires greater attention in the future.

4 Conclusions

This study presents an analysis of the effect of the environmental conditions on the MLR in case of mechanically ventilated compartments constituting complex and realistic fire scenarios with hybrid ventilation systems. The database used, produced during the PRISME projects, includes large-scale configurations involving several compartments with ventilation of the fire compartment combining mechanical ventilation and natural ventilation through openings (doorway or vent). The main objective was to analyse the behaviour of the MLR on these new data-base involving complex situations and to compare them with the results observed on reduced or intermediate scales and on simple ventilation configurations. The following conclusions were obtained.

A review of the WSR model highlighted the properties specific to fire scenarios in a mechanically ventilated compartment. The under-ventilated combustion regimes reported in mechanically ventilated enclosures can be classified using two parameters, the ventilation factor ϕ_o, and the mass factor ϕ_m, both calculated from known variables. Depending on the value of these parameters, several combustion regimes are identified by comparing the MLR with that obtained in the open environment: either similar to the open environment, or weaker in the open environment with three particular situations: stationary, unstable or transient with rapid extinction. The WSR model also highlights the critical ventilation factor indicating the conditions under which ventilation regimes are obtained.

The well-stirred reactor model's interpretation, carried out to date on a reduced and intermediate scales (up to 38 m^3 compartment) or for simplified configurations, is also valid and robust for the PRISME projects data-base comprising complex configurations representative of real fire event (120 m^3 compartment with hybrid ventilation systems).

The different combustion regimes observed on a reduced scale are also found in complex scenarios. The duration of the combustion phase and the mass loss rate are strongly correlated with the ventilation factor normalised by its critical value. This generalisation to both small- and large-scale tests and to both simple and complex scenarios confirms the robustness of the interpretation.

The analysis of the law relating the MLR to environmental conditions is also found for the database studied. This result confirms the robustness of this law and thus explains why the simulation attempts for the PRISME project tests have generally given satisfactory results. However, the analysis also confirms that for certain configurations, this law needs to be improved, to take into account situations where the influence of external flows and temperature are non-negligible compared with the effect of oxygen. The analysis also shows that knowledge

of the conditions of extinction and its introduction into the models need to be be improved in order to deal with regimes at the extinction limit.

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Figure captions

Fig. 1. Examples of simulation with the WSR model (where Me=0.44 and Ye=0.76) (top) time variation of O2 concentration with ϕ_m=0.2, (left) and with ϕ_m=0.6 (right)- (Bottom) t_ext^* versus the ventilation factor ϕ_o for three values of ϕ_m (right), Iso-contours of t_ext^* in the (ϕ_m, ϕ_o) domain.

Fig. 2. Illustration of the configurations considered in the PRISME projects (arrows indicate the air flows).

Fig. 3. Representation of the data set in the (ϕ_m, ϕ_o) domain.

Fig. 4. MLR per unit area versus the pool diameter for the Heptane, HTP, Dodecane and lubricant oil.

Fig. 5. Effect of the ventilation flow rate on the MLR time variation for various configurations (a) effect of the ACH with 0.2 m2 with HTP (b) effect of the ACH with 0.4 m2 with HTP (c) effect of the ACH with 0.4 m2 with heptane (d) effect of the ACH with 0.4 m2 with two compartment configuration - DOOR series, (e) effect of the opening SI and DOOR series (f) effect of the air intake position SI series.

Fig. 6. Dimensionless time to extinction versus the ventilation factor for each configuration (first line) mechanical ventilation only (second and third lines) mechanical ventilation and natural ventilation with doorway and vent

Fig. 7. Dimensionless time to extinction versus the ventilation factor scaled by its critical value (Regime R1 in green, regime R2 in red and regime R3 in blue)

Fig. 8. Dimensionless MLR versus the ventilation factor scaled by its critical value (Regime R1 in green and regime R2 in red)

Fig. 9. Relationship between the dimensionless MLR and oxygen concentration near the fire location at steady state

Fig. 10. Classification of fire scenario in a (ϕ_o, ϕ_m) map with the PRISME project tests as examples