Effect of environmental conditions on fire combustion régimes in mechanically ventilated compartments

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Abstract

This publication deals with under-ventilated combustion regimes in case of pool fire in a confined- and mechanically-ventilated enclosure. The objective is to improve the understanding of combustion regimes in a ventilated compartment focusing on the effect of fire size and the ventilation rate. It is based on dodecane pool fire tests conducted on a reduced scale (1.875 m^3) enclosure and considering two varying parameters, the pool diameter and the ventilation air flow rate prior to ignition. Three combustion regimes were identified: two steady burning regimes with extinction by lack of fuel or oxygen (fuel burnout) and a transient burning regime with extinction by lack of oxygen. A representation of these regimes is proposed with two scaling parameters: the reference global equivalence ratio, ϕ_o, and the volumetric fire heat release rate. Results demonstrate that increasing ϕ_o reduces the burning rate in comparison to its value in an open atmosphere. While for a low volumetric fire heat release rate (HRR), the reduction in burning rate is mainly due to oxygen depletion, gas temperature has an additional effect at higher volumetric HRR (about 16 kW/m^3). The effect of gas temperature compensates for the effect of oxygen depletion and increases the burning rate. The conditions leading to the highest gas temperature inside the enclosure were obtained in fire scenarios with high volumetric fire HRR and moderate ϕ_o.

Keywords: compartment fires, pool fire, under-ventilated burning, ventilation

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M	Dimensionless burning rate (-)	b	boiling
m	Mass (kg)	ref	Ambient condition
$\dot{m}$	Mass flow rate (kg/s)	o	Open atmosphere
$\dot{q}$	Volumetric flow rate (m^3/s)	ex	Exhaust (ventilation)
r	Stoichiometric ratio	ext	Extinction
t	Time (s)	in	Inlet (ventilation)
T	Temperature (C)	O_2	Oxygen
RR	Renewal rate (s^{-1})	f	Fuel
y	Mass fraction (g/g)	init	Prior to ignition
x	Molar fraction (mol/mol)		
Y	Dimensionless mass fraction (-)		
V	Volume (m^3)		
τ	Dimensionless time (-)		
ϕ_o	Reference global equivalence ratio (-)		

1 Introduction

Due to new challenges aiming to reduce greenhouse gas emissions and meet low energy requirements, houses and buildings have become significantly airtight, with a high level of thermal insulation, and are equipped with mechanical ventilation systems. In case of a fire event, these environments lead to changes in fire scenarios in comparison to those encountered with naturally-ventilated enclosures connected to the outside. In confined and forced ventilated enclosures, fire events are characterized by particular physical phenomena such as pressure variations and under-ventilated combustion regimes with possible unsteady burning. These are also typical phenomena and fire scenarios encountered in fire risk assessment studies for nuclear facilities. For those applications, enclosures are confined and ventilated in order to control the transport of radioactive aerosols [1]. Although these combustion phenomena have been identified in several studies, there is still a need for them to be further addressed in order to better understand combustion phenomena and develop appropriate modeling from well ventilated to under ventilated conditions including situations at high gas temperature levels.

The specific scenario of forced ventilated compartment fire has been largely addressed for many decades for many applications such as in the nuclear industry, transportation or the space industry [2], [3], [4]. Several particular phenomena characterize these scenarios. One is the effect of pressure variations induced by the unsteady behavior of the fire and the significant air flow resistances of connections to the outside (ventilation lines) [5], [6], [7]. A second phenomenon is smoke propagation in a reduced environment inducing smoke filling and stratification [8]. A third phenomenon is the unsteady behavior of the burning rate and its strong dependence on the environment. The ventilation air flow rate designed for the industrial process is mostly quite low in a fire event, and a vitiated environment with low oxygen levels are the conditions typically encountered around the fire. The burning rate is then affected by environmental conditions [9], [10], [11]. Theoretical approaches have been proposed to consider these configurations including the situation near the extinction limit [12] [13], [14]. Numerical attempts to predict such fire events have been conducted with encouraging results [15][16][17][18][19]. For these scenarios, one key issue is understanding the relationship between the burning rate and the vitiated environment characterized by low oxygen contents and high concentrations of CO_2, CO and soot. In addition, in some particular cases, the vitiated environment may also be significantly hot leading to non-negligible incident heat fluxes toward the fire. The burning rate is then the result of two antagonist effects, the vitiation of the atmosphere and the hot environment. Up to now, the effect of a reduced oxygen concentration on the burning rate has been considered the most and encouragingly reproduced using a linear relationship such as the one reported in [20], [21], [22], [23], [24], [25]. Combined effects integrating those of temperature and external heat flux has been less investigated. In addition, most studies have been based on a limited number of real scale fire tests, [2], [18], [20], and very few analytical approaches at a small scale allowing for a larger data base have been performed.

The aim of this study is to investigate the effect of the environment on burning by considering a dimensionless parameter, the reference global equivalence ratio, ϕ_o, based on the enclosure ventilation flowrate and the pool diameter. This approach allows different conditions to be generated in a vitiated environment leading to combustion regimes ranging from fuel controlled to ventilation controlled. This study is based on a reduced-scale experimental fire test campaign and supported with a theoretical description based on the well-stirred reactor approach as described in [26]. The results bring new inputs regarding the combustion regimes encountered in compartment fire scenarios and dependency between the burning rate and environmental conditions. These results improve the understanding of combustion phenomena in case of a fire event in a closed and ventilated room. They also allow for a more detailed critical analysis of fire scenario predictions with CFD modeling tools in the framework of fire risk assessments.

Section 2 presents first the theoretical approach based on the well-stirred reactor model. The dimensionless parameter which we refer to as the reference global equivalence ratio, ϕ_o, is defined, as well as its critical value defining the boundary between the well and under-ventilated combustion regime. The next part of this section defines the fire tests. The facility also described in [26] is briefly presented in this work. Measurements and uncertainties are listed. Section 4 presents the analysis of the experimental results. First, a general description is proposed and the effects of the ventilation flow rate on the burning rate, the oxygen concentration near the fire and mean gas temperature are analyzed. The combustion regimes are then defined, based on the theoretical approach and the effect of ϕ_o is discussed. Finally, some fire extinction conditions are analyzed.

2 Material and methodology

2.1 Theoretical approach

Combustion regimes and the associated parameters are identified from a theoretical approach based on the well-stirred reactor model [9] which aims to simply describe the combustion phenomena involved in a closed mechanically-ventilated enclosure. It considers the gas phase within the compartment as homogeneous, and for which mean pressure, temperature and species concentrations are considered. The mechanical ventilation system consists of two branches, one supplying air via an inlet and one extracting smoke via an exhaust at a constant flow rate. The benefits of this model are to investigate the way the environment influences the burning rate based on mean variables. The total mass of gas and the mass of oxygen conservation equations are expressed as:

$$\frac{d}{dt}m = \dot{m}^{in} - \dot{m}^{ex} + \dot{m}_f \quad \text{and} \quad \frac{d}{dt}m_{O_2} = \dot{m}^{in}_{O_2} - \dot{m}^{ex}_{O_2} - r\dot{m}_f \qquad (1)$$

r is the oxygen to fuel stoichiometric ratio, m the mass of gas, $\dot{m}_f$ the fuel burning rate and $\dot{m}^{in}$ and $\dot{m}^{ex}$ are the ventilation mass flow rates at the inlet (upper script "in") and exhaust (upper script "ex") lines and are assumed to remain constant over time. According to the two conservation equations (relations (1)), the variation in oxygen concentration becomes:

$$m\frac{d}{dt}y_{O_2} = \left(y^o_{O_2} - y_{O_2}\right)\dot{m}^{in} - \dot{m}_f\left(y_{O_2} + r\right) \qquad (2)$$

where y_{O_2} is the oxygen concentration that varies over time and $y^o_{O_2}$ the initial condition of the oxygen concentration prior to ignition (or the reference level in open atmosphere). In dimensionless form, this equation becomes:

$$\frac{d}{d\tau}Y = (1 - Y) - \phi_o M\left(\frac{y^o_{O_2}}{r}Y + 1\right) \qquad (3)$$

with the dimensionless oxygen fraction $Y = y_{O_2}/y^o_{O_2}$ and the dimensionless time $\tau = t\dot{q}^{in}/V = tRR$. The variable $\dot{q}^{in}$ is the volumetric flow rate at the inlet branch of the ventilation system defined as $\dot{q}^{in}$=$\dot{m}^{in}/\rho$ where ρ is the gas density that is considered constant in this theoretical approach. No consideration of the energy equation and then of temperature variation is needed. V is the volume of the enclosure and RR the renewal rate ($RR = \dot{q}^{in}/V$). A dimensionless burning rate $M = \dot{m}_f/\dot{m}_f^o$, and the reference global equivalence ratio $\phi_o = r\dot{m}_f^o/(y_{O_2}^o \dot{m}^{in})$ are introduced. $\dot{m}_f^o$ is the burning rate of the combustible in an open atmosphere (upper script o). The variable ϕ_o is a dimensionless parameter based on the fuel mass loss rate in an open atmosphere and the initial ventilation flow rate. This parameter is similar to the global equivalence ratio (GER) defined to characterize the completeness of combustion. However, in the present case, it only considers boundary conditions known prior to ignition, i.e. the burning rate in an open atmosphere and the ventilation flow rate.

In addition to relation (3), a second relation is introduced to incorporate the change in burning rate caused by the environment (mainly oxygen concentration and gas temperature). For simplicity, only the coupling between the burning rate and oxygen concentration are considered without incorporating the additional effect of gas temperature. The effect of oxygen has been clearly demonstrated experimentally by showing a decrease in fuel mass loss rate as oxygen concentration decreases [20]. Although this phenomenon is complex due to the change in flame temperature and soot production within the fire reactive zone, simple linear relationships between the MLR and the oxygen concentration only are often considered as [10] [20] [27]:

$$\frac{\dot{m}_f-\dot{m}_f^{ext}}{\dot{m}_f^o-\dot{m}_f^{ext}} = \frac{y_{O_2}-y_{O_2}^{ext}}{y_{O_2}^o-y_{O_2}^{ext}} \quad \text{or} \quad \frac{M-M^{ext}}{1-M^{ext}} = \frac{Y-Y^{ext}}{1-Y^{ext}} \qquad (4)$$

where $Y^{ext} = y_{O_2}^{ext}/y_{O_2}^o = x_{O_2}^{ext}/x_{O_2}^o$, the dimensionless oxygen extinction limit (also referred to as LOI for Limiting Oxygen Index) and $M^{ext} = \dot{m}_f^{ext}/\dot{m}_f^o$, the corresponding dimensionless mass loss rate at extinction or burnout (the "ext" index stands for extinction). The Peatross & Beyler correlation ($\dot{m}_f = 10x_{O_2} - 1.1$) often considered in the literature is a particular case with $\dot{m}_f^{ext} = 0$ and $y_{O_2}^{ext} = 0.11\, M_{O2}/M_{air}$.

Finally, extinction prediction is introduced considering two modes. The first one is extinction by "lack of oxygen" which occurs if the oxygen concentration reaches the limiting oxygen index ($y_{O_2} = y_{O_2}^{ext}$ or in dimensionless form $Y=Y^{ext}$) before all fuel is burned. The second one is extinction "by lack of fuel" or fuel burnout which occurs if the initial mass of fuel is entirely burned out and the oxygen concentration remains higher than the LOI ($\int_o^{t_{ext}} \frac{\dot{m}_f(t)}{\dot{m}_f^o} dt = t_{ext}^o$ or in dimensionless form $\int_o^{\tau_{ext}} M(\tau)d\tau = RR.t_{ext}^o$). t_{ext}^o is the time to extinction considering the mass of fuel prior to ignition and the burning rate in an open atmosphere, $t_{ext}^o = m_f^{init}/\dot{m}_f^o$.

The two equations (3) and (4) coupled with the extinction criteria are solved numerically leading to variation in the burning rate (M) and oxygen concentration (Y) over time as well as the determination of extinction time t_{ext}. The parameters used are the volume of the enclosure V, the type of fuel (ratio r), the burning rate in an open atmosphere $\dot{m}_f^o$, the initial mass of fuel m_f^{init}, the ventilation flow rate, $\dot{q}^{in}$, and the extinction features (M^{ext} and Y^{ext}) involved in equation (4).

An example of calculations is proposed in Fig. 1 which shows variation in oxygen concentration (left) and burning rate (right) over time for several ventilation flow rates and therefore different reference global equivalence ratios.

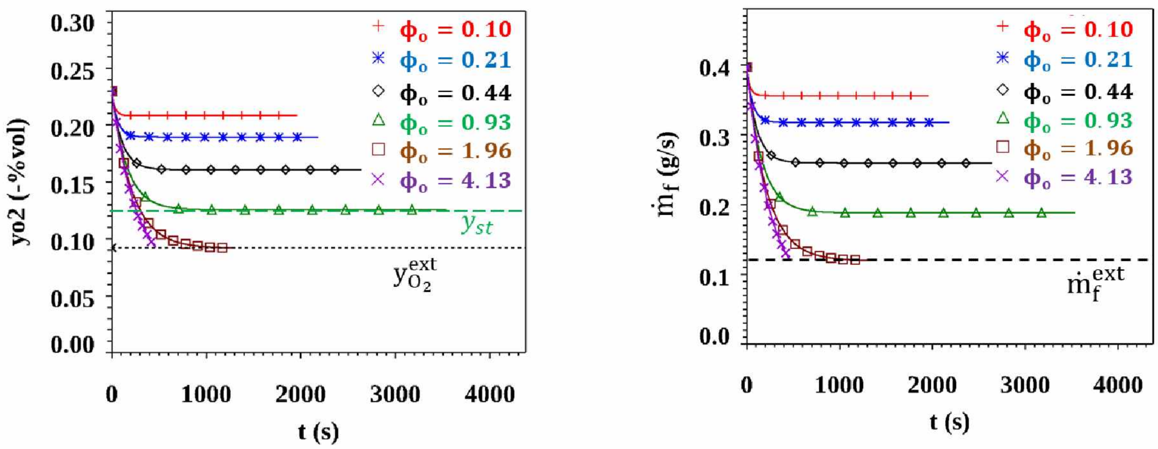

Fig. 1. Variation in oxygen concentration (left) and burning rate (right) over time for several values of ϕ_o i.e. for different values of the ventilation flow rate $\dot{q}^{in}$ (the fixed parameters are V=1.875 m^3, $\dot{m}_f^o$=0.4 g/s, r=3.48, m_f^{init}=0.7 kg, M^{ext}=0.3 and Y^{ext}=0.40).

Fig. 1 illustrates the effect of the reference global equivalence ratio on variation in oxygen concentration and burning rate over time. Two regimes are identified. The first one, for low values of ϕ_o, is characterized by a decrease in oxygen concentration and burning rate up to steady state combustion due to the quantities of oxygen supplied by the ventilation system balancing those consumed by the combustion reaction. The steady oxygen concentration is greater than the LOI and burning is maintained until extinction occurs by fuel burnout. The relationship giving the oxygen concentration at steady state versus the dimensionless burning rate can easily be derived from equation (3) as:

$$Y_{st} = \frac{1-\phi_o M}{1+\phi_o \frac{y_{O_2}^o}{r} M} \tag{5}$$

The second combustion regime for higher values of ϕ_o is only characterized by a decrease in oxygen concentration and burning rate with time due to a high pyrolysis rate in comparison to the oxygen rate supplied by the ventilation system. The LOI is reached before steady state is achieved and extinction occurs by lack of oxygen.

A critical ϕ_o delimiting the two regimes can be deduced from equation (5) in expressing ϕ(Y,M) as:

$$\phi_o^c = \frac{1-Y^{ext}}{M^{ext}\left(1+\frac{y_{O_2}^o}{r}Y^{ext}\right)} \tag{6}$$

It is worth noting that the critical ϕ_o tends to infinity for $M^{ext} = 0$. For that particular case, the second regime cannot be predicted. As $M^{ext} = 0$ is an intrinsic assumption in the Peatross & al correlation, if this correlation is used, the second regime cannot be considered.

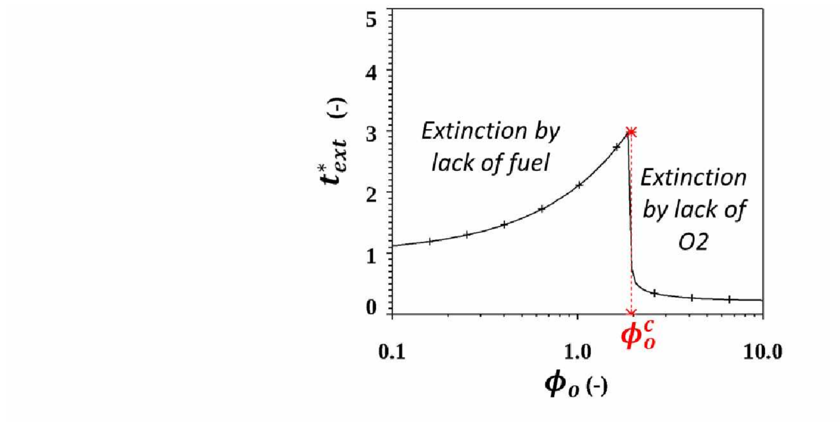

Fig. 2. Time to extinction versus ϕ_o (V=1.875 m^3, $\dot{m}_f^o$=0.4 g/s, r=3.48, m_f^{init}=0.7 kg, M^{ext}=0.3 and Y^{ext}=0.4).

The variation in time to extinction, t_{ext}, (or in dimensionless form $t^*_{ext} = t_{ext}/t^o_{ext}$ where t^o_{ext} is the time to extinction in an open atmosphere) versus the ϕ_o enhances the two regimes (Fig. 2). The first regime is characterized by an increase in time to extinction versus the ϕ_o. The burning rate diminishes due to the reduction in oxygen (equation (4)) and therefore for the same initial mass of fuel, time to extinction is longer. In this first regime, time to extinction is controlled by the amount of fuel. The second regime is characterized by a much shorter time to extinction which decreases with the increase in ϕ_o. Time to extinction is controlled by the ventilation flow rate in this case. These predictions also indicate that there is a finite value for the maximum fire duration which corresponds to about 3 times the duration of the fire in an open atmosphere.

As illustrated with equation (4), the parameters influencing the critical ϕ_o are the parameters M^{ext} and Y^{ext} , i.e., the boundary conditions for burning rate and oxygen concentration at extinction. The Fig. 3 presents several simulations of the time to extinction t^o_{ext} versus ϕ_o. for different values of M^{ext} (Fig. 3-left) and Y^{ext} (Fig. 3-right). The decrease in both parameters contributes to shifting the critical ϕ_o to higher values. Changing the burning rate at extinction M^{ext} modifies the maximum time to extinction whereas the extinction oxygen limit, Y^{ext}, has no effect on time to extinction (about t^o_{ext} =3 in this case).

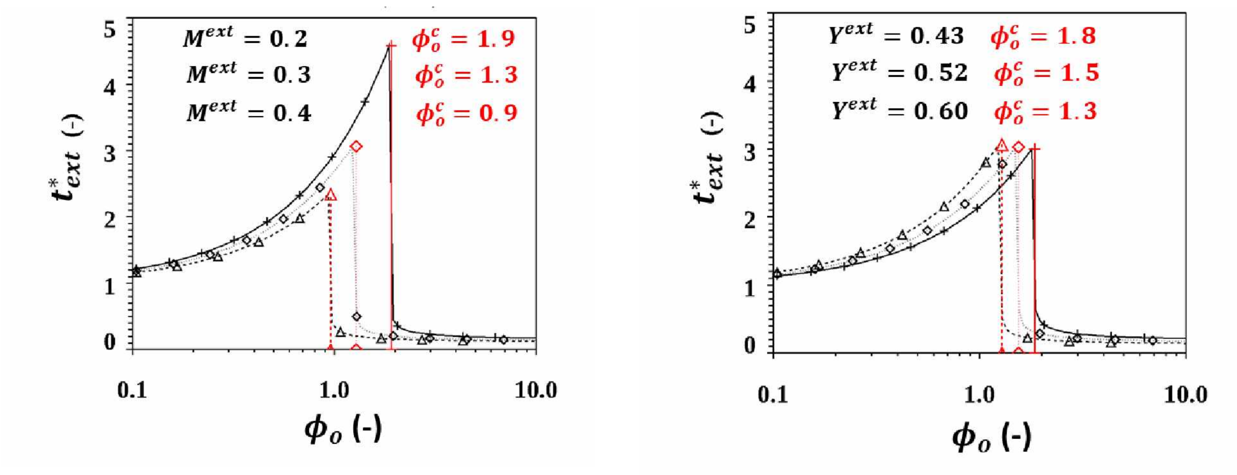

Fig. 3. Effect of the burning rate M^{ext} (left with fixed $Y^{ext} = 0.6$) and the oxygen concentration Ye (right with fixed $M^{ext} = 0.3$) at extinction on time to extinction versus ϕ_o ($V = 1.875$ m^3, $\dot{m}_f^o=0.4$ g/s, r=3.48, m_f^{init}=0.7 kg).

Other influencing parameters are the initial mass of fuel and the burning rate in an open atmosphere. As illustrated in Fig. 4, variation in these two parameters does not influence the critical ϕ_o (equal to 1.84 in this example). However, these parameters may influence the amplitude of the time to extinction. Whereas the change in burning rate in an open atmosphere, $\dot{m}_f^o$, has no effect (Fig. 4, right), the change in the initial mass of fuel, m_f^{init}, modifies the time to extinction, especially around the transition between the two regimes (Fig. 4, left). These results will be considered in the next section for the fire test analyses

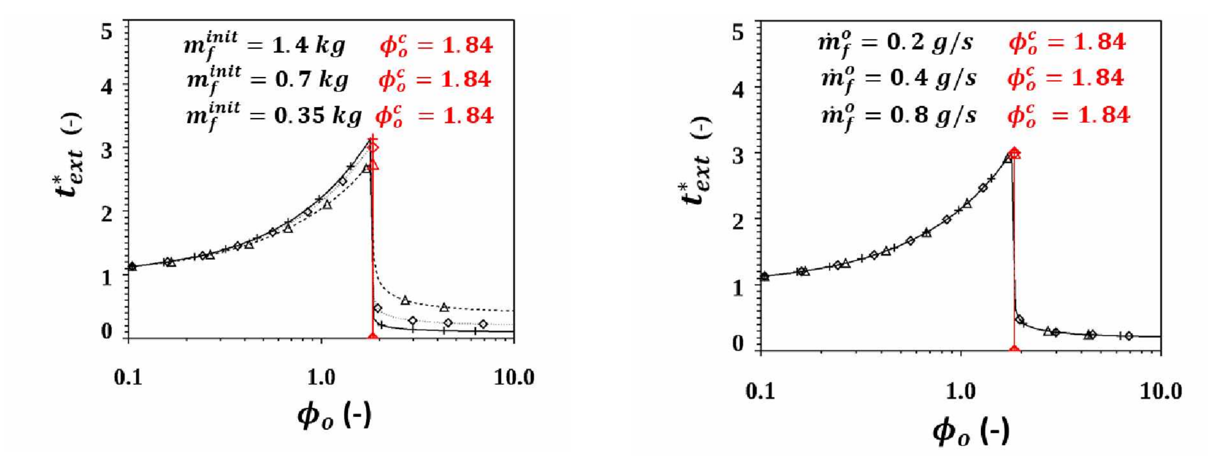

Fig. 4. Effect of the initial mass of fuel (left with fixed $\dot{m}_f^o$=0.4 g/s) and the burning rate in an open atmosphere (right with fixed m_f^{init}=0.7 kg) on variation in dimensionless time to extinction versus ϕ_o (V=1.875 m^3, r=3.48, M^{ext}=0.3 and Y^{ext}=0.43).

2.2 Fire tests

In order to confirm the effective occurrence of the combustion regimes enhanced from the well-stirred reactor model as well as to improve the understanding of the relationship $M=f(Y^{ext},M^{ext})$, a set of fire tests were carried out at an IRSN NYX experimental facility, which is a 1:4 scale reduction of real scale DIVA facility (Fig. 5). The NYX dimensions are $l = 1.5$ m × $L = 1.25$ m × $H = 1$ m = 1.875 m^3. The total surface of walls is about 7.36 m^2. Walls are made of two layers, one of 2 mm thick steel and one of 45 mm thick calcium silicate panels on the inside of the room ($k = 0.22$ W/°C/m, $Cp = 720$ J/kg/°C, $\rho = 970$ kg/m^3). The enclosure is equipped with a ventilation network including intake and exhaust lines and a fan at the exhaust. Inlet and outlet connection branches are located in the upper part of the room.

Fuel mass is continuously measured during burning with a weighing system used to derive the fuel mass loss rate (MLR). Ventilation flow rates are measured in both lines with average bi-directional probes connected to pressure transducers. Inside the compartment, gas temperature is measured from four masts equipped with 6 K-type 0.5 mm diameter thermocouples. Oxygen and carbon dioxide concentrations are measured with gas analyzers with two sampling points located in the vicinity of the fire and in the exhaust line. More details about apparatus and locations can be found in [28].

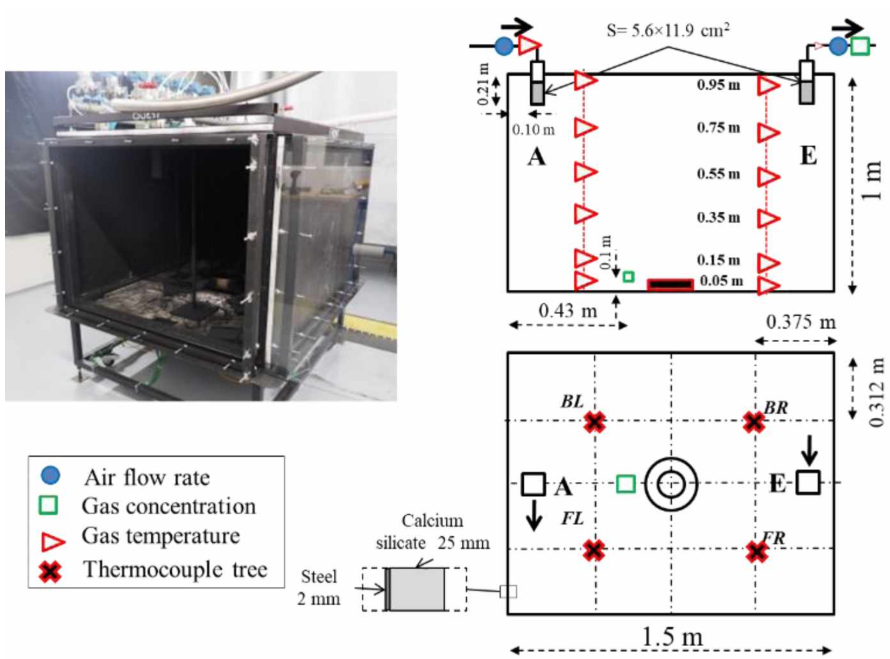

Fig. 5. Schematic and view of the NYX facility and location of the sensors

The measurement uncertainties were evaluated from calibration tests, carried out before or after the tests, and from the data provided by the sensor manufacturers. The calibration tests consisted in obtaining the differences between standard values (from specific calibrated sensors or samples) and the measured values, read off the acquisition system. Two levels of uncertainties were defined following the procedure given by Hamins [29]. The standard uncertainties were obtained at room temperature without fire. A second level, expanded uncertainty, took into account the fire test conditions and test repeatability, and was introduced through a coverage (or correction) factor, applied to standard uncertainty (Table 1).

Table 1: Uncertainties for reduced-scale experiments.

Physical variable	Range	Standard Uncertainty	Coverage Factor	Expanded Uncertainty
Mass	(0-6200) g	0.01 g	2	0.02 g
O2 molar fraction	(0-0.25) mol/mol	0.0025 mol/mol	1	0.0025 mol/mol
Pressure	(−1000 to +3000) Pa	4 Pa	2	8 Pa
Gas temperature	(0-1300) °K	2°K	3	6°K
Plume temperature	(0-1300) °K	4°K	4	16°K
Air flow rate	(5 to +50) m^3/h	1.5 m^3/h	2	3 m^3/h

The fire source is a pool fire with dodecane fuel with the chemical formula $C_{12}H_{26}$ and physical properties: ΔH_c = 42 MJ/kg and T_{eb} = 210°C and r = 3.48. The fuel had been characterized in an open atmosphere. The variation in fuel mass loss rate per unit area obeys Babrauska's law, $\dot{m}''_f = \dot{m}''_{f,\infty}(1 - \exp(-k\beta D))$ with the set coefficients $\dot{m}''_{f,\infty} = 35$ g/s/m^2 and $k\beta = 2.5$ m^{-1} [26]. This equation gives the steady burning rate in an open atmosphere $\dot{m}^o_f$. Fuel is poured in a circular pan with a height-to-diameter ratio of about 0.25, made of pyrex or borosilicate glass. The initial mass of fuel is similar for all tests with the same pool diameter but increases with pool diameter.

About fifty fire tests were performed with two varying parameters, the internal pool diameter, D, and the renewal rate RR (or the measured volumetric air flow rate $\dot{q}^{in}$ in the ventilation lines prior to ignition). The renewal rate range is [6 ; 42] h^{-1} set by the capability of the ventilation network. Eight pool diameters are considered (0.11 m, 0.12 m, 0.14 m, 0.15 m, 0.17 m, 0.18 m, 0.20 m and 0.24 m), which correspond to fire heat release rates in an open atmosphere ranging from 3.5 kW to 31.2 kW. For each pool diameter, several tests are performed with different renewal rates ranging from well ventilated to under-ventilated conditions.

The test protocol is as follows. First, one side of the enclosure is open to pour the fuel in the pan. This side is then closed as per a specific protocol such as ensuring the airtightness of the facility does not change between tests. The ventilation system is then set to a given ventilation flow rate $\dot{q}^{in}$. After few minutes of stabilization, the fuel is ignited with a blow-torch propane burner for approx. 10 to 20 s. The fuel then burns until extinction by lack of fuel or lack of oxygen. The enclosure tightness is regularly checked in order to maintain the same airtightness during the entire test campaign.

3 Results

3.1 General behavior

An example of generic behavior for all tests is presented in Fig. 6 showing the variation in the main variables over time. During the first few minutes, the burning rate is similar to the one in an open atmosphere because the air in the enclosure is not yet vitiated. Then the oxygen concentrations near to the fire and at the exhaust rapidly decrease because of burn-up and the generation of combustion products. As expected, the reduction in oxygen concentration correlates with a decrease in fuel mass loss rate. During the combustion phase, the mass flow rates in the ventilation lines remain rather stable except peaks at ignition and extinction because of the rapid change in gas temperature or gas density in the enclosure. During a steady state, the ventilation flow rate is slightly lower than the initial ventilation flow rate (set prior to ignition) because of combustion. The gas temperature initially rises significantly and then progressively. The flow shows very similar vertical thermal stratification for the four locations (BF, BR, FR and FL) in the room. Then, according to the test conditions, a steady state situation may be encountered. The combustion phase ends with extinction either by lack of fuel (burnout) or by lack of oxygen. Regarding the temperature, the mean gas temperature continuously increases due to the continuing transient energy balance caused by thermal inertia in the enclosure. The four vertical temperature profiles give similar stratification at any position in the room. This behavior is similar for all tests. The main changes because of the variation of the pool area and the ventilation flow rate are the achievement of steady state, the duration of the fire, the extinction mode and the amplitudes of the burning rate, oxygen concentration and temperature.

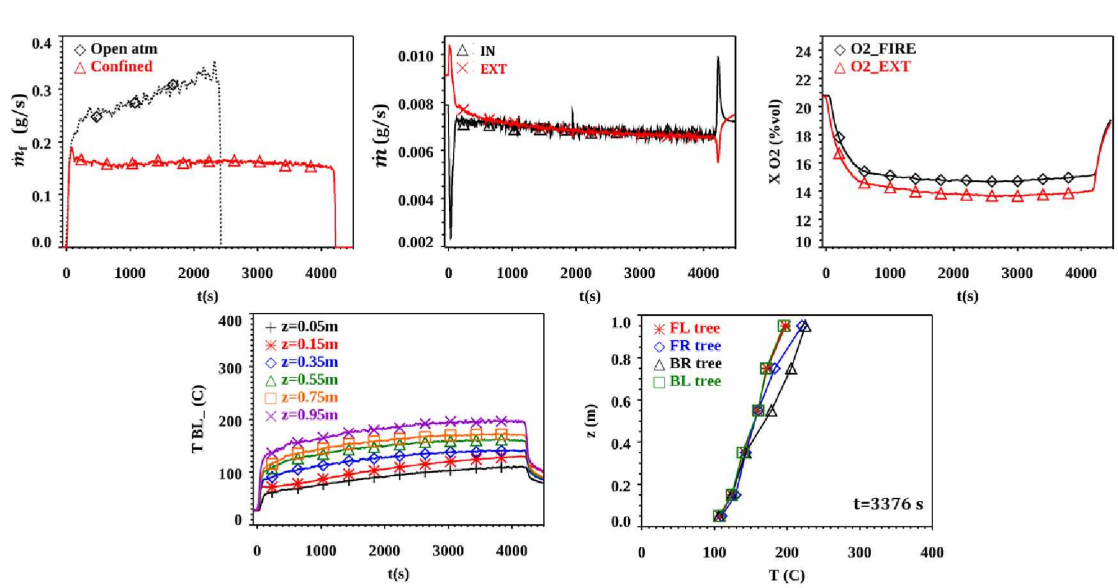

Fig. 6. Variation over time for burning rate in an open atmosphere and in the compartment, the ventilation mass flow rate and oxygen concentration at two locations and gas temperature on the thermocouple tree BL. The last plot shows vertical temperature profiles at a given time for the four thermocouple trees (example for the test with D = 0.18 m and RR = 15 h^{-1}).

3.2 Effect of ventilation flow rate

The effect of the reduction in ventilation flow rate for a given pool dimension is investigated. Variation in time for fuel mass loss rates, oxygen concentrations and mean gas temperatures (mean value for the four thermocouple trees) are presented in Fig. 7 for four typical pool diameters. For a given diameter, the reduction in renewal rate, RR, leads to a reduction in the steady state levels of oxygen concentration and burning rate as expected. This effect is less pronounced for gas temperature. The highest temperature is reached at time of extinction for the highest ventilation flow rate. The decrease in the renewal rate also influences time to extinction and the extinction mode. Regarding extinction mode, the two situations theoretically identified are experimentally reported. If the ventilation flow rate is high enough, steady burning will continue until extinction by fuel burnout in the pan. With a low ventilation flow rate, the LOI is reached before steady state conditions are established and extinction occurs by lack of oxygen with fuel remaining in the pan. Similar behaviors are reported for pool diameters in the range [0.11 ; 0.20] m.

For higher diameter (0.24 m), some specific behaviors are reported. First, low frequency oscillatory behavior of the burning rate is reported for renewal rate between 15 h^{-1} and 18 h^{-1}. The phenomenon is typical for configurations in which the fire environment is characterized by an oxygen concentration near to the LOI and a high enough temperature such that unstable combustion can take place [30], [28], [19]. The second specific behavior reported with 0.24 m diameter is that the test with the highest renewal rate (42.3 h^{-1}) does lead to extinction by lack of fuel, but with very atypical unsteady burning rate before extinction. This phenomenon occurs because of the high gas temperature in the enclosure close to the fuel boiling temperature (210°C for dodecane), which leads to a rapid combustion of the remaining amount of fuel in the entire volume. The effect of the renewal rate on the mean gas temperature is morer significant than for the other pool diameters.

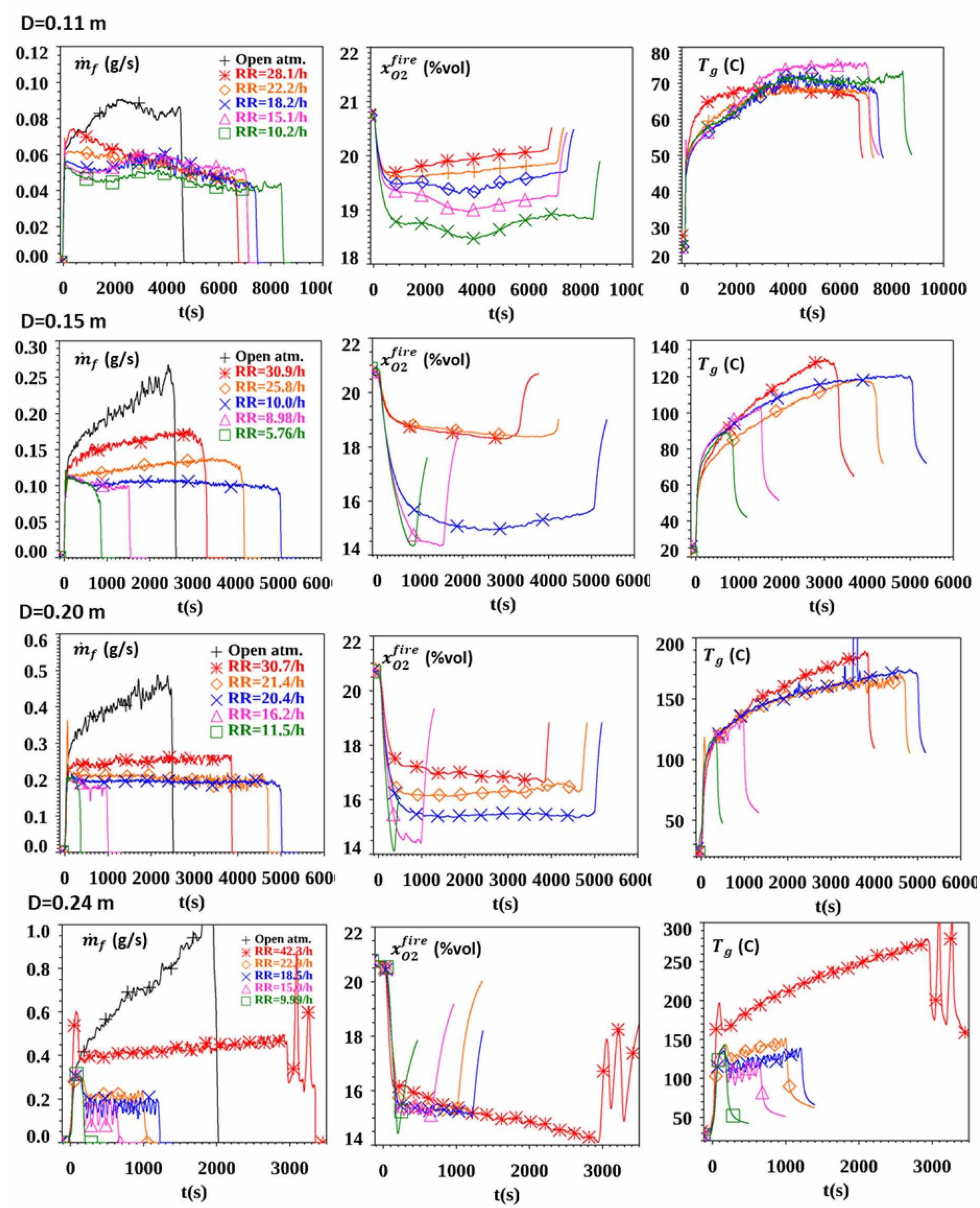

Fig. 7. Variation in burning rate (left), oxygen concentration (center) and mean temperature (right) over time for different renewal rates and 4 typical pool diameters.

3.3 Identification of combustion regimes

Time to extinction, extinction mode (lack of fuel or oxygen) and occurrence of a steady state can be used to identify three combustion regimes.

The first regime corresponds to tests in which steady state conditions are reached and extinction occurs by lack of fuel. The combustion is said to be well-ventilated because the regime is fuel-limited but the fuel mass loss rate is lower than in an open atmosphere and the oxygen concentration is lower than 0.23 g/g. Equilibrium is achieved between the amounts of oxygen consumed by combustion and supplied by the ventilation system, and the oxygen concentration is greater than the LOI. This regime corresponds to tests with the highest renewal rates.

The second regime corresponds to tests in which a steady state regime is reached, but extinction occurs by lack of oxygen. Equilibrium is maintained between the oxygen consumed by combustion and the oxygen supplied by the ventilation system, but the resulting steady oxygen concentration stabilizes at a level very close to the LOI. Extinction may occur at any time.

The third regime corresponds to tests in which no steady state conditions are achieved. The oxygen concentration reaches the LOI before steady state conditions are achieved and extinction occurs by lack of oxygen. This regime corresponds to tests with the lowest renewal rates.

It is worth noting that the second and the third regimes can be used to experimentally determine the burning rate at extinction (M^{ext}) as well as the LOI (Y^{ext}) introduced in equation (4).

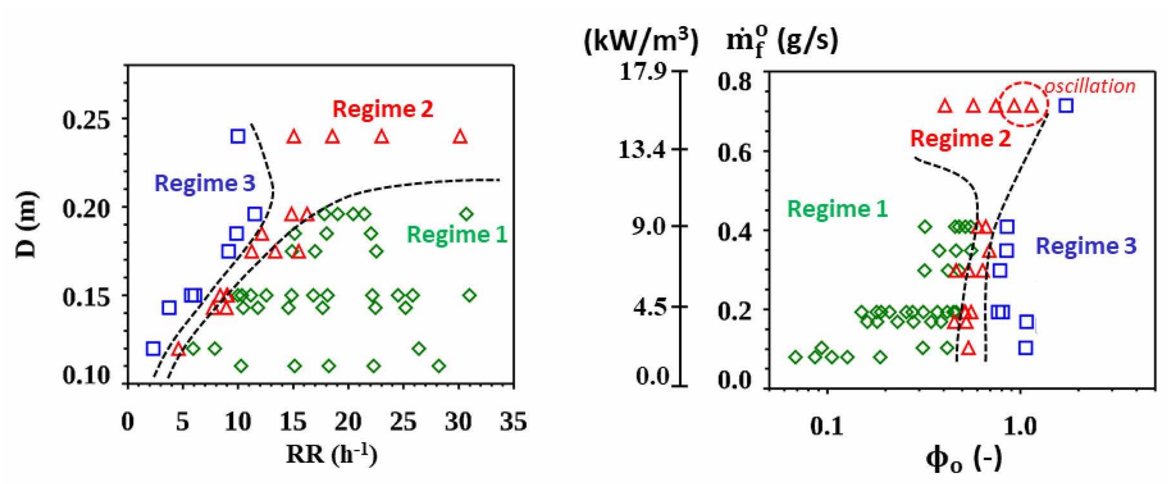

Fig. 8. Two maps illustrating combustion regimes in the (RR, D) domain (left) or (ϕ_o, $\dot{m}_f^o$) domain (right); each point in the graph corresponds to a fire test.

Fig. 8 shows maps representing three regimes according to two input test parameters: (D; RR) or ($\dot{m}_f^o$; ϕ_o). For pool diameters ranging between 0.15 m and 0.18 m, the three regimes have been captured and the transition between regimes 1 and 3 corresponds to a critical ϕ_o of about 0.6. For the lowest pool diameter, 0.11 m, only regime 1 has been reported due to the fact that the ventilation capability of the facility could not accurately generate flow rates lower than 6 m^3/h. For the pool diameter 0.20 m, the three regimes are reported and it is noted that the ϕ_o interval for the transition regime (regime 2) is larger than for the lower pool diameters (0.15 and 0.18 m). The increase in pool diameter (D = 0.24 m) leads to a wider range of ϕ_o for the transitional regime 2. During this series of tests, it was not possible to reach regime 1 with a pool diameter of 0.24 m due to the ventilation capability of the facility (maximum flow rate of 40 m^3/h).

The results show that the increase in the pool diameter leads to a wider reference global equivalence ratio interval corresponding to transitional regime 2, and consequently leads to enlarged fire scenarios inducing combustion regimes near to the LOI. The results also show that regime 1 cannot be achieved for D = 0.24 m. The larger the pool diameter, the higher the temperature inside the room, leading to more unstable combustion. The conditions for regime 1 (i.e.: steady well-ventilated combustion) only seem to exist for small pool diameters. This regime corresponds to small fires in large enclosures (corresponding to a low heat release rate per unit of volume enclosure) where the gas temperature does not increase enough to influence burning. The increase in the pool diameter leads to an increase in gas temperature. In these conditions, the burning rate results from the combination of two antagonist effects: oxygen depletion and gas temperature rise leading to unstable combustion.

The burning rate in an open atmosphere can be converted into volumetric heat release rate as per the equation $\dot{Q}''' = \dot{m}_f^o \Delta H / V$ leading to the interval [1.6 ; 16.7] kW/m^3 for this set of tests. The benefits of the volumetric heat release rate include the introduction of the temperature effects (higher volumetric heat release rate and higher gas temperature at a fixed ϕ_o). This parameter can be used as a criterion for characterizing two typical combustion regimes: regime 1 which corresponds to the conditions $\dot{Q}'''<13$ kW/m^3 and $\phi_o < 0.6$ and the oscillatory phenomenon in regime 2 which corresponds to $\dot{Q}'''\sim 15$ kW/m^3 and $\phi_o \sim 1.2$ (i.e. high volumetric heat release rate and ϕ_o near to the transition value).

It is worth noting that this regime map was obtained for set wall thermal properties, specific positions of the ventilation inlet and outlet and small scale pool fires. Variations in these properties and features could distort the boundaries of the combustion regimes.

3.4 Time to extinction

Time to extinction versus the reference global equivalence ratio highlights the three regimes (Fig. 9). Regime 1 corresponds to an increase in time to extinction. As the initial mass of fuel is constant, the decrease in MLR leads to an increase in time to extinction. Regime 3 corresponds to very low values of time to extinction that decrease slightly with ϕ_o. In this case, time to extinction corresponds to the duration required to consume the amount of oxygen in the enclosure prior to ignition plus the additional amount supplied by the ventilation system. If the ventilation flow rate decreases (increase in ϕ_o), the total amount of oxygen decreases and thus time to extinction. Regime 2 is considered as a transitional regime between regimes 1 and 3. Times to extinction under regime 2 vary between large values under regime 1 and small values under regime 3.

The well-stirred reactor approach satisfactorily reproduces regimes 1 and 3 (Fig. 9). There is also good agreement regarding a mean critical ϕ_o of 0.52 (determined theoretically using equation (4) and the parameters $M^{ext} = 0.44$ and $Y^{ext} = 0.76$) and the experimental range between 0.5-0.7 corresponding to transitional regime 2. Results show that critical ϕ_o may slightly vary with pool diameter. This effect can be attributed to the influence of the gas temperature that increases with pool diameter as well as the oxygen concentration field around the fire. As mentioned in the section describing the well-stirred reactor, the theoretical results also show that the amplitude of dimensionless time to extinction varies with pool diameter (especially for regime 3) because of the change in the initial mass of fuel and the burning rate in an open atmosphere.

These results clearly show that time to extinction for the compartment fire scenario can be assessed from fire characteristics in an open atmosphere, the initial mass of fuel and the reference global equivalence ratio. A critical ventilation condition exists, at which time to extinction is maximum and can be greater than about two times the open atmosphere time to extinction.

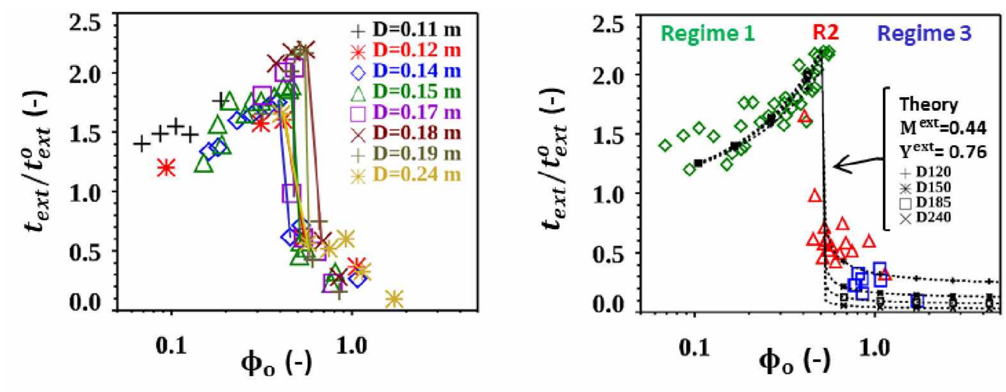

Fig. 9. Dimensionless time to extinction versus ϕ_o: (left) effect of pool diameter, (right) effect of the regime and comparison with theory.

3.5 Effect of reference global equivalence ratio, ϕ_o

In order to highlight the relevance of the reference global equivalence ratio ϕ_o introduced theoretically, its influence on the burning rate, the oxygen concentration and the gas temperature is reported in Fig. 10. The top line of Fig. 10 shows a dimension form. The x-axis is 1/RR in (s) which represents the time it takes for the volume to renew once. The value (1/RR) = 0 stands for open atmosphere. The longer this time, the lower the ventilation flow rate. Only tests leading to steady state are considered (i.e. tests belonging to regimes 1 and 2). For any pool dimension, an increase of ϕ_o leads to a reduction in the burning rate as well as the oxygen concentration in comparison to their amplitudes in an open atmosphere. The increase in ϕ_o vitiates the air in the enclosure and consequently reduces the burning rate. On this basis, the dimensionless time plots with ϕ_o indicate the relevance of this parameter when scaling the burning rate and oxygen concentration. The oxygen concentration decreases with ϕ_o up to the LOI conditions obtained for $\phi_o = 0.5$ (near to the critical ϕ_o). Then from $\phi_o = [0.5; 1]$, the oxygen concentration remains almost constant and equal to the LOI, which is equal to about 14.5%vol for this data.

The predictions of the well-strirred reactor model are compared to the experimental data for the dimensionless burning rate M and oxygen concentration Y. This prediction is achieved by solving two equations (4) and (5) and depends on the two parameters: the burning rate and oxygen concentration at extinction (M^{ext}, Y^{ext}). These values may vary according to the pool area and the ventilation flow. For comparison with the data, two predictions with two extreme conditions are proposed here for these parameters as mentioned in Fig. 10. The experimental data are in agreement within the two predicted lines showing the relevance of the model.

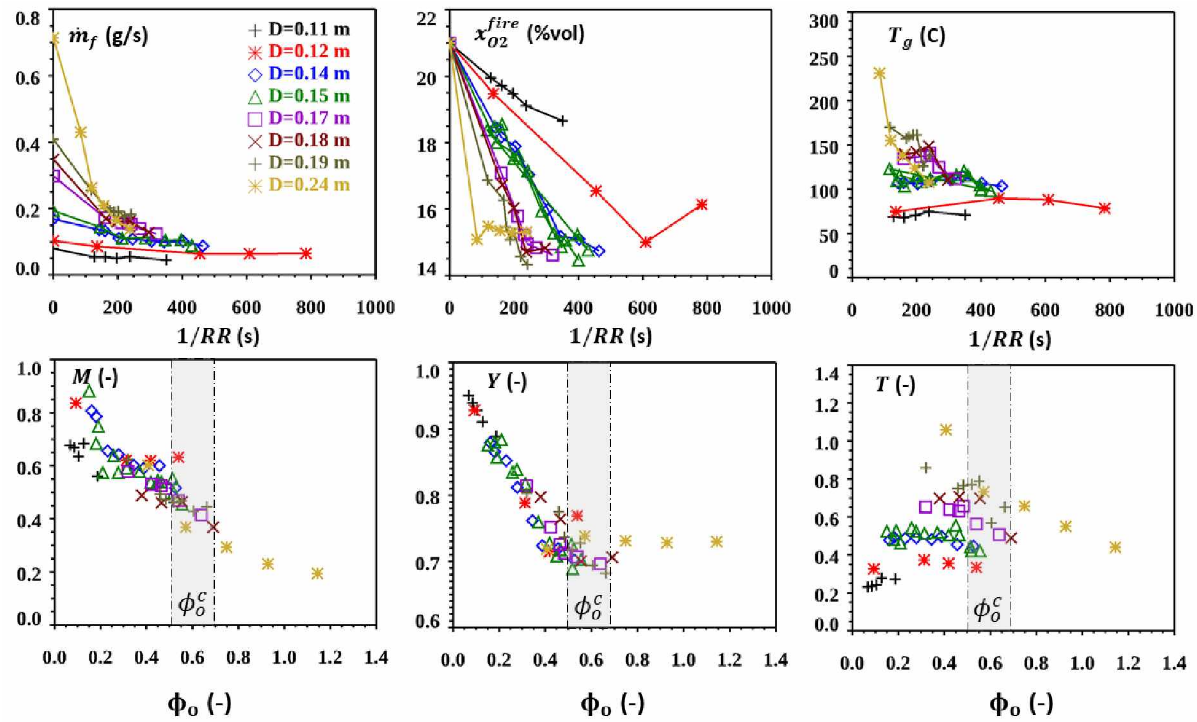

Fig. 10. Variation in burning rate (left), oxygen concentration (center) and gas temperature (right) versus the ventilation flow rate (top line in term of variable with dimension and bottom line with dimensionless variables).

The effect of $\phi_o$on gas temperature behaves differently. The dimensionless temperature is expressed as $(T_g - T_{ref})/(T_b - T_{ref})$ where T_{eb} is the boiling temperature of dodecane. For each pool diameter in the range [0.11; 0.20] m, the gas temperature in the enclosure remains nearly constant with change in the ventilation flow rate. The temperature is influenced by two antagonist effects; (i) increase in time to extinction, which increases temperature and (ii) decrease in the burning rate, which decreases temperature. The net result is nearly no effect for diameter in the range [0.11; 0.20]. However, for the highest pool diameter (0.24 m), the ventilation flow rate is reported to be affected. Temperature decreases with ventilation flow rate because time to extinction decreases. According to this data, the highest temperature in the enclosure is reached at critical ϕ_o (0.5) for the highest pool diameter (i.e. the highest volumetric power).

3.6 Extinction conditions

Extinction conditions are especially important in the relationship between the burning rate and the oxygen concentration (equation (4)). Two key variables that characterize this state are the limiting oxygen index (or LOI), $y_{O_2}^{ext}(T)$ that may vary with temperature and the minimum burning rate $\dot{m}_f^{ext}$ (or M^{ext}), under which the combustion reaction cannot be maintained due to an inadequate flame radiating towards the fuel surface. Only fire tests with extinction by any mode other than lack of fuel are considered (Regimes 2 and 3) and data are reported in Fig. 11.

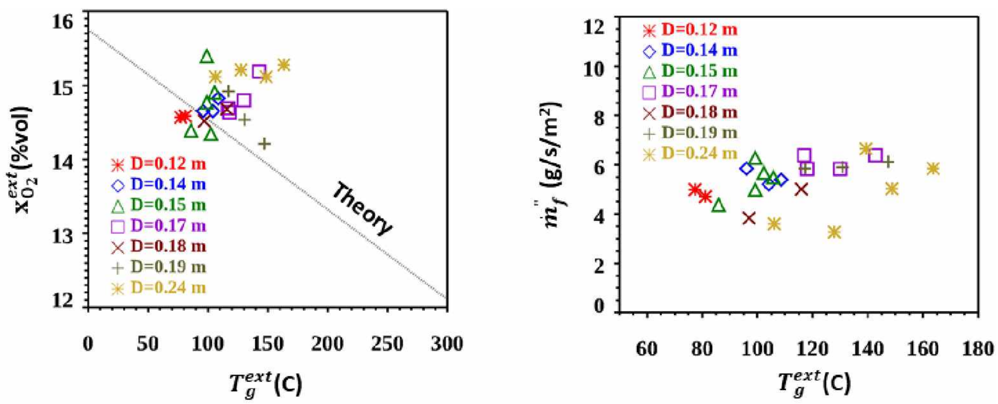

Fig. 11. Conditions at extinction: (left) oxygen concentration versus gas temperature (right) burning rate per unit area versus temperature.

The limiting oxygen index (LOI) is in the interval [14.5; 15.5] %vol. This range is in accordance with prediction using the theory of Quintiere & al [14] with the simplified relation $y_{O_2}^{ext} = C_p(T_f\text{-}T_{ext})/((\Delta H_c\text{-}L)/r).M_{air}/M_{O2}$ with $C_p = 1.6$ J/g/K, $T_f = 1300$°C, $\Delta H_c = 42$ MJ/kg and $L = 350$ kJ/kg. However, the experimental LOI seems to increase in proportion to temperature rises, on the contrary to the theory. This result is attributed to the way the quantity is determined experimentally, which may not be representative of the mean conditions around the burning area. Oxygen is measured at one point and temperature is taken as the mean temperature within the whole enclosure. To highlight the relationship $Y^{ext}(T)$ experimentally, the measurement should be improved to better represent conditions near to the burning zones. This result highlights the importance of the shape and dimension of the volume around the fire that should be considered to assess representative values of oxygen concentration and temperature that are to be used to predict the burning rate.

The burning rate at extinction is also investigated. It is reported that although the minimum burning rate increases with the pool diameter, the burning rate per unit of area remains rather constant at about 5 g/s/m^2. This result confirms that there is a minimum burning rate at extinction and that the condition $M^{ext} = 0$ is not satisfactory. The amplitude reported is similar to the one measured for heptane pool fire in [14]. This observation would be worth considering in the models so that regimes 2 and 3 can be predicted.

3.7 Burning rate versus oxygen concentration dependency

The effect of oxygen concentration on the burning rate is illustrated in Fig. 12 (left) considering only fire tests under regimes 1 and 2. As expected, the decrease in oxygen concentration leads to a decrease in burning rate. The comparison with the linear relationship proposed by Peatross & al shows the same trends. However, experimental data remains significantly scattered, an observation which is also reported by other authors [21]. Two explanations are proposed. The first one concerns the experimental challenge of correctly characterizing oxygen concentrations near to the burning area as well as avoiding any system effect induced by the pan that may influence the determination of burning rate. Additional experimental difficulties apply to compartment fire experiments due to the forced ventilation inducing specific flow field and thermal stratification. This is illustrated by the fire tests with a pool diameter of 0.15 m for which several different steady burning rates are reported for the same oxygen concentration of 18%-vol or for the fire tests with a 0.11 m pool diameter, which give a significant reduction in burning rate with a weak reduction in oxygen concentration. The second explanation concerns the simplicity of the Peatross & al relationship that does not consider the finite level of the burning rate at extinction M^{ext} and its possible dependency on pool diameter as shown previously, or the LOI that also may depend on gas temperature. Based on this data, a new correlation is suggested considering equation (4) where $x_{O_2}^{ext}$=14.5%vol and $\dot{m}_f^{ext} = S.\dot{m}_f^{'',ext}$ with $\dot{m}_f^{'',ext}$=5 g/s/m^2. A comparison with the data is presented on Fig. 12 (right) showing an acceptable agreement, but without considering tests with diameter 0.11 m and some tests with diameter 0.15 m that give results which differ from the prediction. Nevertheless, there are still discrepancies that can be explained by the simplicity of equation (4) and the difficulties of correctly characterizing a representative concentration of the volume of gas influencing burning.

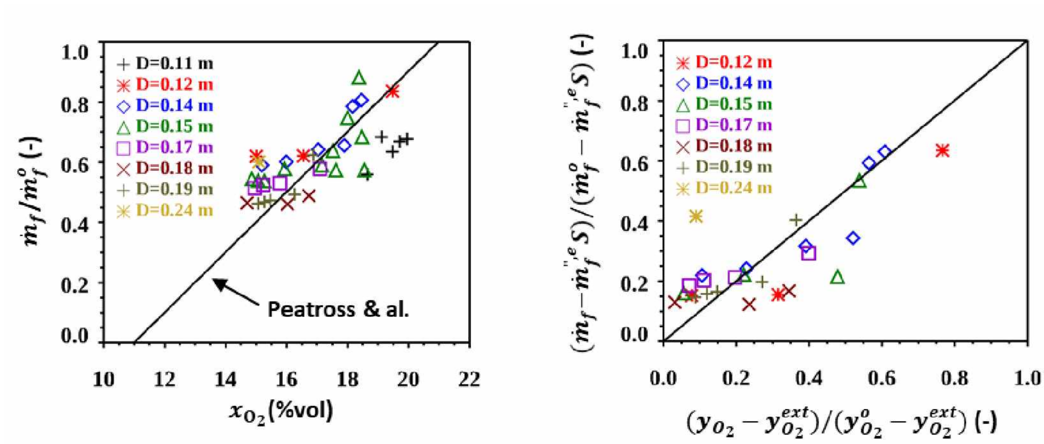

Fig. 12. Relationship between burning rate and oxygen concentration; comparison with Peatross & al. relationship (left), comparison with a new correlation (right).

4 Conclusions

This study investigates combustion regimes in case of a pool fire in an enclosure with forced ventilation using an experimental data obtained at a reduced scale as well as theoretical data obtained using a well-stirred reactor model. A series of fire tests with various pool diameters and ventilation flow rates is presented. Several outcomes are proposed that help to improve our understanding of the effects of environmental conditions on the burning rate:

- Three combustion regimes are identified: (i) steady burning with extinction by lack of fuel, (ii) steady burning with extinction by lack of oxygen and (iii) transient burning with extinction by lack of oxygen. Regime 1 is characterized by a long fire duration whereas regimes 2 and 3 are characterized by a short fire duration. Regime 2 is a transitional regime between regimes 1 and 3 and corresponds to burning near the limiting oxygen index.
- The reference global equivalence ratio, ϕ_o, and the volumetric fire heat release rate, based on fire conditions in an open atmosphere and before ignition are relevant scaling parameters for characterizing these combustion regimes. The transitional regime 2 is

characterized by a critical ϕ_o in the range 0.5-0.7. The low frequency oscillatory behavior of fire is observed for the fire scenario corresponding to critical ϕ_o and a high volumetric heat release rate (about 16 kW/m^3). The reference global equivalence ratio can scale the combined effect of pool size (or thus the fire size) and enclosure ventilation flowrate.

- Increasing ϕ_o reduces the burning rate in comparison to values in an open atmosphere. The reduction in the burning rate closely correlates to the reduction in oxygen concentration. A new relationship between the burning rate and oxygen concentration is suggested introducing a non-zero minimum burning rate. This improvement is required in order to predict combustion under regime 3. According to the experimental data set, the minimum burning rate correlates to a minimum burning rate per unit of area of about 5 $g/s/m^2$. This improvement can be used to predict combustion regimes 2 and 3 leading to extinction by lack of oxygen.
- With a view to developing a global relationship MLR=f(O_2,T), it is essential to define the appropriate volume of gas around the fireplace as well as the position of the measurement point in order to characterize the required conditions in terms of temperature and oxygen concentration.
- Combustion regime 2 (scenarios with a high volumetric heat release rate and/or a low enclosure ventilation flowrate) appears to be one of the most complex configurations to predict because the combustion regime is near to the extinction limit and the high gas temperature affects the burning rate. Within the framework of fire risk assessment studies, these scenarios and the associated "design fire" remain difficult to predict and additional works should be conducted.

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