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1 **Experimental and numerical analysis of fire scenarios involving two**  
2 **mechanically ventilated compartments connected together with a hor-**  
3 **izontal vent**

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8 **ABSTRACT**

9 This work deals with an experimental and numerical investigation of fire scenario involving two  
10 rooms mechanically ventilated and connected together with a horizontal vent. The objective is to  
11 investigate the effect of a horizontal opening on a fire scenario and especially on the burning  
12 rate. The study is based on the analysis of a set of large scale fire experiments performed in the  
13 framework of the OECD PRISME-2 project in the DIVA multi-room facility of the Institut de Radi-  
14 oprotection et de Sûreté Nucléaire (IRSN), and of numerical simulations performed with the ISIS  
15 CFD code developed by IRSN. The fire scenario consists of two rooms, one above the other, me-  
16 chanically ventilated, and connected to each other with a horizontal vent of 1 m<sup>2</sup>. The fire is hep-  
17 tane pool fire located in the lower room. The analysis focuses on the coupling between the burn-  
18 ing rate, the flow at the vent and the configuration of the mechanical ventilation. Several regimes  
19 of combustion are encountered from well ventilated steady fire to under-ventilated unsteady  
20 and oscillatory fire. The results show that the burning rate is controlled by both the mechanical  
21 ventilation and the downward flow from the vent. The numerical simulations highlight the spe-  
22 cific pattern of the oxygen concentration field induced by the downward flow at the vent.

23

24 **KEYWORDS:** fire, horizontal opening, vent, under-ventilation, compartment

25

26 **NOMENCLATURE LISTING**

<i>A</i>	Vent Area (m <sup>2</sup> )	<b>Greek</b>	27
<i>C<sub>D</sub></i>	Discharge coefficient (-)	$\rho$	Density (kg/m <sup>3</sup> )
<i>GER</i>	Global equivalent ratio (-)	<b>subscripts</b>	
$\dot{m}$	Mass flow rate (kg/s)	<i>adm, A</i>	Admission
<i>M</i>	Dimensionless mass flow rate (-)	<i>ext, E</i>	Exhaust
<i>r</i>	Stoichiometric ratio (-)	<i>up</i>	Upward flow
$\Delta P$	Pressure difference (Pa)	<i>do</i>	Downward flow
$\dot{q}$	Volume flow rate (m <sup>3</sup> /h)	<i>L3</i>	Fire room L3
$\dot{Q}$	Heat release (W)	<i>L4</i>	Adjacent upper room L3
<i>Tr</i>	Renewal rate (h <sup>-1</sup> /h)	*	Dimensionless
<i>Y</i>	Mass fraction	$\infty$	Ambient atmosphere
		<i>f</i>	Fuel or fire
		<i>air</i>	Air
		<i>v</i>	Vent
		<i>O<sub>2</sub></i>	oxygen
		<i>o</i>	Initial or reference

28

29

## 1 INTRODUCTION

2 The propagation of smoke and hot combustion products is an issue of practical importance for  
3 fire safety assessment. In many industrial situations, smoke, responsible for the transport of  
4 heat and soot particles, may lead to the failure of safety systems. In the particular domain of nu-  
5 clear industry, typical events related to smoke that should be prevented are the clogging of high-  
6 efficiency (HEPA) filters located in a ventilation network or the malfunction of electrical or elec-  
7 tronic devices. The understanding and the development of appropriate modeling for smoke  
8 flows are of practical importance in the field of fire safety assessment.

9 The understanding and the prediction of fire scenario involving smoke flows through horizontal  
10 openings remain a challenging exercise (Figure 1). Indeed, as for doorways, the flow at a hori-  
11 zontal opening section may be bi-directional, induced by buoyancy and the mass conservation  
12 condition. However, because of the horizontal section, normal to the direction of gravity, the  
13 vent flow shows a much more complex behavior than the one for a vertical section, as doorway  
14 or window. The flow at the vent may experience several regimes, depending on the pressure and  
15 temperature differences conditions at the orifice: one-directional upward, bi-directional upward  
16 and downward, and one-directional downward. In addition, the bi-directional flow regime  
17 shows a complex flow pattern characterized by a time variation of the upward or downward  
18 flows locations in the vent section. One challenging issue is the fire scenario involving a fire  
19 compartment equipped with a vent for which a strong interaction may occur between the fire  
20 and the vent flow. In case of a bi-directional flow regime at the vent, the downward contribution  
21 may have a substantial influence on the combustion process, by modifying the flow rate of oxy-  
22 gen entering the fire enclosure, Figure 1.

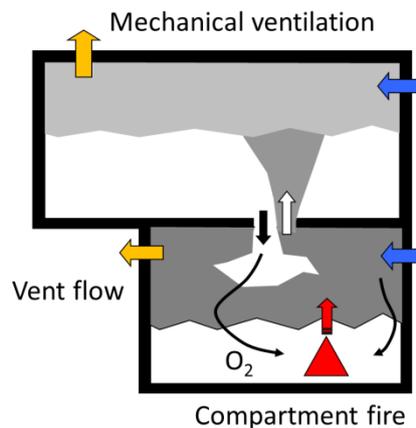


Figure 1: Illustration of a typical fire scenario involving a horizontal opening linking two compartments.

23 Pioneering works on vent flow have been conducted by Mercer *et al.* [1] [2], Perry *et al.* [3],  
24 Brown *et al.* [4], Epstein *et al.* [5], [6], Heskestad *et al.* [7] and Tan *et al.* [8]. Based on small-scale  
25 experimental approaches, these studies led to a theoretical description of the flow for a pure  
26 buoyancy bi-directional flow condition, based on the Froude number, and of the purge condi-  
27 tions, when mechanical ventilation is applied. From these works, Cooper [9]- [10] developed  
28 empirical correlations, predicting the gas flow rate for different flow regimes, from pure natural  
29 convection to mixed convection, with the final aim of introducing them in zone fire models. Re-  
30 cently, additional works were both performed for the validation of the Cooper's models (Pretrel  
31 *et al.* [11]) and the vent flow characterization, using an advanced measurement technique, the  
32 Stereo PIV (Varrall *et al.* [12] [13]).

33 The interaction between the vent flow and the smoke propagation in the compartments have  
34 been studied, pointing out the consequences of the upward flow on the smoke stratification in  
35 the upper room, as well as in the lower room (Hagglund *et al.* [14] Pretrel *et al.* [15]- [16], Dai *et al.* [17], Li [18]). Recent works have emphasized the consequences of the vent flow on the fire

1 and especially on the fire burning rate, for the natural ventilation scenario, with the fire room  
2 only connected to the outside with a horizontal vent (He *et al.* [19], [20], [21], Chen [22]). For  
3 these typical configurations, additional experimental and theoretical researches are needed to  
4 improve the general understanding of these flows and their consequences of a fire.

5 The present contribution focuses on the behavior of a compartment fire scenario, involving a  
6 vent and the consequences on the fire, for the specific configuration of closed and mechanically  
7 ventilated enclosures. This work extends the He's studies, conducted in natural ventilation, and  
8 considering forced ventilation. The present objectives are to improve the knowledge of fire sce-  
9 nario involving rooms, linked with vent and in particular to investigate the effect of three specifi-  
10 c scenario of ventilation on the burning rate and the vent flow. It carries on previous studies  
11 performed with constant and controlled burning rate with gas propane fire (Audouin *et al.*, [23]  
12 Pretrel *et al.* [11], [15], [16]). The present study is based on fire tests involving heptane pool fire  
13 whom the burning rate varies in time depending on the vent flow.

14 This study is based on the analysis of large scale fire tests performed in the framework of the  
15 Vertical Smoke Propagation, VSP, campaign of the OECD PRISME2 project and is supported by  
16 numerical simulations performed with the ISIS CFD code, developed by IRSN. First the fire tests  
17 are described. Then, the analysis focuses on the typical behavior of the fire scenario, the regimes  
18 of burning rates and the flow at the vent. Numerical simulations are then presented in order to  
19 better describe the influence of the downward flow on the oxygen concentration field in the fire  
20 room.

## 21 **DESCRIPTION OF THE TEST CAMPAIGN**

### 22 **Experimental facility**

23 The facility was the DIVA facility of IRSN, identical to the one of previous works with propane  
24 gas fire [16]. As illustrated in Figure 2, it consisted of two superposed rooms connected together  
25 by a horizontal opening or vent. The room dimensions were as follows: 4 m in height  
26  $\times 5 \text{ m} \times 6 \text{ m} = 120 \text{ m}^3$  for the lower room, named "L3", and 4 m in height  $\times 5 \text{ m} \times 8.5 \text{ m} = 170 \text{ m}^3$   
27 for the upper room, named "L4". The two rooms were linked by a rectangular vent of  
28  $1,030 \text{ mm} \times 1,030 \text{ mm} = 1,061 \text{ m}^2$ , centered in the fire room. They were mechanically ventilated  
29 by an industrial network, with admission and exhaust branches located in the upper part of each  
30 room. The ventilation inlets and outlets within the room were positioned so that they did not  
31 influence the flow at the horizontal opening; the directions are indicated by red and blue arrows  
32 in Figure 3.

33 The fire source was a  $0.4 \text{ m}^2$  heptane fuel pool fire located in the lower room. The pool was a  
34 circular, 13 cm in height metallic pan, filled with a given amount of fuel before the test. Ignition  
35 was performed with a propane gas burner. The amount of fuel diminished during the combustion  
36 phase. Two positions were considered, either at the centre of the room, either at the North-  
37 West corner, as indicated in Figure 2 and Figure 3.

### 38 **Measurements**

39 Heptane mass was measured during the experiment with a SARTORIUS weighting balance accu-  
40 rate within 2 g. The fuel mass loss rate was then determined from the time derivative of the  
41 mass. The ventilation flow rates were measured with average Pitot probe devices, located in the  
42 ventilation ducts and connected to membrane pressure transducers.

43 The vent was fitted with 13 bi-directional velocity probes, together with K-type thermocouples  
44 in a cross-section of the vent as detailed in [16]. The two rooms were equipped with four ther-  
45 mocouple trees, named SW, CC, NE and SE for the upper room L4, and SW, CC, NW and NE for the  
46 fire room L3. Each mast were equipped with nine K-type thermocouples located at 0.05 m,  
47 0.55 m, 1.05 m, 1.55 m, 2.05 m, 2.55 m, 3.05 m, 3.55 m and 3.90 m from the ground. The oxygen,  
48 carbon dioxide and carbon monoxide concentrations were measured inside the room at three  
49 locations (upper and lower part on the SW tree and near the pool) and in the admission and ex-  
50 haust branches. The gas analyzers EMERSON XSTREAM and SIEMENS ULTRAMAT apparatuses

1 measured concentration of dry gas sample. A time delay of about 20 seconds was determined  
 2 and then corrected for the analysis and post processing of the data.

3 The measurement uncertainties are shown in Table 1. They were evaluated from calibration  
 4 tests, carried out before or after the tests and using the data provided by the manufacturers of  
 5 the sensors. The calibration tests consisted in obtaining the differences between standard values  
 6 (from specific calibrated sensors or samples) and the measured values, read on the acquisition  
 7 system. Two levels of uncertainties were defined. The standard uncertainties, obtained at room  
 8 temperature, without fire. A second level, the expanded uncertainty, took into account the fire  
 9 test conditions by introducing a coverage (or correction) factor, applied to the standard uncer-  
 10 tainty. This coverage factor balance fire effects that can significantly influence the measurement  
 11 results.

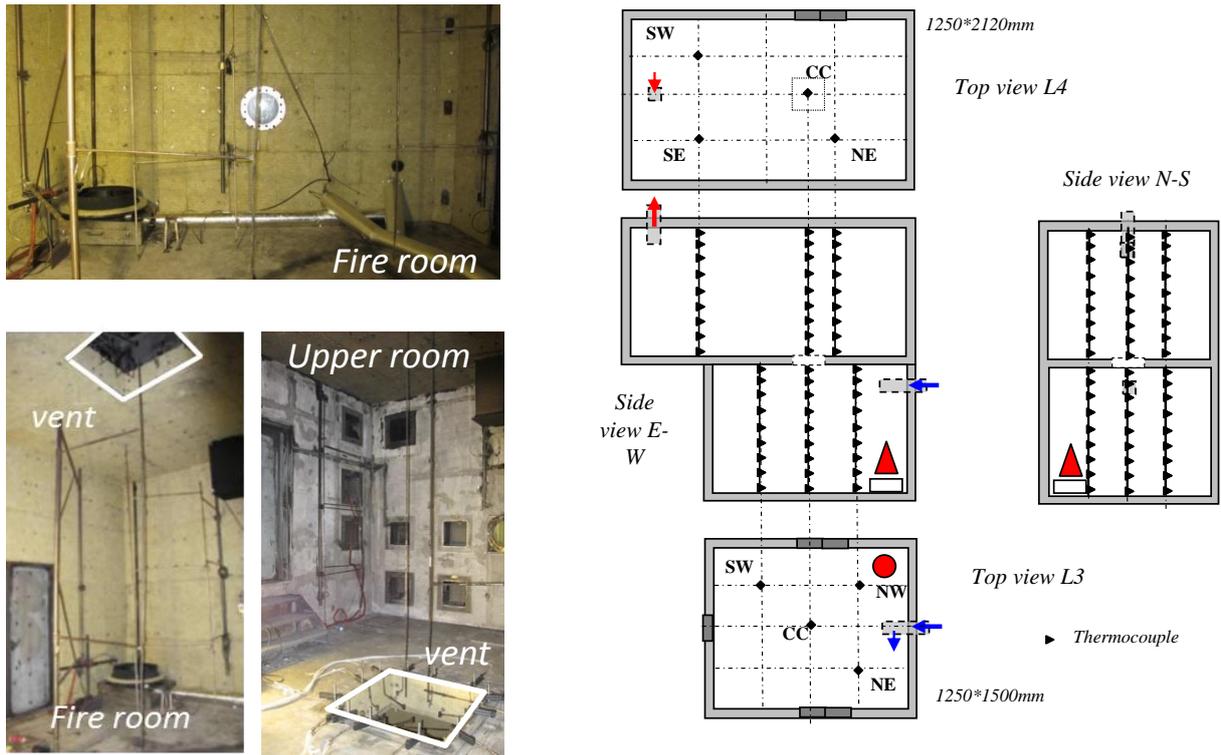


Figure 2: Pictures and drawings of the facility

12

Table 1 – Uncertainty assessment of physical quantities

Physical variable	Range	Standard uncertainty	Coverage factor	Expanded uncertainty
Mass	[0-300] kg	0.002 kg	2	0.004 kg
O <sub>2</sub> molar fraction	[0; 0.25] mol/mol	0.0025mol/mol	1	0.0025mol/mol
CO <sub>2</sub> molar fraction	[0; 0.10] mol/mol	0.001mol/mol	1	0.001mol/mol
CO molar fraction	[0; 1000] ppm	5 ppm	2	10 ppm
Pressure transducers	[-2500; +2500] Pa	4 Pa	2	8 Pa
K type thermocouple	[0;1300] °K	2°K	1	2°K
Air flow rate	[-2500;+2500] m3/h	100 m <sup>3</sup> /h	2	200 m <sup>3</sup> /h

13

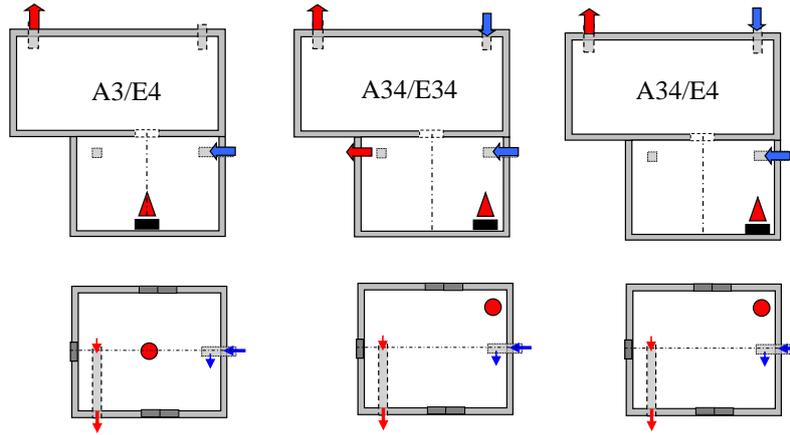


Figure 3: Schematic illustration of the three ventilation configurations

### 1 Test matrix and experimental procedure

2 Four fire tests, named PR2\_VSP\_2, PR2\_VSP\_3, PR2\_VSP\_4 and PR2\_VSP\_4BIS were performed  
 3 and the test parameters are shown in Table 2. The test parameters were the position of the fire  
 4 source in the fire room (either centre in the room or off-centre in the North West corner), the  
 5 ventilation configurations, named A3/E4, A34/E34 and A34/E3, and the ventilation flow rate.

6 The ventilation configuration specified different manner of blowing air within the two rooms, as  
 7 illustrated in Figure 3. The configuration A3/E4 consisted of one admission (inlet) in lower room  
 8 L3 (named “A3”) and one exhaust (outlet) in upper room L4 (named “E4”). The configuration  
 9 A34/E34 consisted of one admission and one exhaust in both rooms L3 and L4. The configura-  
 10 tion A34/E4 consisted of one admission in both rooms L3 and L4 and only one exhaust, in upper  
 11 room L4.

12 The ventilation flow rate was expressed with a renewal rate parameter,  $Tr$ . Two definitions have  
 13 been considered. The global renewal rate,  $Tr$ , defined as the ratio between the sum of the admis-  
 14 sion’s volumetric flow rate (in both rooms), before fire ignition and the total volume of the two  
 15 rooms,  $Tr = (\dot{q}_{adm}^{L3} + \dot{q}_{adm}^{L4})/V$  where ( $V = 120 + 170 = 290 \text{ m}^3$ ) and the renewal rate of the fire  
 16 room,  $Tr_{L3}$ , based on the room L3 parameters :  $Tr_{L3} = \dot{q}_{adm}^{L3}/V_{L3}$ .

17 The flow regime at the vent may vary from pure natural convection (bidirectional flow) to forced  
 18 convection (on-directional). The pressure difference, from both sides of the opening and prior to  
 19 ignition, is the parameter that characterized the flow regime. It is computed as  $\Delta P_o =$   
 20  $\frac{\rho_o}{2} [\dot{q}_v^o / (C_D A_v)]^2$  with  $A_v = 1.061 \text{ m}^2$  the total vent area and  $C_D = 0.74$ , the vent flow coefficient de-  
 21 termined experimentally. The variable  $\dot{q}_v^o$  is the volumetric flow rate at the vent determined  
 22 from the mass balance before ignition, as detailed in [11] and [16]. The flow rate and the pres-  
 23 sure difference prior to ignition are indicated in Table 2.

24 The four tests mimic different situations of flow at the vent. The first test, PR2\_VSP\_2, favored a  
 25 situation with dominant upward flow at the vent because of no exhaust line in the fire room and  
 26 fire position below the vent. The pressure difference at the vent is maximum  $\Delta P_o = 0.41 \text{ Pa}$ . The  
 27 second test, PR2\_VSP\_3, favored a situation with significant downward flow at the vent because  
 28 of equilibrium of pressure and a limitation of local momentum imposed by the fire with its posi-  
 29 tion away from the vent. The pressure difference at the vent prior to ignition is nul  $\Delta P_o = 0 \text{ Pa}$  and  
 30 corresponds to a regime of natural convection. The two tests, PR2\_VSP\_4 and PR2\_VSP\_4BIS,  
 31 correspond to intermediate situations between the two first configurations. The test,  
 32 PR2\_VSP\_4BIS, investigated the effect of the ventilation flow rate, in comparison to the  
 33 PR2\_VSP\_4 test, by increasing the total renewal rate. The four tests proposed, therefore, several  
 34 combinations for the two ventilation parameters ( $\Delta P_o$ ,  $Tr_{L3}$ ), with increasing pressure difference

1 and decreasing renewal rate: (0.41; 20.4) for test PR2\_VSP\_2, (0.20; 13.4) for test PR2\_VSP\_4BIS,  
 2 (0.07; 8.2) for test PR2\_VSP\_4 and (0.; 8.5) for test PR2\_VSP\_3.

3 Table 2 – Test parameters and ventilation conditions measured before ignition

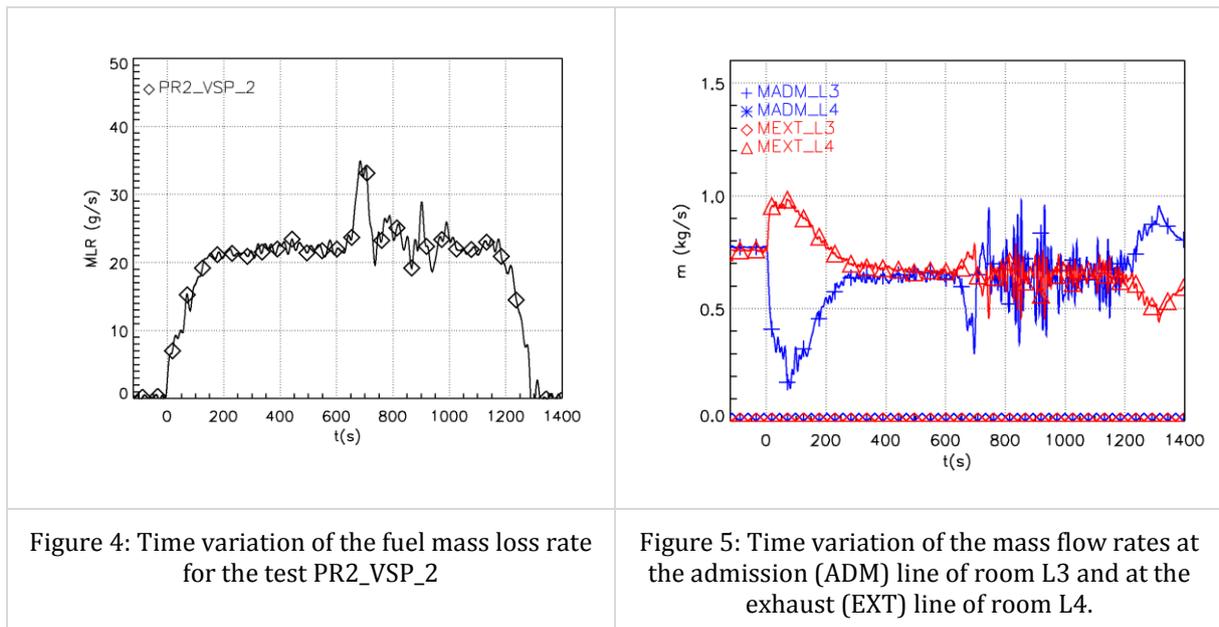
Name		PR2_VSP_2	PR2_VSP_3	PR2_VSP_4	PR2_VSP_4BIS
Fire position		C	Off-C	Off-C	Off-C
Ventilation configuration		A3/E4	A34/E34	A34/E4	A34/E4
$\dot{q}_{adm}^{L3}$	m <sup>3</sup> /h	2356	988	948	1546
$\dot{q}_{ext}^{L3}$	m <sup>3</sup> /h	0	1048	0	0
Tr <sub>L3</sub>	h <sup>-1</sup>	20,4	8,5	8,2	13,4
$\dot{q}_{adm}^{L4}$	m <sup>3</sup> /h	0	1451	1366	1324
$\dot{q}_{ext}^{L4}$	m <sup>3</sup> /h	2371	1460	2373	2967
Tr <sub>L3+L4</sub>	h <sup>-1</sup>	8,1	8,4	8,0	9,9
$\dot{q}_{vent}^{ref}$	m <sup>3</sup> /h	2338	-25	987	1611
$\Delta P_o$	Pa	0,41	0,00	0,07	0,20

4 C=centre in the room; Off-C= off-center in North-West corner

5 The experimental procedure was as follows. First the ventilation network was powered up to  
 6 achieve the targeted ventilation flow rates. Then the heptane pool was ignited. A mixed convec-  
 7 tion flow started to occur at the vent, and smoke progressively filled the adjacent room. The fire  
 8 extinguished by lack of fuel (PR2\_VSP\_2 test) or lack of oxygen in the room (the other tests).

9 **EXAMPLE OF A TYPICAL BEHAVIOUR**

10 The typical behavior of such real fire scenario is presented from the PR2\_VSP\_2 test with the  
 11 ventilation configuration A3/E4. The burning rate of the 0.4 m<sup>2</sup> heptane pool shows a nearly  
 12 steady behavior at about 23 g/s (cf. Figure 4). Before ignition, the air flow rates at the admission  
 13 of room L3 and at the exhaust of room L4 are equal at about 0.75 kg/s (cf. Figure 5). Then, flame  
 14 propagation leads to an expansion of the gas, an increase of the exhaust flow rate and a decrease  
 15 of the admission flow rate. Once the steady behavior is recovered, the two flow rates become  
 16 equal again. After 10 minutes of fire, the fire starts becoming unstable leading consequently to  
 17 fluctuating behaviors of the flow in the ventilation branches (see Figure 5). These fluctuations  
 18 correspond to unstable behavior of the burning rate during this period (cf. Figure 4).



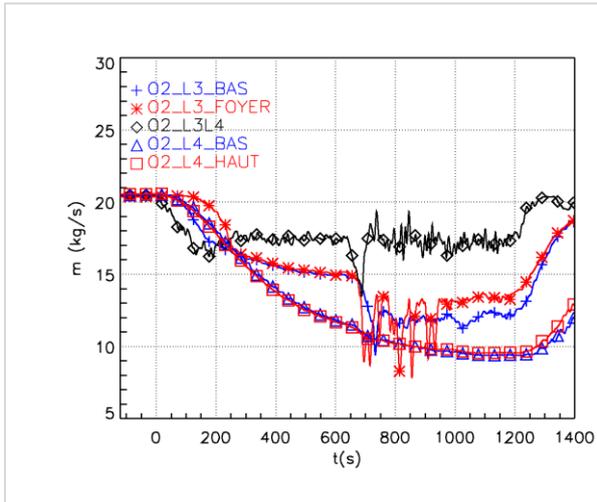


Figure 6: Time variation of the oxygen concentration at three positions in the two rooms L3 and L4 (low (BAS), near the pool (FOYER) and upper (HAUT)) and at the vent (L3L4)

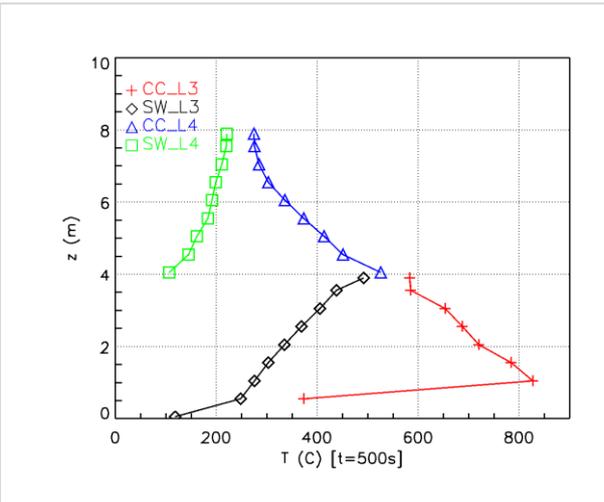


Figure 7: Vertical temperature profiles at the axis of the vent (CC) and on the SW axis in the fire room L3 ( $z=[0;4]$ m) and in the upper room L4 ( $z=[4;8]$ m) at  $t=500$ s.

- 1 The admission flow rate is not sufficient to compensate the oxygen consumption by the fire and
- 2 the oxygen concentrations in the two rooms decrease continuously until a steady situation is
- 3 reached (Figure 6). The oxygen concentrations in the upper room gives the lowest value (about
- 4 10%-vol), and is very homogenous in the room with no significant difference between the upper
- 5 and the lower part (O2\_L4\_BAS and O2\_L4\_HAUT in Figure 6). The concentration in the fire room
- 6 give higher levels (about 12%-vol) because of the fresh air brought by the admission line. The
- 7 oxygen concentration measured at the vent is surprisingly higher than those in the two rooms. It
- 8 is explained by the short distance between the vent and the inlet section that may induce local
- 9 effect of fresh air entrance.
- 10 The smoke propagation within the two rooms leads to a specific vertical temperature distribu-
- 11 tion, illustrated in Figure 7. Along the fire plume axis (masts CC\_L3 and CC\_L4 in Figure 7) the
- 12 temperature decreases from the flame temperature level (up to 800°C) toward about 450°C at
- 13 the vent section and then 250°C at the ceiling of room L4. Away from this axis, the temperature
- 14 profiles in the two rooms show an opposite variation with an increase from the ground to the
- 15 ceiling (masts SW\_L3 and SW\_L4 in Figure 7). These profiles illustrate typical thermal stratifica-
- 16 tion with higher temperature at the top of each room.

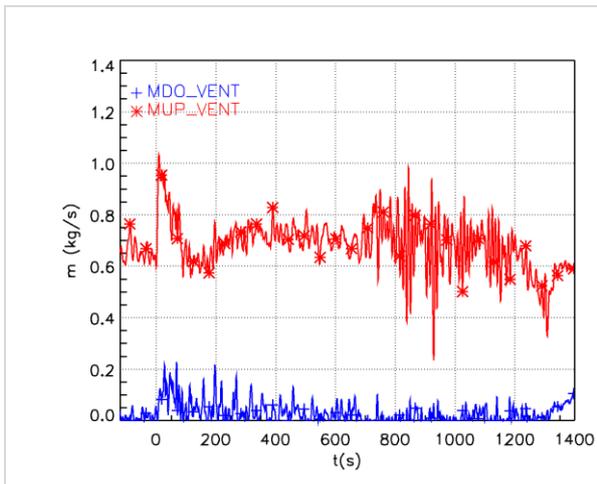


Figure 8: Time variation of the upward (UP) and downward (DO) air mass flow rate at the vent

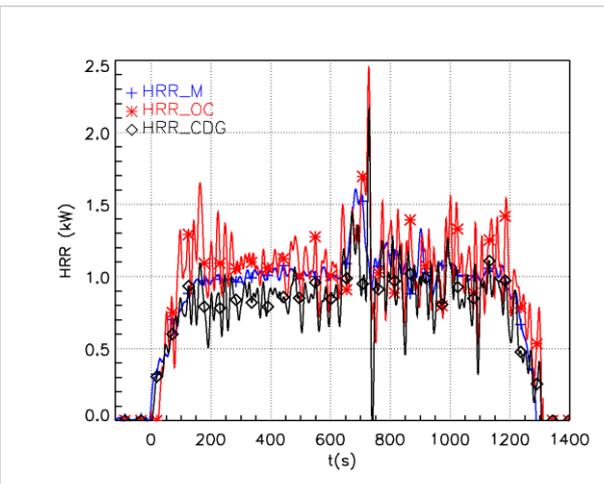


Figure 9: Time variation of the fire Heat release rate computed from mechanical (M), CDG and OC methods

1 For this test, the flow at the vent is mainly one directional upward, with nearly no downstream  
 2 flow coming from the upper room as indicated in Figure 8. This behavior is mainly due to the  
 3 ventilation configuration (admission in the lower room and exhaust in the upper room) that  
 4 tends to avoid any entrance of fresh air from the upper room.

5 The fire heat release rate  $\dot{Q}_f$  is also computing, directly from the fuel mass loss rate (HRR\_M) and  
 6 with chemicals methods: HRR\_OC for the oxygen consumption method and HRR\_CDG for the  
 7 carbon dioxide generation method, [16]. For this test, the average  $\dot{Q}_f$  is about 900 kW and the  
 8 three methods give similar results.

9 The analysis of the other tests shows similar trends. The main differences concern the burning  
 10 rate and its interaction with the flow at the vent.

11 **SEVERAL BURNING RATE REGIMES**

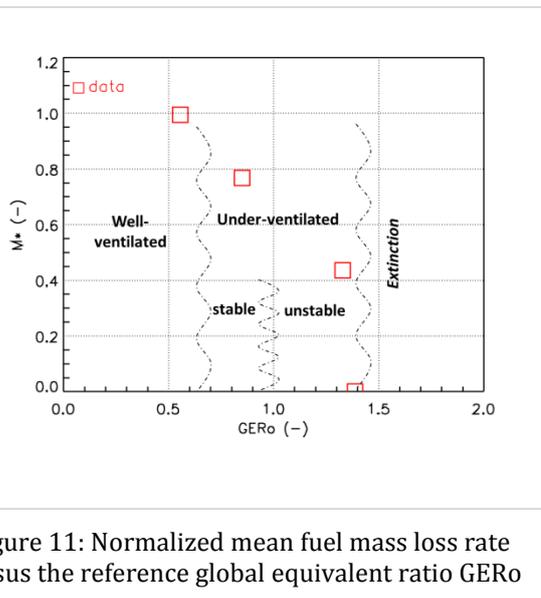
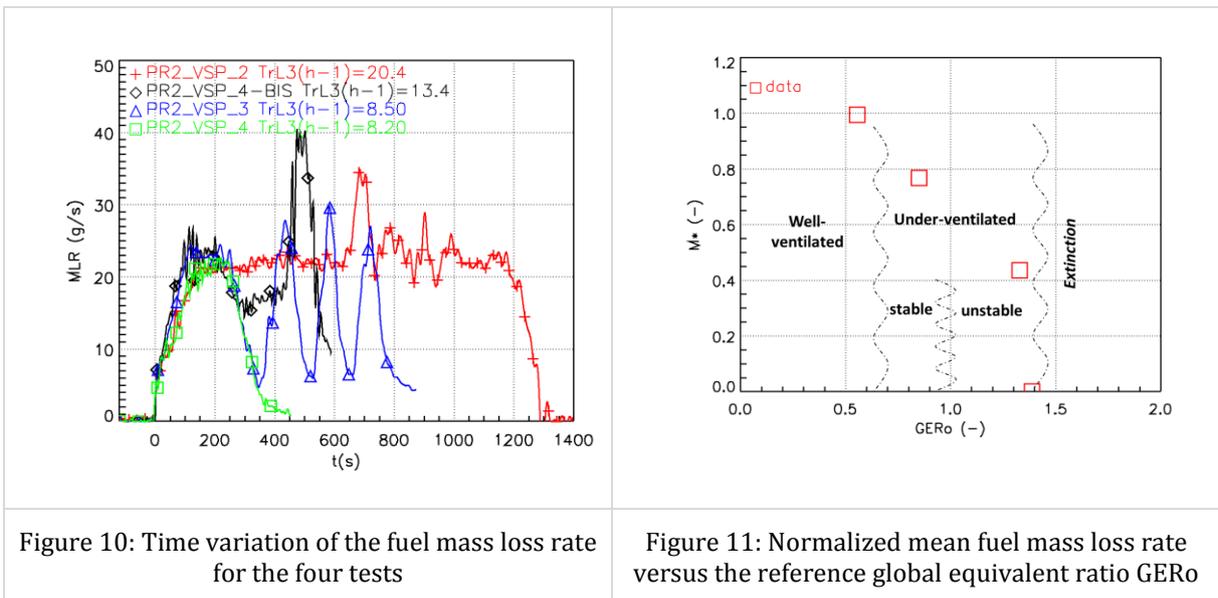
12 The time variation of the burning rate (also named fuel mass loss rate) is presented for the four  
 13 tests in Figure 10. Three particular behaviors are observed and discussed: the reduction of burn-  
 14 ing rate with the ventilation flow rate, the oscillatory behavior and the identification of critical  
 15 pool area.

16 **Reduction of the burning rate with the ventilation**

17 During the first instants (about 200 s) after ignition, the burning rate shows very similar behav-  
 18 ior whatever the tests; the external environment around the fire place being similar. Then after  
 19 this period, the external environment is modified because of the change of the rate of ventilation  
 20 in the fire room and also the ventilation configuration. As a result, different behaviors of the  
 21 burning rate are observed.

22 For the highest ventilation rate of the lower room (PR2\_VSP\_2 test,  $Tr_{L3}=20.4 \text{ h}^{-1}$ , i.e.  
 23  $\dot{q}_{adm}^{L3}=2356 \text{ m}^3/\text{h}$ ), the burning rate gives the highest level (about 23 g/s). This value is close to  
 24 the one expected in open atmosphere (about 22 g/s, i.e.  $54 \text{ g/s/m}^2$  obtained with the Babrauskas  
 25 relationship, [24], with  $\dot{m}_{f,\infty}=100 \text{ g/s}$  and  $\kappa\beta=1.1 \text{ m}^{-1}$ ). Then, extinction occurs after total com-  
 26 bustion of the mass of fuel.

27 With a lower ventilation flow rate (PR2\_VSP\_4BIS test,  $Tr_{L3}=13.4 \text{ h}^{-1}$ , i.e.  $\dot{q}_{adm}^{L3}=1546 \text{ m}^3/\text{h}$ ), the  
 28 burning rate decreases to about 18 g/s, but only during a short period and then increases again  
 29 rapidly up to 40 g/s followed by self-extinction due to lack of oxygen (fuel remains in the pan).  
 30 For the two lowest rates of ventilation, (PR2\_VSP\_3 and PR2\_VSP\_4 tests,  $Tr_{L3}=8.5 \text{ h}^{-1}$ , i.e.  
 31  $\dot{q}_{adm}^{L3}=988 \text{ m}^3/\text{h}$ ), the burning rate shows either a rapid self-extinction (PR2\_VSP\_3 test) or an  
 32 oscillatory behavior followed by extinction due to lack of oxygen.



1 The reduction of the burning rate with the ventilation flow rate is typical to compartment fire  
2 scenario. This phenomenon depends, among other parameters, on the reference global equiva-  
3 lent ratio  $GER_o$  defined as the ratio between the rate of oxygen that is required for the combus-  
4 tion in open atmosphere,  $r \dot{m}_{f,\infty}$ , and the rate of oxygen brought to the enclosure by the mechan-  
5 ical ventilation,  $Y_{O_2,\infty} \dot{m}_{air,v}$ , before ignition. The normalized fuel mass loss rate,  $M^* = \dot{m}_f / \dot{m}_{f,\infty}$ ,  
6 diminishes with the increase of the  $GER_o$  (Figure 11) as expected and demonstrated theoretically  
7 for well-stirred reactor [25]. For the present data, different regimes of burning rate are identi-  
8 fied depending on the range of  $GER_o$ . For  $GER_o$  lower than 0.5, the burning rate is similar to the  
9 one in open atmosphere ( $M^* \sim 1$ ). In the range  $GER_o = [0.6 ; 1.3]$ , the dimensionless burning rate  
10 decreases and the combustion regime can be said “under-ventilated”. Above  $GER_o = 1.3$ , there is  
11 extinction, and the burning rate cannot be maintained. These limits are orders of magnitude  
12 determined from the present data. Between these two limits, there is a range  $[1 ; 1.3]$  where the  
13 burning rate is very unstable and oscillatory behaviors are observed. These regimes are very  
14 similar to those identified in natural ventilation by He & al [19]. In the present study with me-  
15 chanical ventilation, the governing parameter  $GER_o$  includes the ventilation flow rate, whereas in  
16 the He’s study; the governing parameter is the ventilation parameter,  $A_v^{5/4} / \dot{Q}_f$ , considering the  
17 vent size  $A_v$  only.

18 In the present study, the two parameters affecting the burning rate are the renewal rate of the  
19 fire room,  $Tr_{L3}$ , (and thus  $GER_o$ ) that characterized the air brought by the ventilation but also the  
20 pressure difference at the vent,  $\Delta P_o$ . This former variable specifies the likelihood of seeing  
21 downward flow at the vent and therefore the level of additional oxygen brought by the vent to  
22 the fire room. This additional effect explains the differences between the two tests PR2\_VSP\_3  
23 and PR2\_VSP\_4 that show different results but with the same  $GER_o$ . These tests have the same  
24  $Tr_{L3}$ , but two different values for  $\Delta P_o$ .

## 25 **Oscillatory behavior**

26 For the PR2\_VSP\_3 test whom the conditions are close to the extinction limit, three large oscilla-  
27 tions of the burning rate are observed with an average frequency of  $6.7 \cdot 10^{-3}$  Hz (average period  
28 of 148 s) and large amplitude of about 20 g/s for an average value of 14.8 g/s. These are typical  
29 to low frequency behavior and very similar to fire oscillations encountered in one forced venti-  
30 lated room without vent [26]. They are explained as a coupling between the burning rate, the  
31 pressure in the room that governs the oxygen entrance and the convective time for the oxygen to  
32 reach the burning area. This oscillatory behavior can also be related to several recent studies  
33 showing the occurrence of oscillatory fire and ghosting flame phenomena with vent in naturally  
34 ventilated room, without mechanical ventilation [19], [27]. The present tests demonstrate that  
35 similar unsteady behaviors can be encountered between scenarios with or without mechanical  
36 ventilation or/and vent. The common features are the under-ventilated conditions, specified  
37 among others parameters with  $GER_o$ , but also the capability of having a strong coupling between  
38 the burning rate and an admission of air (naturally or forced through a vent or a regular admis-  
39 sion pipe) associated with a time delay.

## 40 **Critical pool size leading to self-extinction**

41 When dealing with compartment fire equipped with ceiling vent, an important issue for the de-  
42 sign is the critical vent area under which no steady combustion is maintained and self-extinction  
43 occurs, because the flow rate of oxygen coming from the vent is not sufficient to ensure combus-  
44 tion. In natural convection, without mechanical ventilation, recent studies with pool fires show  
45 that the critical vent size is about 2 to 10 times higher than the pool area [20] [27]. Applying this  
46 criteria to the present study, a critical vent size of  $1 \text{ m}^2$  corresponds to a range of pool fire area  
47 of  $[0.1 ; 0.5] \text{ m}^2$ . The  $0.4 \text{ m}^2$  pool fire considered in the present tests corresponds therefore to a  
48 critical pool size that could have led to self-extinction without mechanical ventilation (natural  
49 ventilation case). The present data confirms that self-extinction can be expected if the ventila-  
50 tion flow rate is low (test PR2\_VSP\_4). If the ventilation flow rate is increased as it is done for the  
51 other tests, steady combustion phase can be achieved due to the additional feed of oxygen.

# 1 CONSEQUENCES ON THE VENT FLOW

## 2 Flow regimes

3 The flow at the vent is governed by temperature and pressure differences from both side of the  
4 opening. With no pressure difference, the flow is bi-directional with equal flow rate in both di-  
5 rections. With a non-zero pressure difference, induced by the forced ventilation for instance, the  
6 flow is unbalanced. For pressure difference above the critical pressure (or purge pressure), the  
7 flow becomes one -directional upward or downward according to the sign of the pressure differ-  
8 ence. For the present tests with variable fire heat release rate, the vent flow varies with time  
9 following the time variation of the fire. The upward and downward mass flow rates are present-  
10 ed in Figure 12. The four tests with three ventilation configurations, A3/E4, A34/E34 and  
11 A34/E3, are sorted according to the initial pressure difference at the vent,  $\Delta P_o$ .

12 For test PR2\_VSP\_2 with A3/E4 configuration, the flow is mainly upward and nearly no down-  
13 ward flows are measured (Figure 12). The corresponding initial vent pressure difference is  
14 0.41 Pa. The test PR2\_VSP\_3 with  $\Delta P_o=0$  Pa leads to bidirectional flow with equal upward and  
15 downward flows similar to a situation encountered for natural ventilation. This result confirms  
16 that the reduction of the initial pressure difference contributes to decrease the upward flow and  
17 to increase the downward flow. This result demonstrates also that bidirectional regime at the  
18 vent, corresponding to natural convection case, can be encountered with mechanical ventilation  
19 scenario, provided the ventilation is set-up with no pressure difference at the vent, which is the  
20 case with the ventilation configuration A34/E34.

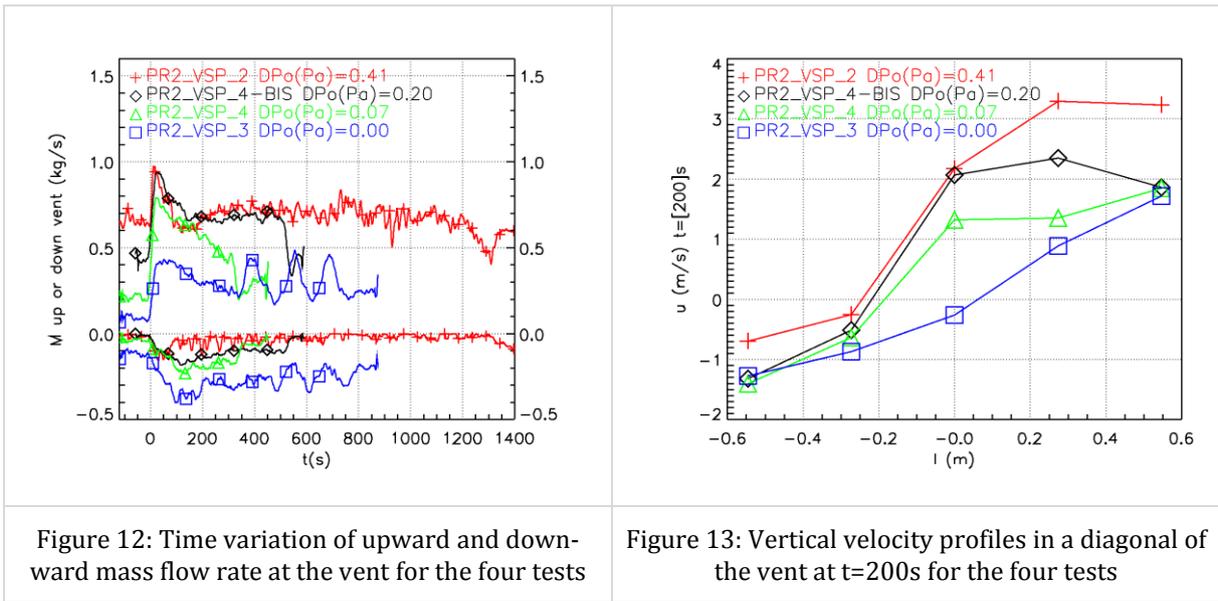


Figure 12: Time variation of upward and downward mass flow rate at the vent for the four tests

Figure 13: Vertical velocity profiles in a diagonal of the vent at t=200s for the four tests

21

22 The effect of the pressure difference at the vent is also noticed on the velocity field. Figure 13  
23 compares the velocity profiles in one diagonal of the vent. With no initial pressure difference at  
24 the vent,  $\Delta P_o = 0$  Pa for test PR2\_VSP\_3, the velocity profile shows a form with equal downward  
25 and upward flows. The increase of the initial pressure difference contributes to unbalance the  
26 flow with an increase of the upward flow and a reduction of the downward one. The initial pres-  
27 sure difference at the vent is an appropriate parameter to characterize the flow regime and the  
28 distribution between the upward and downward flow.

## 29 Contribution of the downward flow to the fire room

30 An important issue for the understanding of the burning rate variation is to assess the contribu-  
31 tion of the downward flow to the total amount of air available for combustion in the fire room.  
32 Figure 14 presents the time variations of the downward flow rate at the vent, of the admission  
33 flow rate, from the ventilation and of the sum of the two terms. The tests are characterized by

1 two parameters, the renewal rate  $Tr_{L3}$ , that specified the admission flow rate in the fire room  
2 and the initial pressure difference at the vent,  $\Delta P_o$ , that characterized the flow regime and thus  
3 the weight of the downward flow.

4 Figure 15 presents the average contribution of each term over the whole duration of the com-  
5 bustion phase versus the initial pressure reference at the vent.

6 The ventilation configuration A3/E4 (test PR2\_VSP\_2 with  $[\Delta P_o, Tr_{L3}] = [0.41 ; 20.4]$ ) is the one  
7 that brings the largest amount of air, mostly by the ventilation, with nearly no air coming from  
8 the vent. This configuration leads to the larger level of burning rate with steady regime.

9 The configuration A34/E34 (test PR2\_VSP\_3 with  $[\Delta P_o, Tr_{L3}] = [0.0 ; 8.5]$ ) is the one that gives  
10 equal contributions from the admission line of the ventilation and from the vent, but also the  
11 largest amount of downward flow. This configuration corresponds to the test where oscillatory  
12 burning rate are encountered. The downward flow is then an important criterion in the occur-  
13 rence of oscillatory of the burning rate.

14 From Figure 15, it is noticed that the test PR2\_VSP\_4 with configuration A34/E4 leads to the  
15 lowest total amount of air entering the fire rooms. This result is in accordance with the time var-  
16 iation of the burning rate that shows rapid extinction due to lack of oxygen.

17 This results show that the reduction of the pressure difference at the vent prior to ignition fa-  
18 vors the increase of the downward flow at the vent that can be a catalyst for unstable oscillatory  
19 behaviors of the burning rate.

20

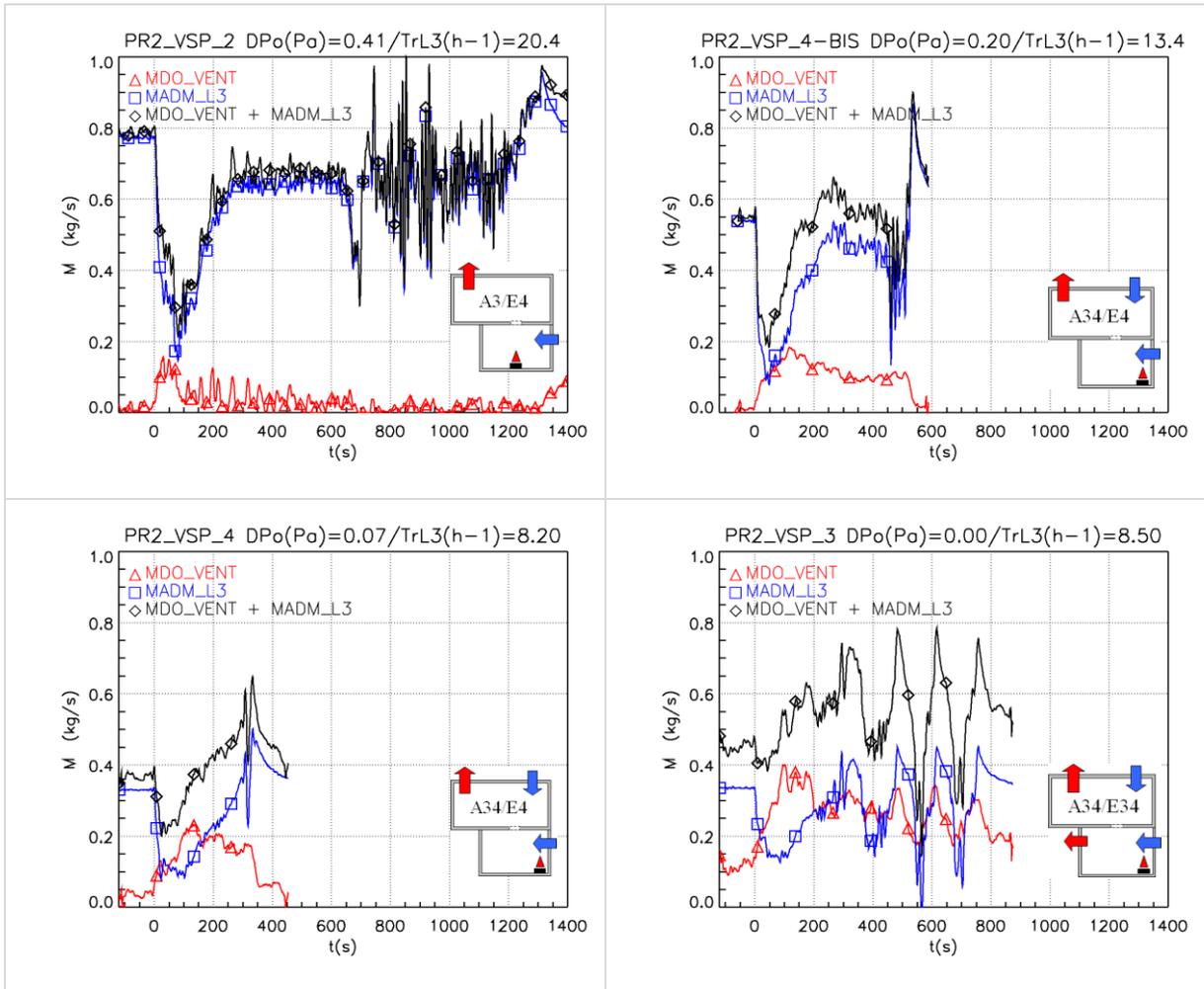


Figure 14: Time variation of the mass flow rates entering the fire room by the ventilation (MADM\_L3) and by the vent (MDO\_VENT) for the four tests

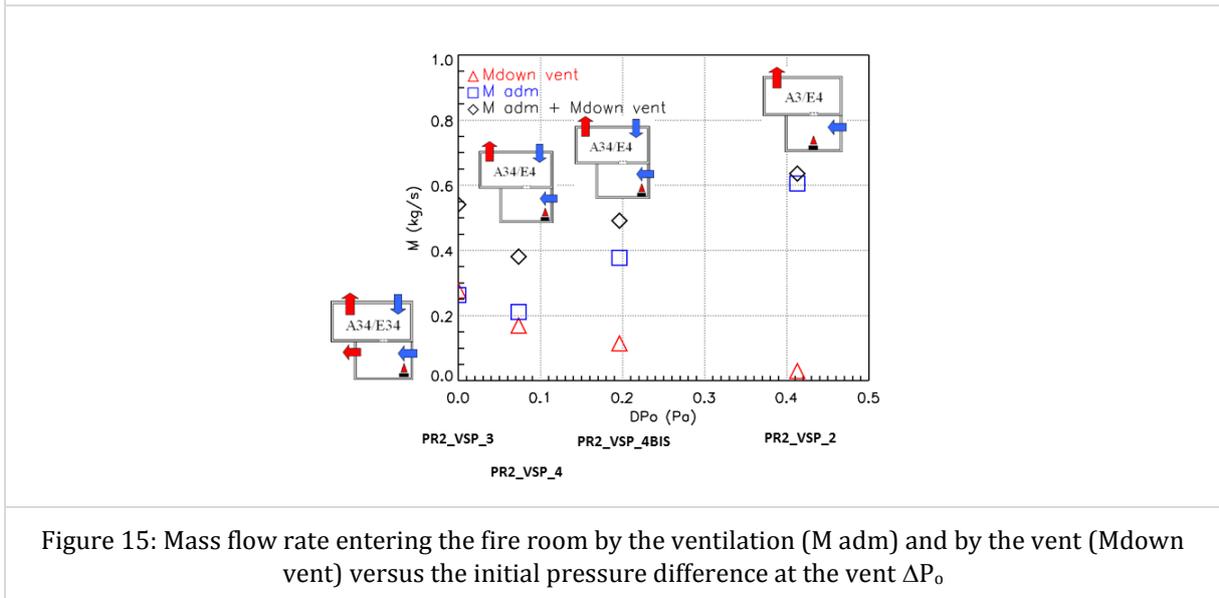


Figure 15: Mass flow rate entering the fire room by the ventilation (M adm) and by the vent (Mdown vent) versus the initial pressure difference at the vent  $\Delta P_o$

## 1    **DOWNWARD FLOW ANALYSIS FROM NUMERICAL SIMULATIONS**

2    Numerical simulations of the fire tests have been performed in order to improve the physical  
3    description of the vent flow and especially the downward flow feeding the fire room in oxygen.

### 4    **Numerical software ISIS**

5    The ISIS<sup>1</sup> software, computational tool based on low-Mach number approximation, was especial-  
6    ly developed for simulations of fires in mechanically ventilated compartments. The Reynolds-  
7    stress tensor and turbulent scalar fluxes are modelled using the eddy viscosity hypothesis and  
8    the first-order  $k - \epsilon$  model with two balance equations. Standard wall functions are used to take  
9    into account the boundary layers as the two-equation closure model is no more valid near the  
10   walls, where viscous effects are predominant. Turbulent combustion is based on the infinitely  
11   fast chemistry conserved scalar approach, using the mixture fraction and the fuel mass fraction.  
12   The mean reaction rate, controlled by the turbulent flow mixing, is determined by the Eddy-  
13   Dissipation Combustion (EDC) model [19]. A one-step irreversible combustion reaction for the  
14   fuel is considered and involves oxygen and products in the presence of a neutral gas. The model  
15   for the soot production and transport is based a simple approach considering a constant soot  
16   conversion factor,  $v_s$  in the single one-step reaction [20]. The radiative transfers are dealt with  
17   the finite volume method [21] assuming a gray and non-diffusive media. The gas absorption co-  
18   efficient of the mixture used the total emissivity approach of the weighted sum of gray gases  
19   model (WSGGM) and the soot absorption coefficient is related to the soot volume fraction ac-  
20   cording to the Mie theory. The wall conduction is taken into account through the 1D Fourier's  
21   equation and the convective flux is given by standard laws based on laminar and turbulent  
22   Prandtl numbers [22].

23   Concerning the boundary conditions, the experimental mass loss rate is imposed for the fire  
24   source area, and classical wall boundary conditions are applied on the walls.

### 25   **Validation of the ISIS simulation**

26   The numerical simulations are compared to experimental data in order to assess the capability  
27   of prediction of the flows in both room and at the vent. The variables to be compared are gas  
28   temperature in the fire room, the volume flow rates in the ventilation and the mass flow rate at  
29   the vent.

30   First the prediction of the gas temperature in the fire room is compared to the experimental data  
31   in Figure 16. The simulations reproduce satisfactorily the amplitude of the temperature as well  
32   as the vertical thermal stratification in the fire room with a nearly constant vertical gradient of  
33   temperature. This result demonstrates the capability of the ISIS code to reproduce the tempera-  
34   ture field in the fire room which governs then the buoyancy flux at the vent.

35   Then, the comparison between the simulations and the experiments for the flow rates in the  
36   ventilation is presented in Figure 17 (left columns). The simulations reproduce satisfactorily the  
37   experiments with similar trends. The increase of the exhaust flow rates and the decrease of the  
38   admission flow due to the temperature rise in the enclosure are correctly captured by the simu-  
39   lations. This result indicates that the temperature fields within the room are globally well pre-  
40   dicted by simulations.

41   The comparisons of mass flow rates at the vent are also presented the three tests Figure 17 (left  
42   columns). There is also a good agreement between experiments and simulations. The three re-  
43   gimes of flow at the vent are correctly predicted by the simulations: mainly one directional up-  
44   stream for test PR2\_VSP\_2, bidirectional with equal contribution in both directions for test  
45   PR2\_VSP\_3 and an intermediate regime for test PR3\_VSP\_4 (bidirectional but with a dominant  
46   upward flow in comparison to the downward flow). This result demonstrates that the equilibri-

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<sup>1</sup> The CFD code ISIS can be freely downloaded from <https://gforge.irsn.fr/gf/project/isis/>.

1 um between the buoyancy that governs the bidirectional regime and the forced convection that  
2 tends to unbalance this regime is well captured by the simulations. With the fuel mass flow rate  
3 (and thus the fire heat release rate) as an input condition, the simulations predict satisfactorily  
4 the mixed convection flow fields induced by buoyancy and inertia.

5 This validation on the flow field gives credit on the simulations in order to analysis the behavior  
6 of the downward flow within the fire room.

7

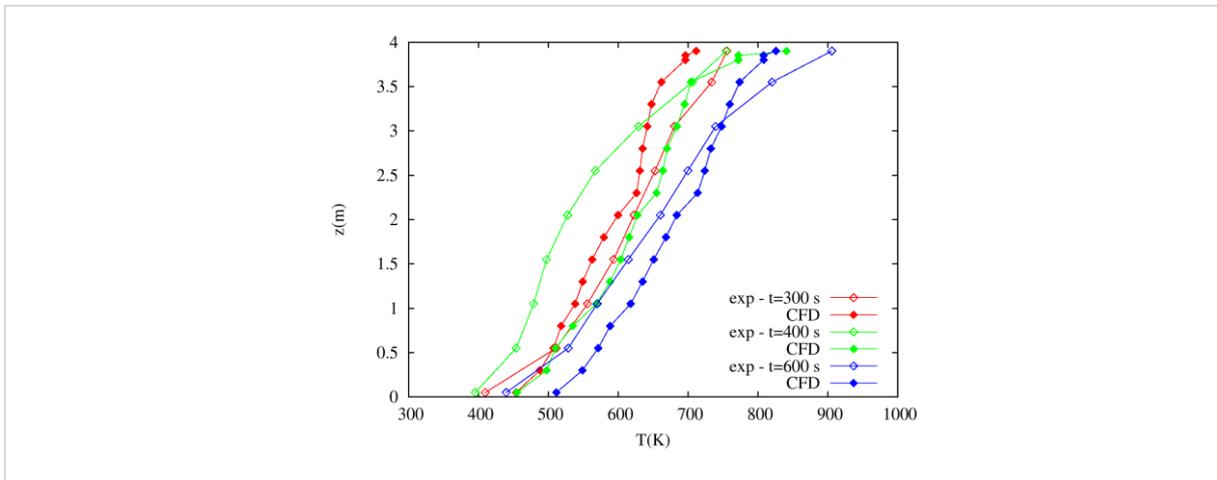


Figure 16: Comparison between the experimental and numerical gas temperature in the fire room at three times for the test PR2\_VSP\_3.

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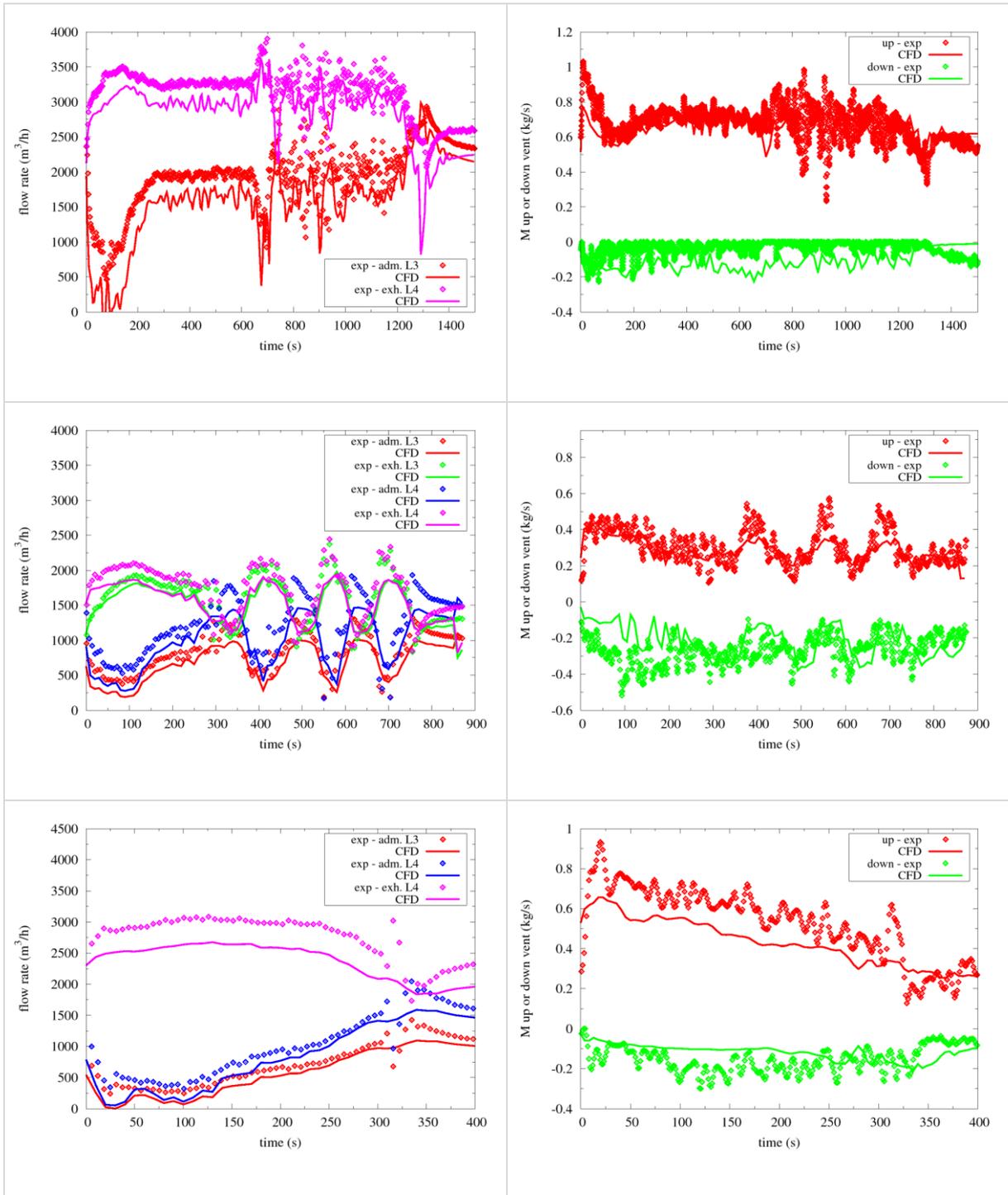


Figure 17: Comparison between the experimental and numerical flow rates in the admission and exhaust branches of the ventilation (left columns) and at the vent (right columns) for the three tests PR2\_VSP\_2 (one admission in room L3 and one exhaust in room L4), PR2\_VSP\_3 (one admission and one exhaust in both rooms) and PR2\_VSP\_4 (two admissions in rooms L3 and L4 and one exhaust in room L4)

1 **Flow pattern induced by the downward flow**

2 In order to better describe the way the downward flow is transported in the fire room, numeri-  
3 cal simulations of the flow field in the fire room are investigated. The analysis of the oxygen con-  
4 centration fields superimposed with the velocity field is presented in Figure 18 for two tests  
5 PR2\_VSP\_3 and PR2\_VSP\_4 for which the downward flow is significant. The downward flow is  
6 characterized by higher oxygen concentrations and by vertical downward velocities that can  
7 reached at least the mid-height of the fire room and nearly the ground level for test PR2\_VSP\_3  
8 (Figure 18 - a). These velocity fields attest that the downward flow is not re-entrained by the  
9 smoke in the vicinity of the vent but can deeply penetrate the lower room and contributes to  
10 feed the burning regions with “fresh” air. This result may be an element that explains the oscilla-  
11 tory behavior of the burning rate. The way the oxygen is brought to the fire room by the down-  
12 ward flow, possibly with a time delay, may be a condition for unsteady behavior of the burning  
13 rate.

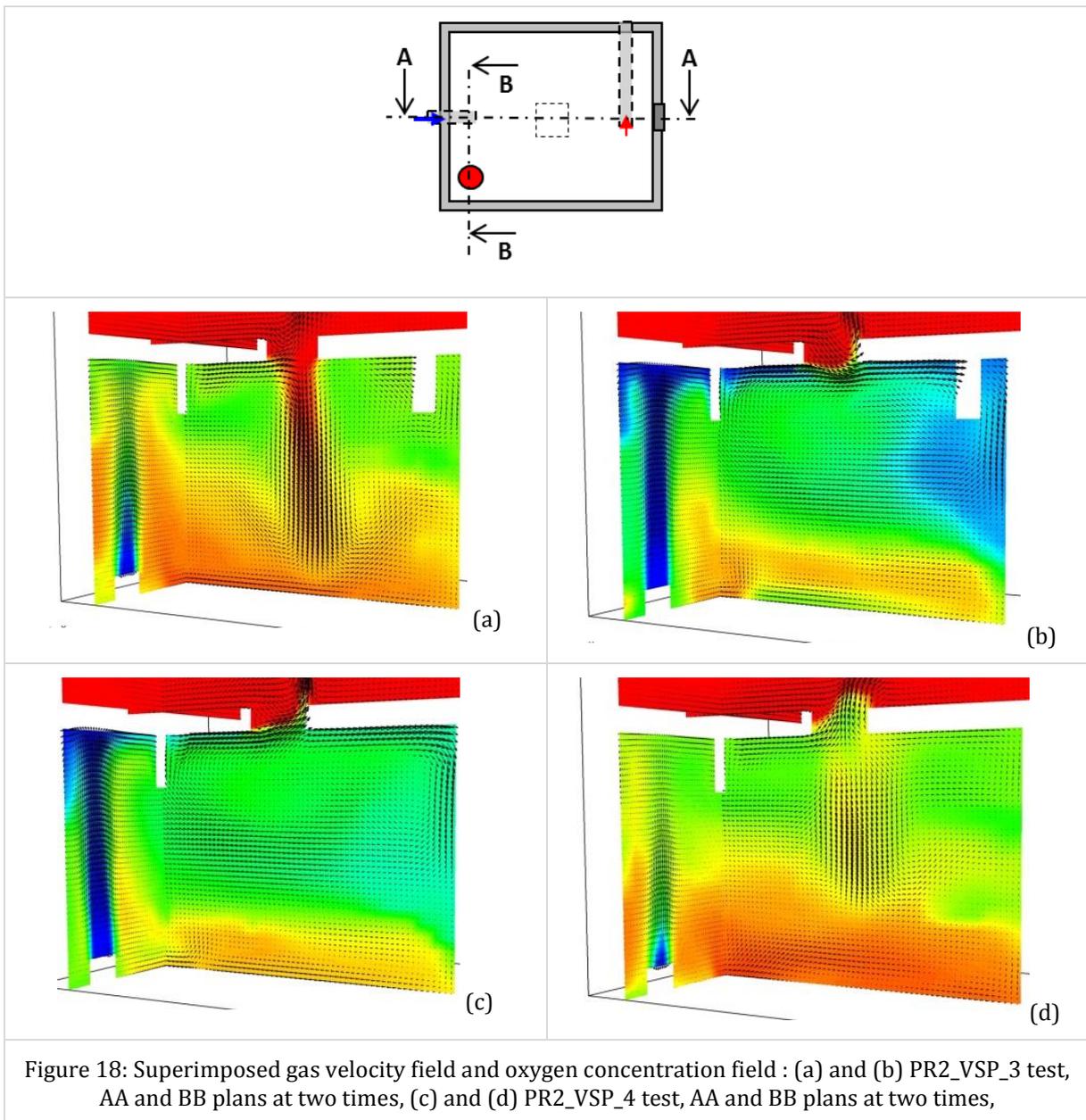


Figure 18: Superimposed gas velocity field and oxygen concentration field : (a) and (b) PR2\_VSP\_3 test, AA and BB plans at two times, (c) and (d) PR2\_VSP\_4 test, AA and BB plans at two times,

14

15

## 1 **CONCLUSION**

2 This work deals with a phenomenological investigation of fire scenario within two rooms, me-  
3 chanically ventilated and connected together with a horizontal vent. The objective is to investi-  
4 gate the effect of a horizontal opening on a fire scenario in confined and forced ventilated encl-  
5 sures. A set of large scale experiments performed in the framework of the OECD PRISME-2 pro-  
6 ject in the multi-room facility DIVA of IRSN are considered. The scenario consists of two rooms  
7 mechanically ventilated and linked with a horizontal vent of 1 m<sup>2</sup>. The fire is heptane pool fire  
8 located in the lower room. Three specific configurations of ventilation are investigated leading to  
9 different flow regime at the vent from one directional upward to bidirectional. The analysis fo-  
10 cuses on the coupling between the burning rate, the flow at the vent and the configuration of the  
11 mechanical ventilation. The main conclusions are listed below.

- 12 • Several regimes of combustion are encountered from steady well ventilated to under-  
13 ventilated unsteady and oscillatory fire. The burning rate is controlled by both the me-  
14 chanical ventilation and the downward flow from the vent.
- 15 • The downward flow at the vent can be significant and can permit to ensure combustion  
16 for specific configuration of the ventilation. The amplitude of the downward flow is a key  
17 element in the onset of unstable oscillatory fires. The flow regime at the vent and the  
18 prediction of the downward flow are therefore of importance in the global understand-  
19 ing of the fire scenario.
- 20 • Numerical simulations with the ISIS fire field model reproduced correctly the flow fields  
21 in the rooms, provided the burning rate is set as a boundary condition. The simulations  
22 provide a better description of the flow field induced by the downward flow and its abil-  
23 ity to supply “fresh air” in the fire area.

24 This study has highlighted that the fire scenario involving mechanical ventilation and a vent re-  
25 mains a challenging issue both experimentally and numerically.

26

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