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ABSTRACT

This work deals with an experimental and numerical investigation of fire scenario involving two rooms mechanically ventilated and connected together with a horizontal vent. The objective is to investigate the effect of a horizontal opening on a fire scenario and especially on the burning rate. The study is based on the analysis of a set of large scale fire experiments performed in the framework of the OECD PRISME-2 project in the DIVA multi-room facility of the Institut de Radioprotection et de Sûreté Nucléaire (IRSN), and of numerical simulations performed with the ISIS CFD code developed by IRSN. The fire scenario consists of two rooms, one above the other, mechanically ventilated, and connected to each other with a horizontal vent of 1 m^2. The fire is heptane pool fire located in the lower room. The analysis focuses on the coupling between the burning rate, the flow at the vent and the configuration of the mechanical ventilation. Several regimes of combustion are encountered from well ventilated steady fire to under-ventilated unsteady and oscillatory fire. The results show that the burning rate is controlled by both the mechanical ventilation and the downward flow from the vent. The numerical simulations highlight the specific pattern of the oxygen concentration field induced by the downward flow at the vent.

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

NOMENCLATURE LISTING

A	Vent Area (m^2)	**Greek**	
C_D	Discharge coefficient (-)	ρ	Density (kg/m^3)
GER	Global equivalent ratio (-)	**subscripts**	
$\dot{m}$	Mass flow rate (kg/s)	*adm, A*	Admission
M	Dimensionless mass flow rate (-)	*ext, E*	Exhaust
r	Stoichiometric ratio (-)	*up*	Upward flow
ΔP	Pressure difference (Pa)	*do*	Downward flow
$\dot{q}$	Volume flow rate (m^3/h)	*L3*	Fire room L3
$\dot{Q}$	Heat release (W)	*L4*	Adjacent upper room L3
Tr	Renewal rate (h^{-1}/h)	*	Dimensionless
Y	Mass fraction	∞	Ambient atmosphere
		f	Fuel or fire
		air	Air
		v	Vent
		O_2	oxygen
		o	Initial or reference

INTRODUCTION

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

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

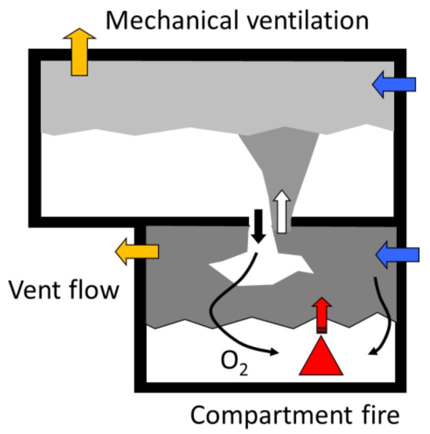

Figure 1: Illustration of a typical fire scenario involving a horizontal opening linking two compartments.

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

The interaction between the vent flow and the smoke propagation in the compartments have been studied, pointing out the consequences of the upward flow on the smoke stratification in 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 and especially on the fire burning rate, for the natural ventilation scenario, with the fire room only connected to the outside with a horizontal vent (He *et al.* [19], [20], [21], Chen [22]). For these typical configurations, additional experimental and theoretical researches are needed to improve the general understanding of these flows and their consequences of a fire.

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

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

DESCRIPTION OF THE TEST CAMPAIGN

Experimental facility

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

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

Measurements

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

The vent was fitted with 13 bi-directional velocity probes, together with K-type thermocouples in a cross-section of the vent as detailed in [16]. The two rooms were equipped with four thermocouple trees, named SW, CC, NE and SE for the upper room L4, and SW, CC, NW and NE for the fire room L3. Each mast were equipped with nine K-type thermocouples located at 0.05 m, 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, carbon dioxide and carbon monoxide concentrations were measured inside the room at three locations (upper and lower part on the SW tree and near the pool) and in the admission and exhaust branches. The gas analyzers EMERSON XSTREAM and SIEMENS ULTRAMAT apparatuses measured concentration of dry gas sample. A time delay of about 20 seconds was determined and then corrected for the analysis and post processing of the data.

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

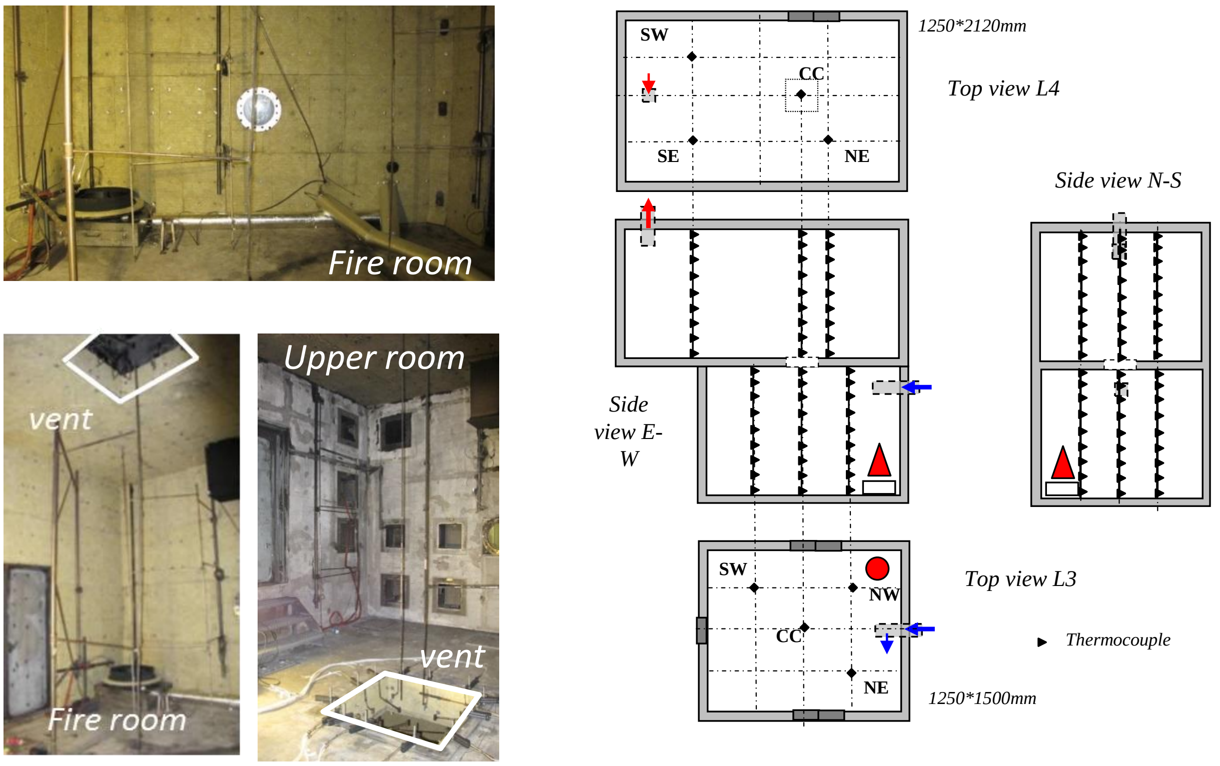

Figure 2: Pictures and drawings of the facility

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_2 molar fraction	[0; 0.25] mol/mol	0.0025mol/mol	1	0.0025mol/mol
CO_2 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^3/h	2	200 m^3/h

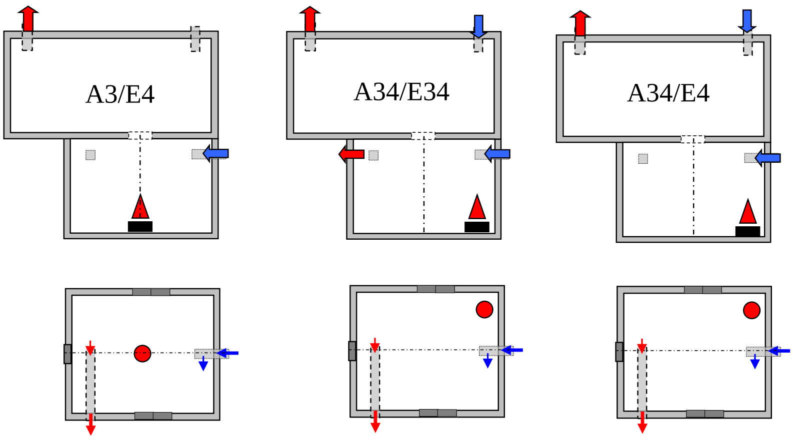

Figure 3: Schematic illustration of the three ventilation configurations

Test matrix and experimental procedure

Four fire tests, named PR2_VSP_2, PR2_VSP_3, PR2_VSP_4 and PR2_VSP_4BIS were performed and the test parameters are shown in Table 2. The test parameters were the position of the fire source in the fire room (either centre in the room or off-centre in the North West corner), the ventilation configurations, named A3/E4, A34/E34 and A34/E3, and the ventilation flow rate.

The ventilation configuration specified different manner of blowing air within the two rooms, as illustrated in Figure 3. The configuration A3/E4 consisted of one admission (inlet) in lower room L3 (named "A3") and one exhaust (outlet) in upper room L4 (named "E4"). The configuration A34/E34 consisted of one admission and one exhaust in both rooms L3 and L4. The configuration A34/E4 consisted of one admission in both rooms L3 and L4 and only one exhaust, in upper room L4.

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

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

The four tests mimic different situations of flow at the vent. The first test, PR2_VSP_2, favored a situation with dominant upward flow at the vent because of no exhaust line in the fire room and fire position below the vent. The pressure difference at the vent is maximum ΔP_o=0.41 Pa. The second test, PR2_VSP_3, favored a situation with significant downward flow at the vent because of equilibrium of pressure and a limitation of local momentum imposed by the fire with its position away from the vent. The pressure difference at the vent prior to ignition is nul ΔP_o=0 Pa and corresponds to a regime of natural convection. The two tests, PR2_VSP_4 and PR2_VSP_4BIS, correspond to intermediate situations between the two first configurations. The test, PR2_VSP_4BIS, investigated the effect of the ventilation flow rate, in comparison to the PR2_VSP_4 test, by increasing the total renewal rate. The four tests proposed, therefore, several combinations for the two ventilation parameters (ΔP_o, Tr_{L3}), with increasing pressure difference and decreasing renewal rate: (0.41; 20.4) for test PR2_VSP_2, (0.20; 13.4) for test PR2_VSP_4BIS, (0.07; 8.2) for test PR2_VSP_4 and (0.; 8.5) for test PR2_VSP_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
$\dot{q}_{adm}^{L3}$	m³/h	2356	988	948	1546
$\dot{q}_{ext}^{L3}$	m³/h	0	1048	0	0
Tr_{L3}	h^{-1}	20,4	8,5	8,2	13,4
$\dot{q}_{adm}^{L4}$	m³/h	0	1451	1366	1324
$\dot{q}_{ext}^{L4}$	m³/h	2371	1460	2373	2967
Tr_{L3+L4}	h^{-1}	8,1	8,4	8,0	9,9
$\dot{q}_{vent}^{ref}$	m³/h	2338	-25	987	1611
ΔP_o	Pa	0,41	0,00	0,07	0,20

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

The experimental procedure was as follows. First the ventilation network was powered up to achieve the targeted ventilation flow rates. Then the heptane pool was ignited. A mixed convection flow started to occur at the vent, and smoke progressively filled the adjacent room. The fire extinguished by lack of fuel (PR2_VSP_2 test) or lack of oxygen in the room (the other tests).

EXAMPLE OF A TYPICAL BEHAVIOUR

The typical behavior of such real fire scenario is presented from the PR2_VSP_2 test with the ventilation configuration A3/E4. The burning rate of the 0.4 m² heptane pool shows a nearly steady behavior at about 23 g/s (cf. Figure 4). Before ignition, the air flow rates at the admission of room L3 and at the exhaust of room L4 are equal at about 0.75 kg/s (cf. Figure 5). Then, flame propagation leads to an expansion of the gas, an increase of the exhaust flow rate and a decrease of the admission flow rate. Once the steady behavior is recovered, the two flow rates become equal again. After 10 minutes of fire, the fire starts becoming unstable leading consequently to fluctuating behaviors of the flow in the ventilation branches (see Figure 5). These fluctuations correspond to unstable behavior of the burning rate during this period (cf. Figure 4).

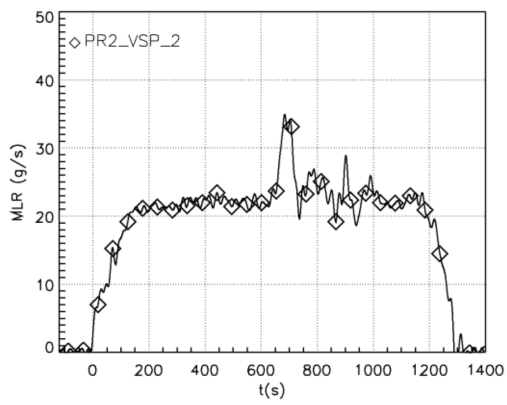

Figure 4: Time variation of the fuel mass loss rate for the test PR2_VSP_2

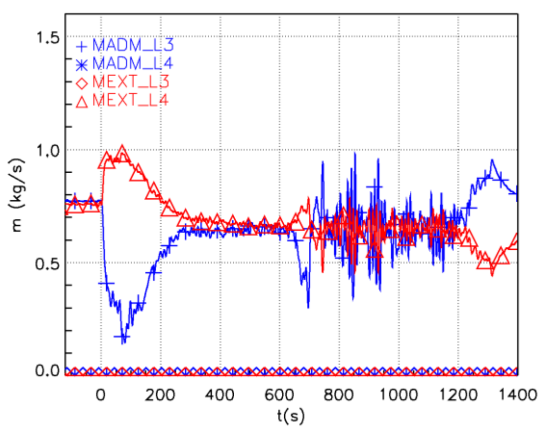

Figure 5: Time variation of the mass flow rates at the admission (ADM) line of room L3 and at the exhaust (EXT) line of room L4.

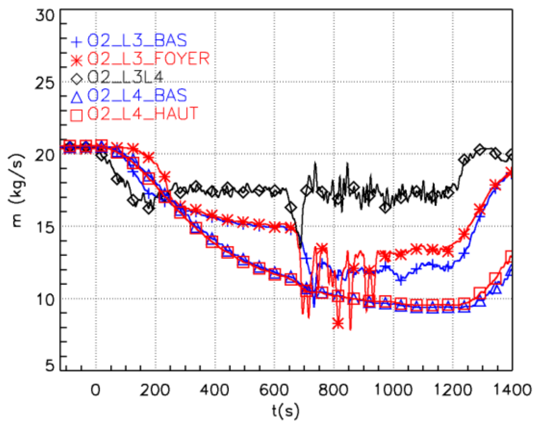

Figure 6: Time variation of the oxygen concentration at three positions in the two rooms L3 and L4 (low (BAS), near the pool (FOYER) and upper (HAUT)) and at the vent (L3L4)

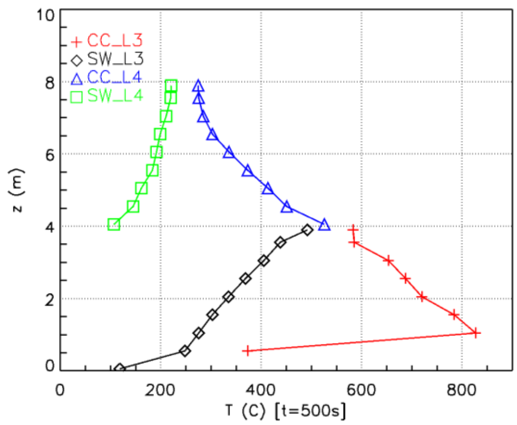

Figure 7: Vertical temperature profiles at the axis of the vent (CC) and on the SW axis in the fire room L3 (z=[0;4]m) and in the upper room L4 (z=[4;8]m) at t=500s.

The admission flow rate is not sufficient to compensate the oxygen consumption by the fire and the oxygen concentrations in the two rooms decrease continuously until a steady situation is reached (Figure 6). The oxygen concentrations in the upper room gives the lowest value (about 10%-vol), and is very homogenous in the room with no significant difference between the upper and the lower part (O2_L4_BAS and O2_L4_HAUT in Figure 6). The concentration in the fire room give higher levels (about 12%-vol) because of the fresh air brought by the admission line. The oxygen concentration measured at the vent is surprisingly higher than those in the two rooms. It is explained by the short distance between the vent and the inlet section that may induce local effect of fresh air entrance.

The smoke propagation within the two rooms leads to a specific vertical temperature distribution, illustrated in Figure 7. Along the fire plume axis (masts CC_L3 and CC_L4 in Figure 7) the temperature decreases from the flame temperature level (up to 800°C) toward about 450°C at the vent section and then 250°C at the ceiling of room L4. Away from this axis, the temperature profiles in the two rooms show an opposite variation with an increase from the ground to the ceiling (masts SW_L3 and SW_L4 in Figure 7). These profiles illustrate typical thermal stratification with higher temperature at the top of each room.

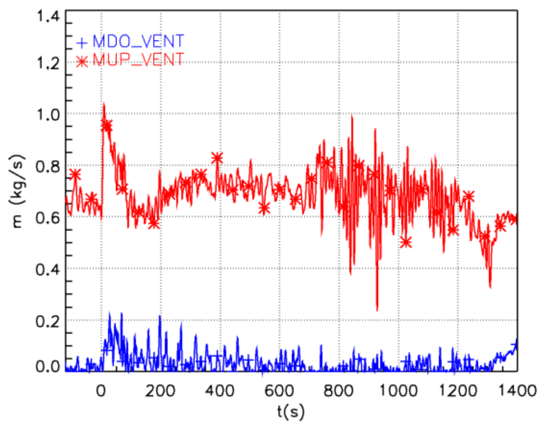

Figure 8: Time variation of the upward (UP) and downward (DO) air mass flow rate at the vent

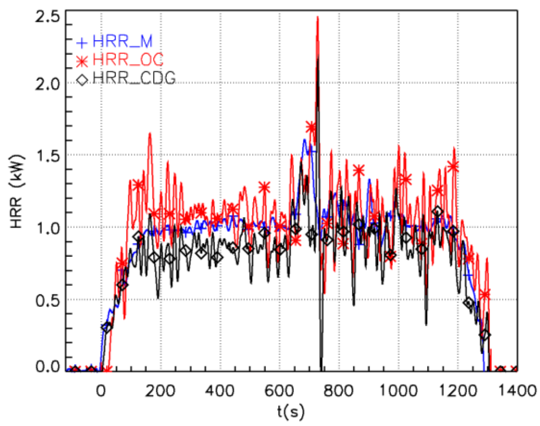

Figure 9: Time variation of the fire Heat release rate computed from mechanical (M), CDG and OC methods

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

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

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

SEVERAL BURNING RATE REGIMES

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

Reduction of the burning rate with the ventilation

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

For the highest ventilation rate of the lower room (PR2_VSP_2 test, Tr_{L3}=20.4 h^{-1}, i.e. $\dot{q}^{L3}_{adm}$=2356 m^3/h), the burning rate gives the highest level (about 23 g/s). This value is close to the one expected in open atmosphere (about 22 g/s, i.e. 54 g/s/m^2 obtained with the Babrauskas relationship, [24], with $\dot{m}_{f,\infty}$=100 g/s and $\kappa\beta$=1.1 m^{-1}). Then, extinction occurs after total combustion of the mass of fuel.

With a lower ventilation flow rate (PR2_VSP_4BIS test, Tr_{L3}=13.4 h^{-1}, i.e. $\dot{q}^{L3}_{adm}$=1546 m^3/h), the burning rate decreases to about 18 g/s, but only during a short period and then increases again rapidly up to 40 g/s followed by self-extinction due to lack of oxygen (fuel remains in the pan). For the two lowest rates of ventilation, (PR2_VSP_3 and PR2_VSP_4 tests, Tr_{L3}=8.5 h^{-1}, i.e. $\dot{q}^{L3}_{adm}$=988 m^3/h), the burning rate shows either a rapid self-extinction (PR2_VSP_3 test) or an oscillatory behavior followed by extinction due to lack of oxygen.

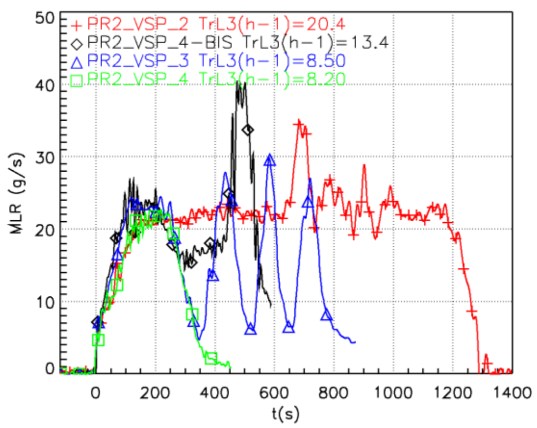

Figure 10: Time variation of the fuel mass loss rate for the four tests

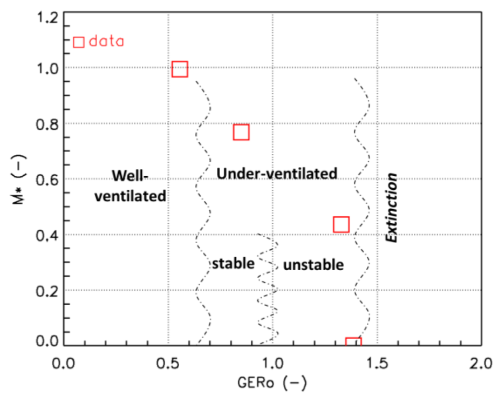

Figure 11: Normalized mean fuel mass loss rate versus the reference global equivalent ratio GERo

The reduction of the burning rate with the ventilation flow rate is typical to compartment fire scenario. This phenomenon depends, among other parameters, on the reference global equivalent ratio GER_o defined as the ratio between the rate of oxygen that is required for the combustion in open atmosphere, $r\ \dot{m}_{f,\infty}$, and the rate of oxygen brought to the enclosure by the mechanical ventilation, $Y_{O2,\infty}\ \dot{m}_{air,v}$, before ignition. The normalized fuel mass loss rate, $M^* = \dot{m}_f / \dot{m}_{f,\infty}$, diminishes with the increase of the GER_o (Figure 11) as expected and demonstrated theoretically for well-stirred reactor [25]. For the present data, different regimes of burning rate are identified depending on the range of GER_o. For GER_o lower than 0.5, the burning rate is similar to the one in open atmosphere ($M^* \sim 1$). In the range GER_o = [0.6 ; 1.3], the dimensionless burning rate decreases and the combustion regime can be said "under-ventilated". Above GER_o = 1.3, there is extinction, and the burning rate cannot be maintained. These limits are orders of magnitude determined from the present data. Between these two limits, there is a range [1 ; 1.3] where the burning rate is very unstable and oscillatory behaviors are observed. These regimes are very similar to those identified in natural ventilation by He & al [19]. In the present study with mechanical ventilation, the governing parameter GER_o includes the ventilation flow rate, whereas in the He's study; the governing parameter is the ventilation parameter, $A_v^{5/4}/\dot{Q}_f$, considering the vent size A_v only.

In the present study, the two parameters affecting the burning rate are the renewal rate of the fire room, Tr_{L3}, (and thus GER_o) that characterized the air brought by the ventilation but also the pressure difference at the vent, ΔP_o. This former variable specifies the likelihood of seeing downward flow at the vent and therefore the level of additional oxygen brought by the vent to the fire room. This additional effect explains the differences between the two tests PR2_VSP_3 and PR2_VSP_4 that show different results but with the same GER_o. These tests have the same Tr_{L3}, but two different values for ΔP_o.

Oscillatory behavior

For the PR2_VSP_3 test whom the conditions are close to the extinction limit, three large oscillations of the burning rate are observed with an average frequency of 6.7 10^{-3} Hz (average period of 148 s) and large amplitude of about 20 g/s for an average value of 14.8 g/s. These are typical to low frequency behavior and very similar to fire oscillations encountered in one forced ventilated room without vent [26]. They are explained as a coupling between the burning rate, the pressure in the room that governs the oxygen entrance and the convective time for the oxygen to reach the burning area. This oscillatory behavior can also be related to several recent studies showing the occurrence of oscillatory fire and ghosting flame phenomena with vent in naturally ventilated room, without mechanical ventilation [19], [27]. The present tests demonstrate that similar unsteady behaviors can be encountered between scenarios with or without mechanical ventilation or/and vent. The common features are the under-ventilated conditions, specified among others parameters with GER_o, but also the capability of having a strong coupling between the burning rate and an admission of air (naturally or forced through a vent or a regular admission pipe) associated with a time delay.

Critical pool size leading to self-extinction

When dealing with compartment fire equipped with ceiling vent, an important issue for the design is the critical vent area under which no steady combustion is maintained and self-extinction occurs, because the flow rate of oxygen coming from the vent is not sufficient to ensure combustion. In natural convection, without mechanical ventilation, recent studies with pool fires show that the critical vent size is about 2 to 10 times higher than the pool area [20] [27]. Applying this criteria to the present study, a critical vent size of 1 m^2 corresponds to a range of pool fire area of [0.1 ; 0.5] m^2. The 0.4 m^2 pool fire considered in the present tests corresponds therefore to a critical pool size that could have led to self-extinction without mechanical ventilation (natural ventilation case). The present data confirms that self-extinction can be expected if the ventilation flow rate is low (test PR2_VSP_4). If the ventilation flow rate is increased as it is done for the other tests, steady combustion phase can be achieved due to the additional feed of oxygen.

CONSCEQUENCES ON THE VENT FLOW

Flow regimes

The flow at the vent is governed by temperature and pressure differences from both side of the opening. With no pressure difference, the flow is bi-directional with equal flow rate in both directions. With a non-zero pressure difference, induced by the forced ventilation for instance, the flow is unbalanced. For pressure difference above the critical pressure (or purge pressure), the flow becomes one -directional upward or downward according to the sign of the pressure difference. For the present tests with variable fire heat release rate, the vent flow varies with time following the time variation of the fire. The upward and downward mass flow rates are presented in Figure 12. The four tests with three ventilation configurations, A3/E4, A34/E34 and A34/E3, are sorted according to the initial pressure difference at the vent, ΔP_o.

For test PR2_VSP_2 with A3/E4 configuration, the flow is mainly upward and nearly no downward flows are measured (Figure 12). The corresponding initial vent pressure difference is 0.41 Pa. The test PR2_VSP_3 with ΔP_o=0 Pa leads to bidirectional flow with equal upward and downward flows similar to a situation encountered for natural ventilation. This result confirms that the reduction of the initial pressure difference contributes to decrease the upward flow and to increase the downward flow. This result demonstrates also that bidirectional regime at the vent, corresponding to natural convection case, can be encountered with mechanical ventilation scenario, provided the ventilation is set-up with no pressure difference at the vent, which is the case with the ventilation configuration A34/E34.

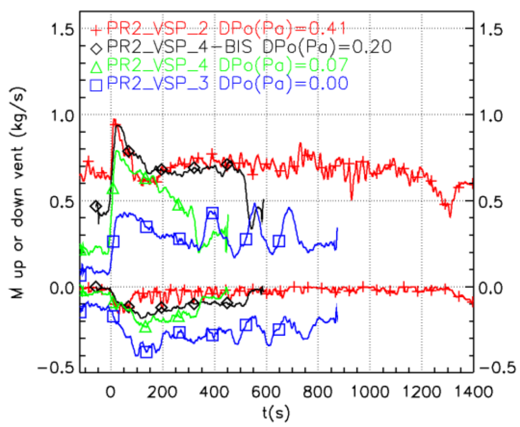

Figure 12: Time variation of upward and downward mass flow rate at the vent for the four tests

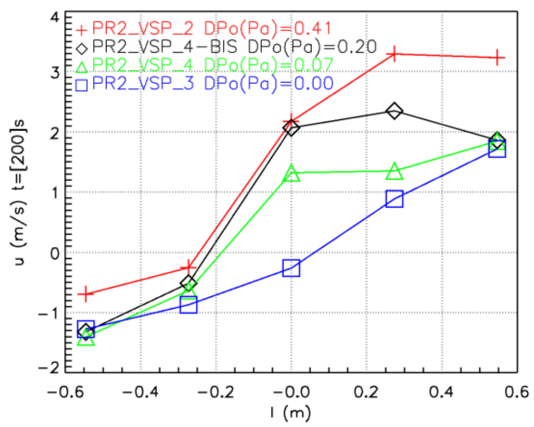

Figure 13: Vertical velocity profiles in a diagonal of the vent at t=200s for the four tests

The effect of the pressure difference at the vent is also noticed on the velocity field. Figure 13 compares the velocity profiles in one diagonal of the vent. With no initial pressure difference at the vent, ΔP_o = 0 Pa for test PR2_VSP_3, the velocity profile shows a form with equal downward and upward flows. The increase of the initial pressure difference contributes to unbalance the flow with an increase of the upward flow and a reduction of the downward one. The initial pressure difference at the vent is an appropriate parameter to characterize the flow regime and the distribution between the upward and downward flow.

Contribution of the downward flow to the fire room

An important issue for the understanding of the burning rate variation is to assess the contribution of the downward flow to the total amount of air available for combustion in the fire room. Figure 14 presents the time variations of the downward flow rate at the vent, of the admission flow rate, from the ventilation and of the sum of the two terms. The tests are characterized by two parameters, the renewal rate Tr_{L3}, that specified the admission flow rate in the fire room and the initial pressure difference at the vent, ΔP_o, that characterized the flow regime and thus the weight of the downward flow.

Figure 15 presents the average contribution of each term over the whole duration of the combustion phase versus the initial pressure reference at the vent.

The ventilation configuration A3/E4 (test PR2_VSP_2 with [ΔP_o, Tr_{L3}]=[0.41 ; 20.4]) is the one that brings the largest amount of air, mostly by the ventilation, with nearly no air coming from the vent. This configuration leads to the larger level of burning rate with steady regime.

The configuration A34/E34 (test PR2_VSP_3 with [ΔP_o, Tr_{L3}]=[0.0 ; 8.5]) is the one that gives equal contributions from the admission line of the ventilation and from the vent, but also the largest amount of downward flow. This configuration corresponds to the test where oscillatory burning rate are encountered. The downward flow is then an important criterion in the occurrence of oscillatory of the burning rate.

From Figure 15, it is noticed that the test PR2_VSP_4 with configuration A34/E4 leads to the lowest total amount of air entering the fire rooms. This result is in accordance with the time variation of the burning rate that shows rapid extinction due to lack of oxygen.

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

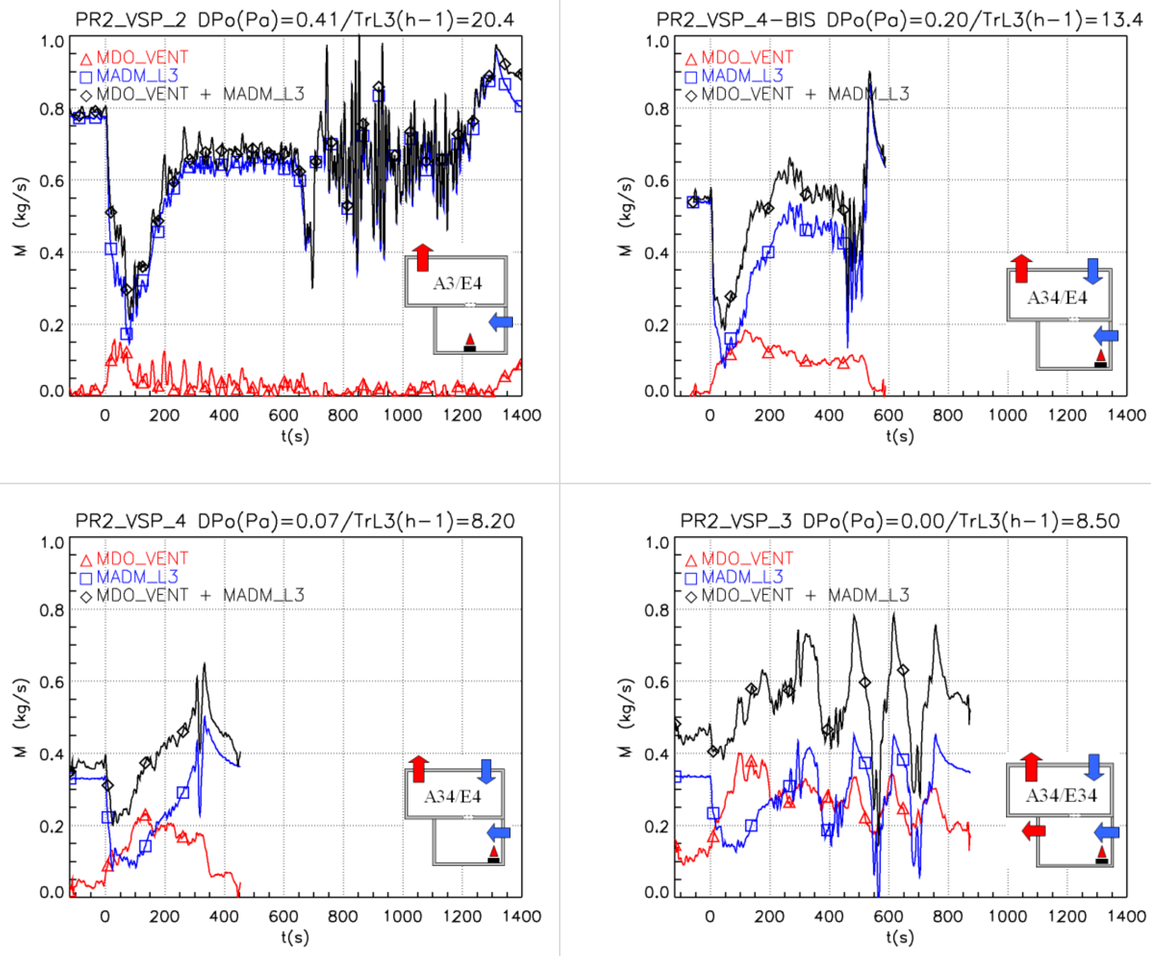

Figure 14: Time variation of the mass flow rates entering the fire room by the ventilation (MADM_L3) and by the vent (MDO_VENT) for the four tests

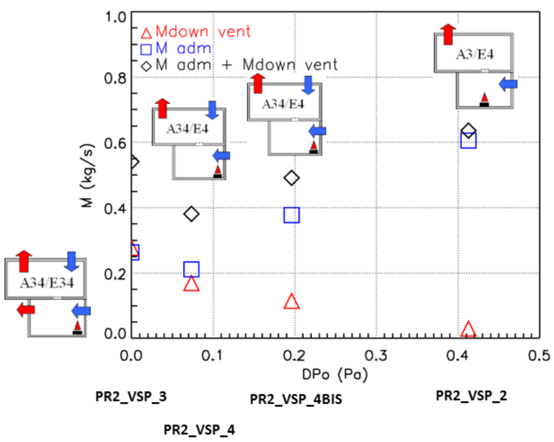

Figure 15: Mass flow rate entering the fire room by the ventilation (M adm) and by the vent (Mdown vent) versus the initial pressure difference at the vent ΔP_o

DOWNWARD FLOW ANALYSIS FROM NUMERICAL SIMULATIONS

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

Numerical software ISIS

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

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

Validation of the ISIS simulation

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

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

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

The comparisons of mass flow rates at the vent are also presented the three tests Figure 17 (left columns). There is also a good agreement between experiments and simulations. The three regimes of flow at the vent are correctly predicted by the simulations: mainly one directional upstream for test PR2_VSP_2, bidirectional with equal contribution in both directions for test PR2_VSP_3 and an intermediate regime for test PR3_VSP_4 (bidirectional but with a dominant upward flow in comparison to the downward flow). This result demonstrates that the equilibri-

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

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

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

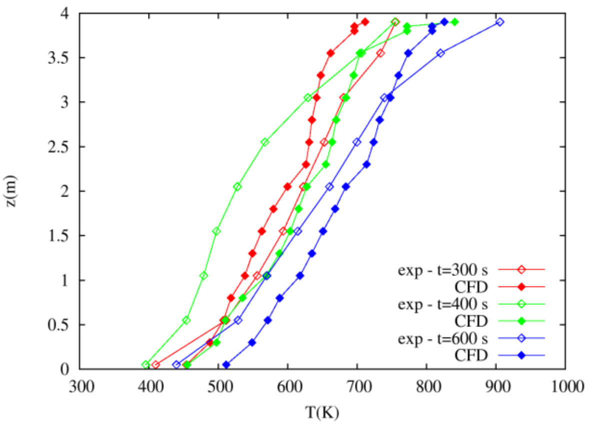

Figure 16: Comparison between the experimental and numerical gas temperature in the fire room at three times for the test PR2_VSP_3.

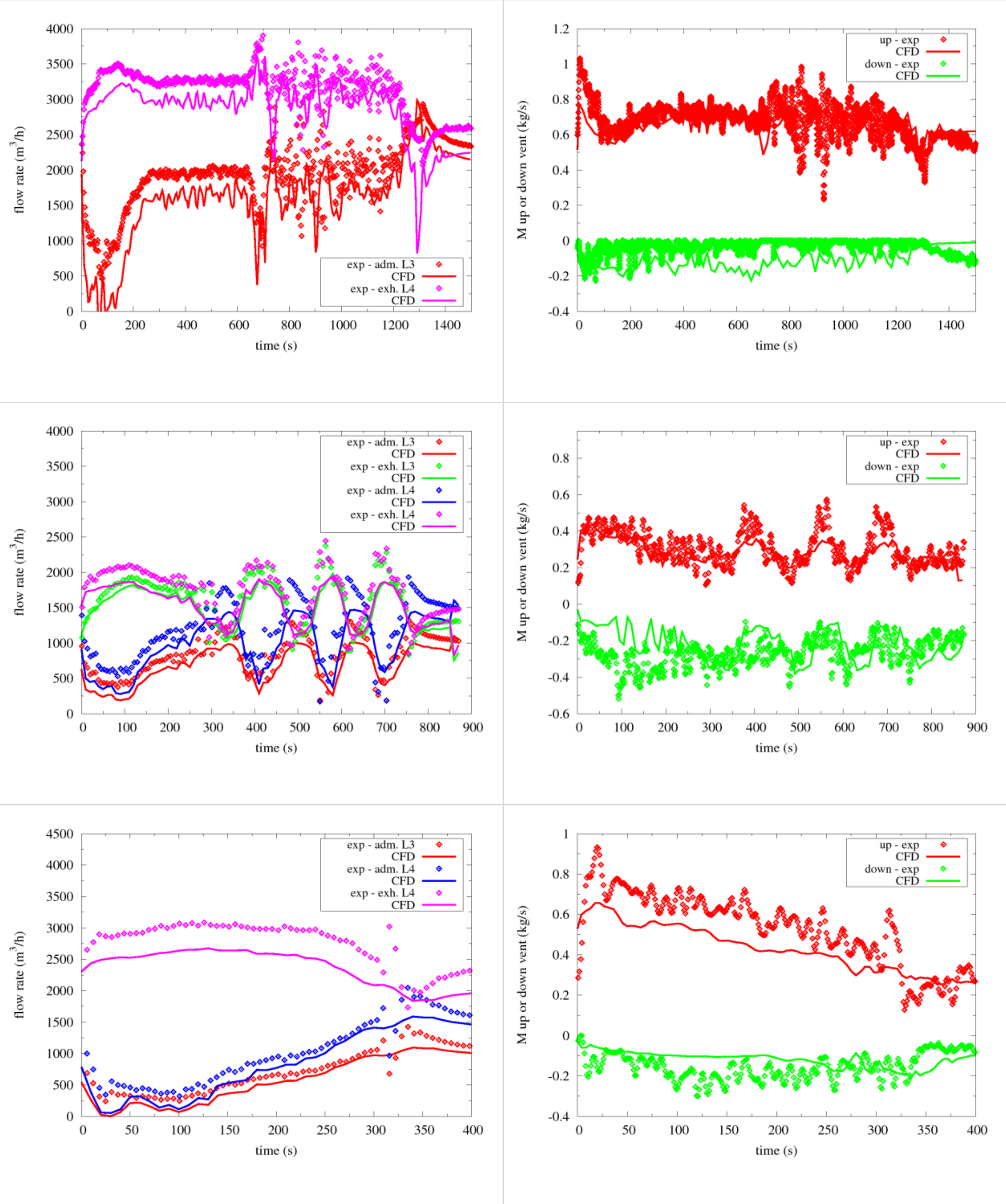

Figure 17: Comparison between the experimental and numerical flow rates in the admission and exhaust branches of the ventilation (left columns) and at the vent (right columns) for the three tests PR2_VSP_2 (one admission in room L3 and one exhaust in room L4), PR2_VSP_3 (one admission and one exhaust in both rooms) and PR2_VSP_4 (two admissions in rooms L3 and L4 and one exhaust in room L4)

Flow pattern induced by the downward flow

In order to better describe the way the downward flow is transported in the fire room, numerical simulations of the flow field in the fire room are investigated. The analysis of the oxygen concentration fields superimposed with the velocity field is presented in Figure 18 for two tests PR2_VSP_3 and PR2_VSP_4 for which the downward flow is significant. The downward flow is characterized by higher oxygen concentrations and by vertical downward velocities that can reached at least the mid-height of the fire room and nearly the ground level for test PR2_VSP_3 (Figure 18 - a). These velocity fields attest that the downward flow is not re-entrained by the smoke in the vicinity of the vent but can deeply penetrate the lower room and contributes to feed the burning regions with "fresh" air. This result may be an element that explains the oscillatory behavior of the burning rate. The way the oxygen is brought to the fire room by the downward flow, possibly with a time delay, may be a condition for unsteady behavior of the burning rate.

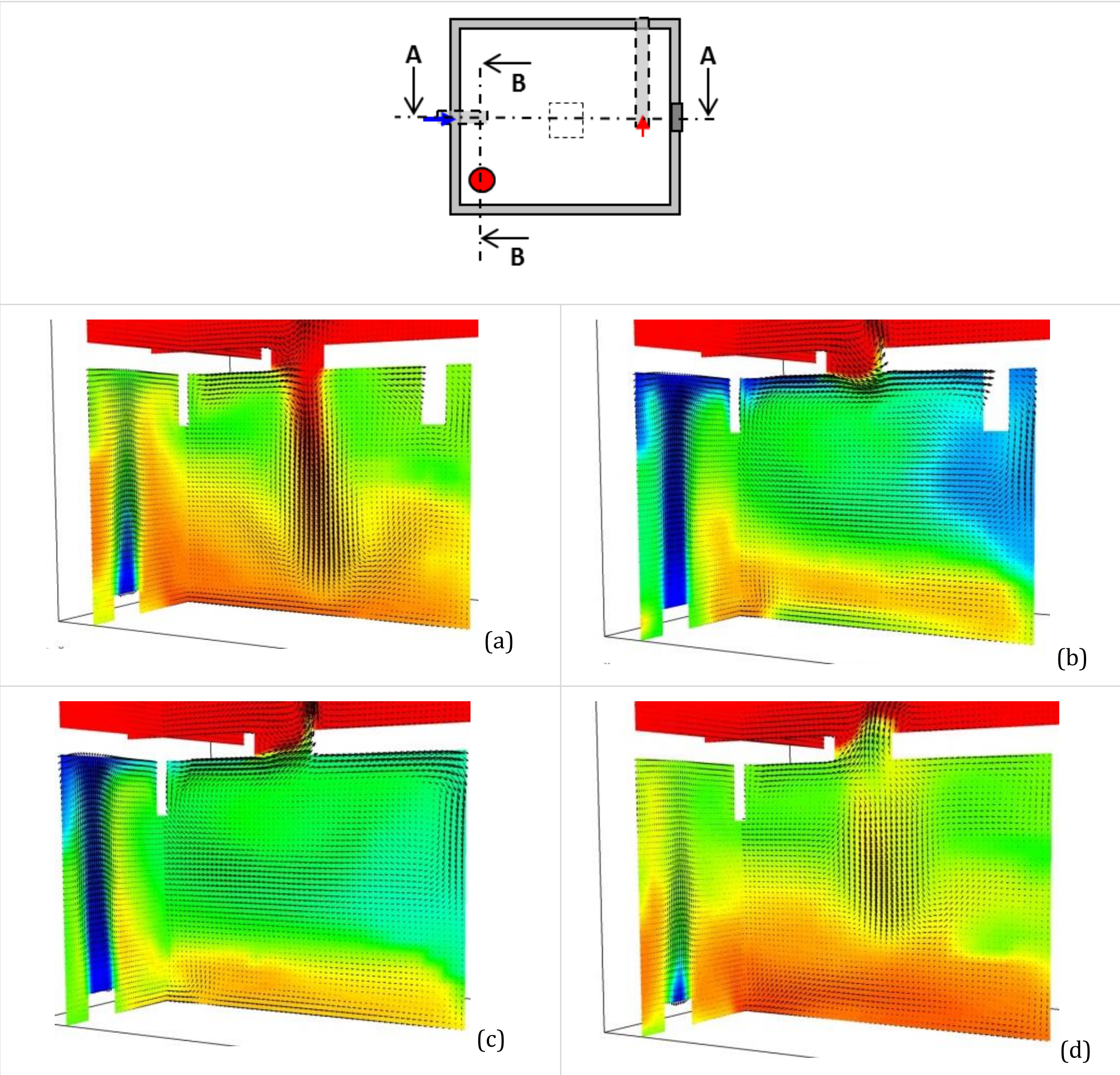

Figure 18: Superimposed gas velocity field and oxygen concentration field : (a) and (b) PR2_VSP_3 test, AA and BB plans at two times, (c) and (d) PR2_VSP_4 test, AA and BB plans at two times,

CONCLUSION

This work deals with a phenomenological investigation of fire scenario within two rooms, mechanically ventilated and connected together with a horizontal vent. The objective is to investigate the effect of a horizontal opening on a fire scenario in confined and forced ventilated enclosures. A set of large scale experiments performed in the framework of the OECD PRISME-2 project in the multi-room facility DIVA of IRSN are considered. The scenario consists of two rooms mechanically ventilated and linked with a horizontal vent of 1 m^2. The fire is heptane pool fire located in the lower room. Three specific configurations of ventilation are investigated leading to different flow regime at the vent from one directional upward to bidirectional. The analysis focuses on the coupling between the burning rate, the flow at the vent and the configuration of the mechanical ventilation. The main conclusions are listed below.

- Several regimes of combustion are encountered from steady well ventilated to under-ventilated unsteady and oscillatory fire. The burning rate is controlled by both the mechanical ventilation and the downward flow from the vent.
- The downward flow at the vent can be significant and can permit to ensure combustion for specific configuration of the ventilation. The amplitude of the downward flow is a key element in the onset of unstable oscillatory fires. The flow regime at the vent and the prediction of the downward flow are therefore of importance in the global understanding of the fire scenario.
- Numerical simulations with the ISIS fire field model reproduced correctly the flow fields in the rooms, provided the burning rate is set as a boundary condition. The simulations provide a better description of the flow field induced by the downward flow and its ability to supply “fresh air” in the fire area.

This study has highlighted that the fire scenario involving mechanical ventilation and a vent remains a challenging issue both experimentally and numerically.

REFERENCES

[1] A. Mercer and H. Thompson, "An experimental investigation of some further aspects of the buoyancy-driven exchange flow between carbon dioxide and air following a depressurization accident in a Magnox reactor - Part I the exchange flow in inclined ducts," *Journal of the British Nuclear Energy Society,* vol. 4, pp. 327-334, 1975.

[2] A. Mercer and H. Thompson, "An experimental investigation of some further aspects of the buoyancy-driven exchange flow between carbon dioxide and air following a depressurization accident in a Magnox reactor - Part II the purging flow requirement," *Journal of British Nuclear Energy Society,* vol. 4, pp. 335-340, 1975.

[3] J. Perry, "Critical flow through sharp-edged orifices," *Trans. American Society of Mechanical Engineers,* vol. 71, pp. 757-764, 1949.

[4] W. G. Brown and K. R. Solvason, "Natural convection through rectangular openings in partitions," *International Journal of Heat and Mass Transfer,* vol. 5, pp. 859-881, 1962.

[5] M. Epstein and M. A. Kenton, "Combined natural convection and forced flow through small openings in a horizontal partition, with special reference to flows in multicompartment enclosures," *Journal of Heat Transfer,* vol. 111, pp. 980-987, nov 1989.

[6] M. Epstein, "Buoyancy-driven exchange flow through small openings in horizontal partitions," *Journal of Heat Transfer (Transactions of the ASME),* vol. 110, pp. 885--893, 1988.

[7] G. Heskestad and R. Spaulding, "Inflow of air required at wall and ceiling apertures to prevent escape of fire smoke," *Proceeding of the third Symposium on Fire Safety Science,* pp. 919-928, 1991.

[8] Q. Tan and Y. Jaluria, "Flow through horizontal vents as related to compartment fire environments," *NIST-GCR-92-607,* 1992.

[9] L. Cooper, "Calculation of the flow through a horizontal ceiling/floor vent," *NISTIR 89-4052,* 1989.

[10] L. Y. Cooper, "Calculating combined buoyancy- and pressure-driven flow through a shallow, horizontal, circular vent: Application to a problem of steady burning in a ceiling-vented enclosure," *Fire Safety Journal,* vol. 27, pp. 23--35, 1996.

[11] H. Pretrel, J. Liberati, O. Vauquelin and L. Audouin, "Smoke flow through a horizontal vent separating two mechanically ventilated rooms from large scale fire tests," in *13rd International Conference on Fire Research and Engineering (Interflam)*, 2013.

[12] K. Varrall, H. Pretrel, S. Vaux and O. Vauquelin, "Stereoscopic Particle Image Velocimetry Investigation of the Bidirectional Natural Convection Flow Through a Horizontal vent," *Fire Technology,* vol. 52, no. 6, 2016.

[13] K. Varrall, H. Pretrel, S. Vaux and O. Vauquelin, "Stereoscopic particle image velocimetry investigations of the mixed convection exchange flow through a horizontal vent," *Experiments in fluids,* vol. 58, no. 151, 2017.

[14] B. Hagglund, P. Werling and S. Bengtson, "An experimental study of the smoke spread in a two plane compartment," in *Proceedings of the third Asia-Oceania symposium on fire science and technology*, 1988.

[15] H. Pretrel, K. Varrall, O. Vauquelin and L. Audouin, "Smoke induced flow in two rooms mechanically ventilated and linked with a horizontal vent type opening," *11th Internationnal Symposium of fire Safety Science,* 2014.

[16] H. Prétrel, R. Sayada, K. Varrall, L. Audouin and O. Vauquelin, "Experimental study based on large-scale smoke propagation fire tests through a horizontal opening connecting two mechanically ventilated compartments," *Fire Safety Journal,* vol. 90, pp. 28-43, 2017.

[17] A. Dai and M. Garcia, "Buoyancy-Driven Flow in a Two-Story Compartment," *Journal of Engineering Mechanics,* vol. 135, pp. 738-742, 2009.

[18] Z. Li, *Characteristics of Buoyancy Driven Natural Ventilation through Horizontal Openings,* PhD Thesis - Aalborg University, 2007.

[19] Q. He, O. A. Ezekoye, C. Li and S. Lu, "Ventilation limited extinction of fires in ceiling vented compartments," *International Journal of Heat and Mass Transfer,* vol. 91, pp. 570--583, 2015.

[20] Q. He, C. Li and S. Lu, "Vent size effect on self-extinction of pool fire in a ceiling vented compartment,"

in *Procedia Engineering, 62, pp242-249*, 2013.

[21] Q. He, C. Li, S. Lu, C. Wang and J. Zhang, "Pool Fires in a Corner Ceiling Vented Cabin: Ghosting Flame and Corresponding Fire Parameters," *Fire Technology,* vol. 51, pp. 537--552, 2015.

[22] A. Chen, Q. Li and Y. Wang, "Investigation of the burning mechanism in an enclosure fire with a horizontal ceiling vent," in *Procedia Engineering*, 2016.

[23] L. Audouin, H. Pretrel and S. Vaux, "Experimental and Numerical Study of Smoke Propagation Through a Vent Separating Two Mechanically Ventilated Rooms," in *14th Internationnal Post-Conference Seminar on Fire safety in Nuclear power plants and installation (Post-SMIRT-23)*, 2015.

[24] V. Babrauskas, "Estimating large pool fire burning rates," *Fire Technology,* vol. 19, pp. 251--261, 1983.

[25] H. Pretrel, S. Suard and L. Audouin, "Well-stirred reactor approach for interpreting the combined effect of oxygen and temperature on the steady burning rate of pool fire in a confined and ventilated enclosure," in *Journées Internationales de Thermique (JITH)*, Marseille, 2015.

[26] H. Pretrel, S. Suard and L. Audouin, "Experimental and numerical study of low frequency oscillatory behaviour of a large-scale hydrocarbon pool fire in a mechanically ventilated compartment," *Fire Safety Journal,* vol. 83, pp. 38--63, 2016.

[27] B. Chen, S. Lu, C. Li and M. Yuan, "Analysis of compartment fires with a ceiling vent," in *Procedia Engineering, 62, pp258-265*, 2013.

[28] H. Emmons and T. Tanaka, "Vent Flows," *The SFPE Handbook for Fire Protection engineering - 4th Edition,* vol. 2, pp. 37-53, 2008.

[29] L. Y. Cooper, "Combined buoyancy- and pressure- driven flow through a horizontal vent : theorical considerations," NIST IR 5252, 1993.