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EXPERIMENTAL AND NUMERICAL STUDY OF FIRE EVENT INVOLVING TWO SIMULTANEOUS FIRE SOURCES IN CONFINED AND VENTILATED COMPARTMENTS

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ABSTRACT

The study deals with fire events involving two simultaneous fire sources in a confined and ventilated set of enclosures. Within the framework of fire safety assessment in nuclear facilities, it aims at investigating two configurations, one with two fire rooms separated by an adjacent empty room and a second one with two adjacent fire rooms. The objective is to analyse how a secondary fire may influence a primary fire, the flows at doorways and the overall smoke propagation. Some experimental results obtained for two large scale fire tests performed with gas burners are discussed. A specific analysis of the level of temperature in the fire rooms and in the adjacent room is presented. Numerical simulations with a zone approach are performed and satisfactory agreements are found between calculations and experimental data. The study shows that the distance between fires in case of multiple fire event is an important parameter. Close fires lead to an increase in aggression around the fire place whereas distance fire contributes to maximize the smoke temperature and therefore the aggression in the neighbouring area around fire places.

INTRODUCTION

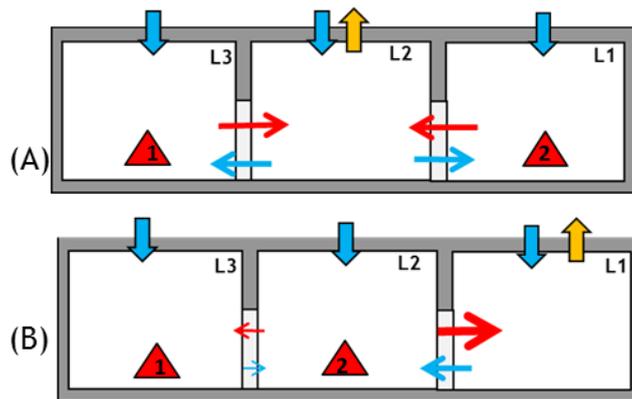
Fire event involving several fire sources simultaneously is a concern for fire safety assessment activities as well as for fire protection design. Multiple fires in the same environment make more complex the fire scenario and the associated physical phenomena. These scenarios are specific and the resulting physics should be better understood as well as reliably predicted. Such scenarios are encountered in open industrial plans with many potential fire sources¹. They are also of concern in case of post-earthquake events for which several sources may ignite simultaneously. Fire event in tunnels or in parking places are also frequent scenarios involving several sources. A particular feature of multiple fire source events is the extent of the damage they can cause. Therefore, they require particular attention in terms of fire safety assessment and fire protection design. Although this type of fire event remains frequent, the amount of researches remains rather weak in comparison to stand alone fire scenarios. A first issue in the understanding of multiple fire events is the fire merging process. This process is closely related to the distance between fires as well as to the environmental conditions, like wind that can favour or not the merging process. First studies appear in the sixties and investigate experimentally the burning of several sources leading to mass fire^{2,3} or arranged in array of sources close to each other⁴⁻⁷ or with only two fires^{8,9}. The results of these experiments show that the fire resulting from the merging of several single sources can lead to much more severe fires than the arithmetic sum of each single fire. Criteria for having merging flame and the features of the resulting fire (flame height and temperature, air entrainment) are investigated with different fire sources (pool fire, wood cribs, gas fire). Multiple fire scenarios may also lead to non-merging flame in case of sufficiently large distances between fires. For such scenarios, main scientific issues concern the interaction between fires and the associated smoke propagation. Configurations of interest are mainly fires in confined spaces as in tunnels, parking places or enclosures (ventilated or not). The specific topics of interest concern the effective radiative heat fluxes emitted by several fires and the

smoke propagation induced in the vicinity of the fires as well as far away (vertical stratification, room filling, flows through openings) ¹⁰⁻¹⁴.

The present research focuses on the second issue and in particular on scenarios with several forced ventilated enclosures where two fires may occur simultaneously. The objective is to study smoke propagation in case of multiple fire scenario in a set of ventilated rooms. Applications concern fire safety assessment in nuclear power plant. A basic configuration has been defined with two fires in an arrangement of three rooms connected together with doorways, the whole set being connected to a ventilation network (Figure 1). Two fire scenarios have been investigated. A first one with two fire rooms separated by an adjacent empty room and a second one with two adjacent fire rooms. The objective is to investigate how a secondary fire (fire N°2 in Figure 1) may influence a primary fire, especially the flow exchanges at doorways and the overall smoke propagation. The analysis focuses on the specific smoke propagation and the room temperature distribution.

The study comprises three stages. First, an experimental study, based on a propane gas fire, has been performed to characterise temperature rise in both configurations. Then, test results are compared to numerical simulation performed with the SYLVIA zone fire model. A third part proposes extrapolation analysis from SYLVIA predictions for other practical configurations in order to enlarge the understanding of multi-fire scenarios.

Figure 1: Schematic of the two configurations.



EXPERIMENTAL STUDY

Test facility, measurement techniques and test grid

The test set-up is part of the DIVA facility of IRSN and comprises three 110 m^3 rectangular rooms, named L1, L2 and L3, ($L = 4.87 \text{ m} \times 1 = 3.84 \text{ m} = 22.5 \text{ m}^2$ and $H = 5.87 \text{ m}$) connected together with doorways of dimensions 2.10 m by 0.80 m (see pictures of room in Figure 2). Walls consist in 35 cm or 40 cm thick re-enforced concrete and the ceiling is covered with silicate of calcium panels to thermally insulate the wall. The ventilation network consists in one admission line in each room and one exhaust line located in the room without fire (L2 or L1 according to the configuration as illustrated in Figure 1). The inlet and exhaust sections of 0.18 m^2 are situated in the upper part of the room at about 0.80 m from the ceiling. The ventilation lines are connected to an industrial ventilation network equipped with blowing and exhaust fans. The fire sources are propane gas burners located at the center of the rooms.

Propane flow rate was measured with a mass flow-meter. The corresponding fire heat release rate (HRR) is determined considering the combustion efficiency equal to one and the effective combustion enthalpy equal to 46.4 MJ/kg . Air flow rates in ventilation lines were measured with

average Pitot probe devices, connected to pressure transducers. Gas temperature and pressure as well as gas species concentrations were also measured in the ventilation lines. Rooms were equipped with a large set of sensors for measuring gas and wall temperatures, radiative and total heat fluxes, velocity at doorways, gas species concentrations. The present work only focused on gas temperature. Temperature stratification in rooms was measured from 1.5 mm K-type thermocouples (uncertainty of $\pm 4^{\circ}\text{C}$) positioned on five vertical masts located at the center of the room and distributed in the four corners. Video cameras were also positioned in each room.

Figure 2: Pictures of the three rooms L1, L2 and L3 in DIVA facility



The study is based on two sets of experiments corresponding to configurations A and B illustrated in Figure 1. Fires are set in rooms L3 and L1 for configuration A and in rooms L3 and L2 for configuration B. The difference between the two configurations is therefore the distance between fires. For configuration A, fire rooms are separated with an adjacent room without fire, whereas the fire rooms are contiguous for configuration B. Regarding the ventilation set-up, each room is equipped with an admission line in both configurations. The exhaust line is located in the room with no fire (L2 for configuration A and L1 for configuration B).

For both configurations, the varying parameter is the secondary fire HRR. It mimics a situation with a main fire in one room and a secondary fire occurring simultaneously in another room. For all experiments, the fire heat release rate in room L3 is set to a constant level, about 278 kW, the varying parameter being the second fire HRR (in room L1 for configuration A or in room L2 for configuration B) that varies between 71 kW and 350 kW (see Table 1). The first test corresponds to a reference test with only one fire in room L3, at constant fire HRR of 279 kW.

Table 1: test matrix with the fire heat release rate during the steady phase (B1 tests correspond to configuration A and B2 tests correspond to configuration B, the test names are those given during the experimental program).

	B1P1	B1P2	B1P3	B1P4	B1P5	B1P6
HRR L3 (kW)	279	279	279	277	279	273
HRR L1 (kW)	0	71	140	210	280	351

	B2P2bis	B2P3	B2P4	B2P5	B2P6
HRR L3 (kW)	279	278	279	279	279
HRR L2 (kW)	71	141	211	279	348

Prior to ignition, the ventilation regime is set to the same operating conditions for all experiments with an air flow rate of $1200 \text{ m}^3/\text{h}$ in each room and a resulting flow rate of $3600 \text{ m}^3/\text{h}$ at the exhaust (in room L2 or L1). The flow rate corresponds to a renewal rate of $\text{Tr} = q_v/V = 10.9 \text{ h}^{-1}$ (with the volume of one room $V = 110 \text{ m}^3$). The test procedure is as follows: first the ventilation network is set to the targeted ventilation flow rate. Then gas burners are turned on simultaneously in the two rooms for a period between 1200 s to 1400 s such as steady state is reached.

Results

As an example, Figure 3 presents time variations of fire HRRs in rooms L3 and L2 for configuration B tests. Fire HRRs are constant with time during all experiment. For configuration B, fire HRR is constant in room L3 and varies from one test to another for room L2. Figure 4 presents an example of gas temperature rise in the three rooms for test B2P3 (HRR_{L3} = 271 kW and HRR_{L2} = 141 kW). Gas temperature rises up to a quasi-steady state after time 1000 s. The temperature is greater in the room having the largest fire HRR (here room L3 with 278 kW). The adjacent room with no fire gives the lowest temperature. The temperature in the second fire room L2 with 141 kW gives temperatures between the two extrema.

Figure 3: Time variation of the fire HRRs in the two rooms, L3 and L2 for configuration B.

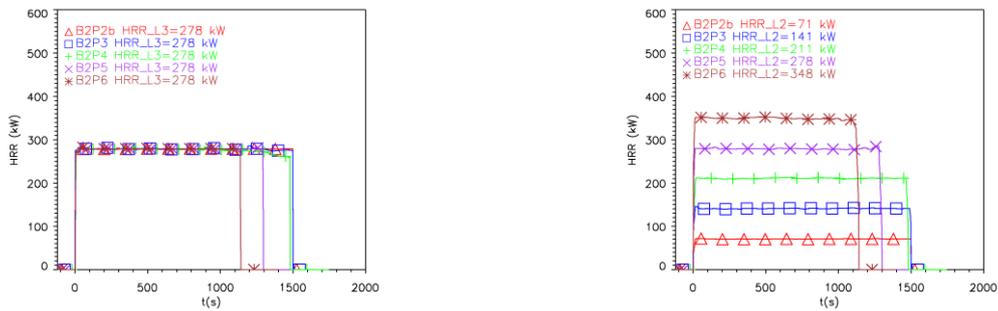
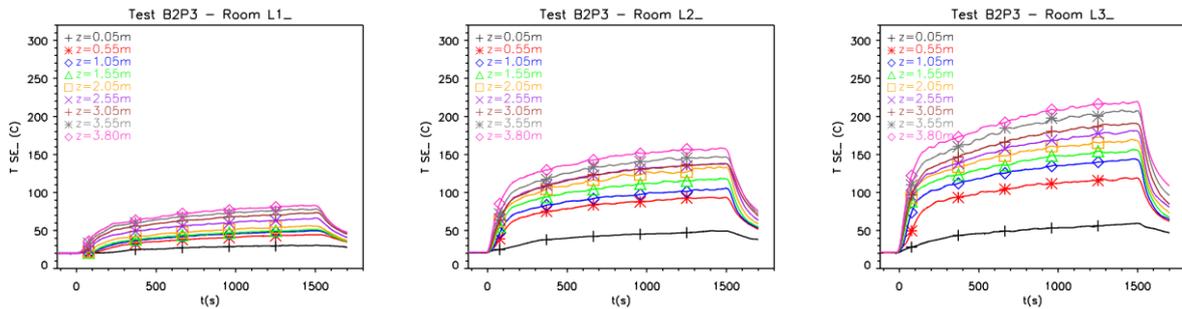
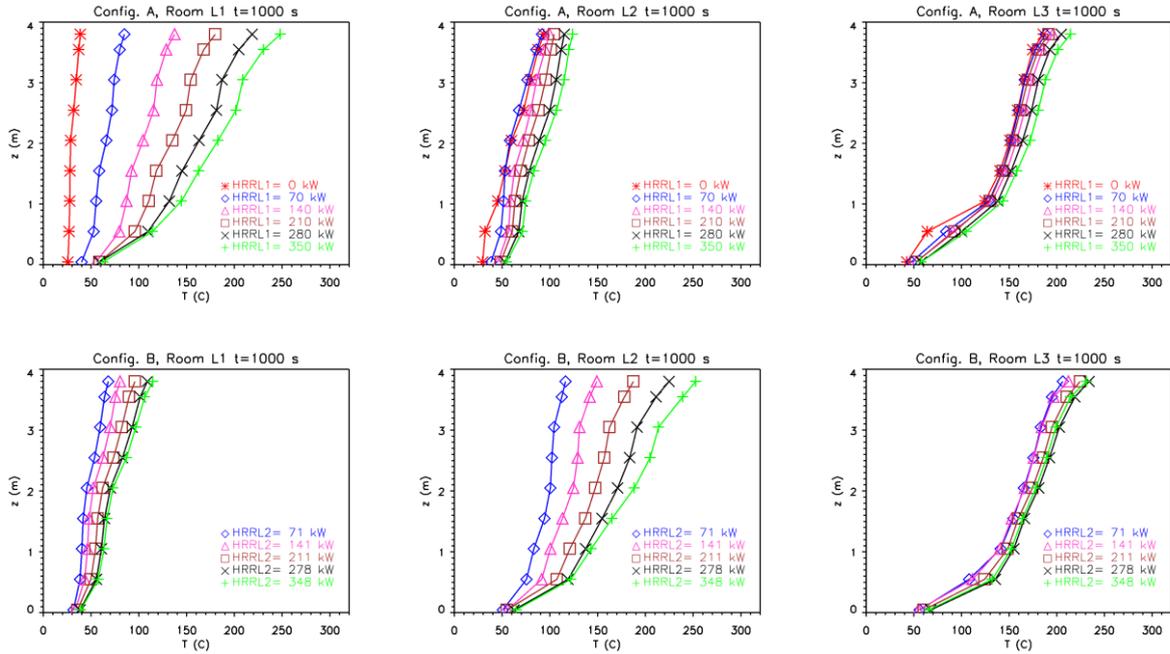


Figure 4: Time variation of gas temperature in one mast in room L1, L2 and L3 for test B2P3.



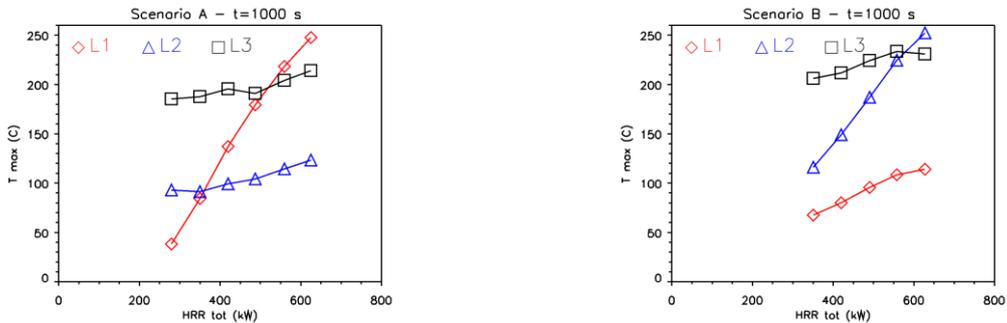
For each room, average vertical temperature profile is determined considering the four masts located in the room corners. These average temperature profiles in each room at $t=1000$ s for the two configurations are presented in Figure 5. For all tests, the temperature profile shows a vertical thermal stratification with higher temperature in the upper part of rooms. However, these stratifications differ between rooms. Temperature profiles in the L3 fire room with constant fire HRR of about 278 kW remain similar for all tests with two temperature gradients, the first one with the strongest gradient (about $100\text{ }^{\circ}\text{C}/\text{m}$) in the first meter from the floor, and the other one above with a gradient of about $40\text{ }^{\circ}\text{C}/\text{m}$. Moreover, the amplitude of temperature increases slightly because of the global increase of the total fire heat release rate $\text{HRR}_{\text{tot}} = \text{HRR}_{\text{L3}} + \text{HRR}_{\text{L1 or L2}}$. In both configurations, the second fire contributes to increase the temperature in the primary fire room. Even if fires are in separate rooms, they do not behave independently. Temperature profile in the adjacent room with no fire shows different shapes between configuration A and B. The vertical temperature gradient is constant in configuration A (with about $12\text{ }^{\circ}\text{C}/\text{m}$) whereas the gradient increases with the increase in fire HRR for configuration B (from 5 to $15\text{ }^{\circ}\text{C}/\text{m}$). These results show that the relative position of the two fire sources modifies the thermal consequences in the adjacent room. In the secondary fire room, the vertical temperature profile shows also a constant gradient which increases with the fire HRR. It is worth noting that for all rooms, temperature profile does not show two homogenous layer stratification but layers with constant gradient. These are typical behaviours observed in confined spaces.

Figure 5: Average temperature profiles in each room at time $t=1000$ s for configurations A (first row) and B (second row).



In order to compare the scenarios with each other, analysis focuses on the maximum temperature reached in each room (at the highest position in the room). This maximum temperature is plotted as a function of the total fire HRR for the two configurations in Figure 6. For both configurations, the room having the highest temperature increase is the fire room where the HRR varies between tests (L1 for configuration A and L2 for configuration B). The temperature in the adjacent room with no fire also increases because of the increase of the total fire HRR_{tot} . In this case, the convective heat is mainly propagated through the doorway. As previously noticed, the temperature in the primary fire room L3 does not remain constant despite a constant fire HRR, but also increases. The secondary fire room also influences the temperature in the primary fire room by limiting the release of smoke through the doorways.

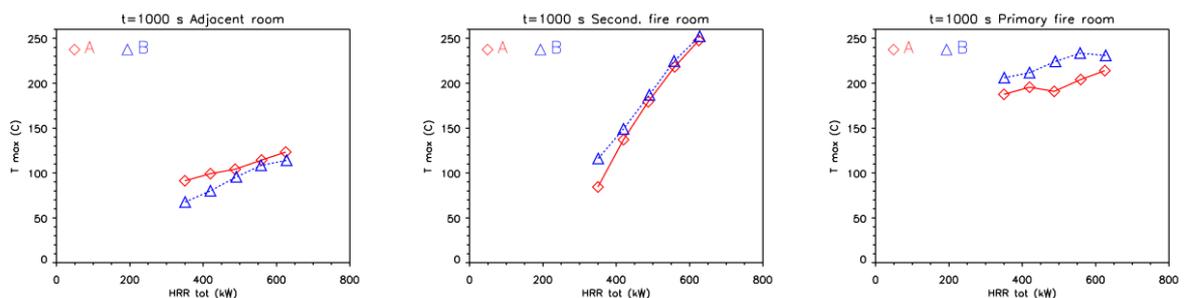
Figure 6: Maximum temperature in the three rooms versus the total fire heat release rate for configurations A (left plot) and B (right plot)



The comparison between the two configurations, A and B, is illustrated in Figure 7. Configuration B leads to a higher temperature in the primary fire room L3. A second fire in a room contiguous to the main fire room contributes to limit smoke propagation at the doorway and therefore to confine heat in the fire room L3. This configuration is the more unfavourable for temperature in the

fire room. Conversely, configuration A leads to a higher maximum temperature in the adjacent room with no fire in enhancing smoke propagation from both fires in the adjacent room. From the point of view of temperature in the adjacent room without fire, the configuration A is the more severe scenario. However, if the concern is the maximum temperature whatever the room, configuration B is the worst scenario with the highest maximum temperature in the fire room L3. The relative position of two fire sources modifies the smoke propagation. In configuration A, the smoke produced by the two fires is released by two doorways whereas it is released by only one doorway in configuration B.

Figure 7: Effect of the configuration on the maximum temperature in, from left to right, the emptied adjacent room (L1 or L2), the secondary fire room (L2 or L1) and the primary fire room (L3) versus the total fire heat release rate.



COMPARISON WITH ZONE CODE MODELING

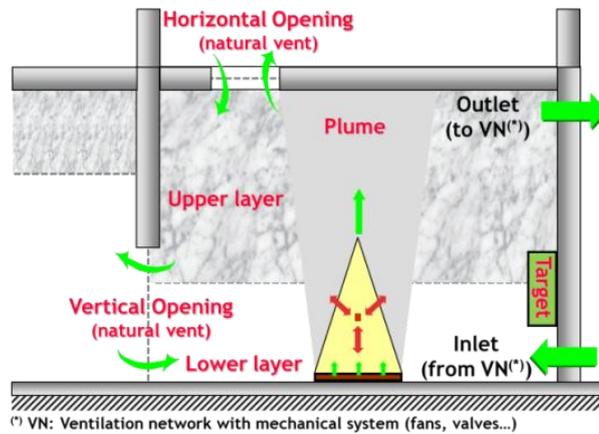
In order to assess the capability of the SYLVIA zone code to take into account multiple fire sources in confined and mechanically ventilated enclosures, test data are compared to numerical simulations. The zone code approach has been chosen for its capability to simulate several complex and large scale scenarios with limited computational times.

Code description and inputs

The SYLVIA software¹⁵ was developed at IRSN. It is designed to predict the behaviors of mechanical/natural ventilation, fire growth, hot gas and smoke propagation, and airborne contamination transfer in confined and mechanically ventilated enclosures. It is a simulation tool for calculating the consequences of multi-compartment fires in industrial and nuclear facilities, which are equipped with a full ventilation network (including ducts, room leaks, fire dampers, fans, horizontal/vertical openings, filters...). The fire design of the SYLVIA software belongs to the well-known two-zone fire modeling¹⁶⁻¹⁷. In such software, each compartment is described with two Lagrangian control volumes separated by a thermal interface (Figure 8). Mass and energy balances are performed in each zone: the lower zone simulating the fresh gas and the upper zone simulating the combustion products and the gas entrained by the plume. In a two-zone approach, a plume feeds the upper zone of the fire room, whose volume increases, which has the effect of lowering the interface and leading to the under-oxygenation of the fire source if the gas flow in the exhaust duct or at the level of openings of the fire room is not sufficient to remove all gases supplied by the plume. The features of ambient quantities (pressure, temperature, mass fraction of species) in each control volume are assumed to be uniform at a given time. These control volumes can be connected by various ventilation components representing either natural or mechanical ventilation. The convective/conductive/radiative heat transfers inside the compartments and in the ventilation network (walls, gas phase) are fully modelled and play a major role for predicting temperature and pressure, especially in rooms and ventilation ducts near the fire. The fire itself is described by correlations (plume, flame height...) available in the literature¹⁶⁻¹⁷. Furthermore, the SYLVIA software has additional specific models for simulating a water spray system, the condensation/adsorption of

gaseous species (as water vapour) on walls, and the transport and deposition of aerosol particles (soot, dust) on solid surfaces as ventilation ducts, room walls or High Efficiency Particulate Air filters.

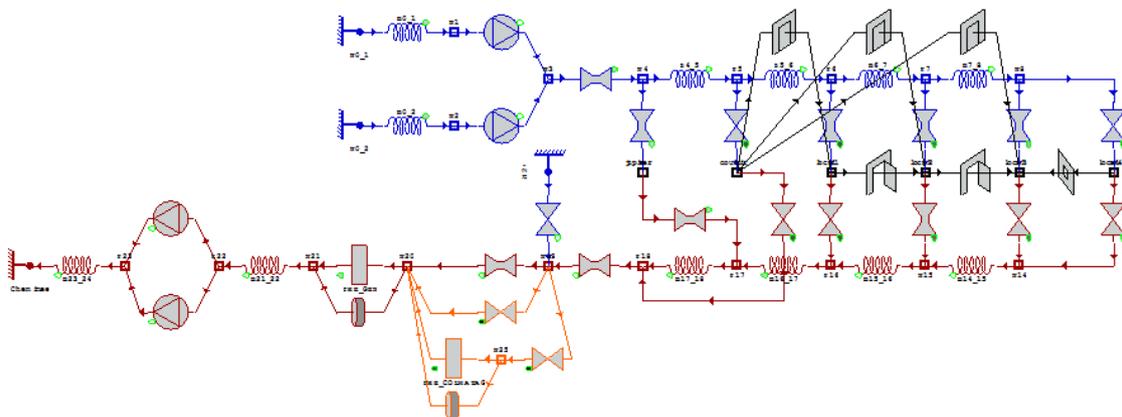
Figure 8: Two-zone approach of fire compartments.



The design of ventilation network is based on the node-and-branch method¹⁸. A node is a point (no volume) or a simple zone (with a fixed volume) in the ventilation network, where the different physical quantities (pressure, temperature, particle and gaseous species mass fractions) are considered uniform. A point can be considered as a simple junction between two or more ducts or linked with an exterior environment (boundary condition node). A zone, which leads to inertial effects under transient conditions due to the fixed volume, may involve a single room (as the fire compartment) or a node between two branches. A branch represents a passive element of the network (for instance, duct, filter, fire damper, leak, etc.) or an active element (for instance, fan, motor-driven valve, etc.). A mass flow rate is assumed to be uniform in 0D branches and is a function of the pressure difference at its boundaries (nodes). A given branch is always connected to two nodes, but there is no limit on the number of branches connected to a given node.

SYLVIA modelling of the ventilation network of the DIVA facility is reported in Figure 9. Various nodes and branches of the modelled ventilation network correspond to aerualic elements for which experimental measurements (pressure, temperature, volume flowrate) were performed. Thus, this modelling allows reproducing at best the experimental aerualic resistivity of the ventilation network of the fire tests in the simulations.

Figure 9: SYLVIA modelling of the ventilation network of the fire tests.



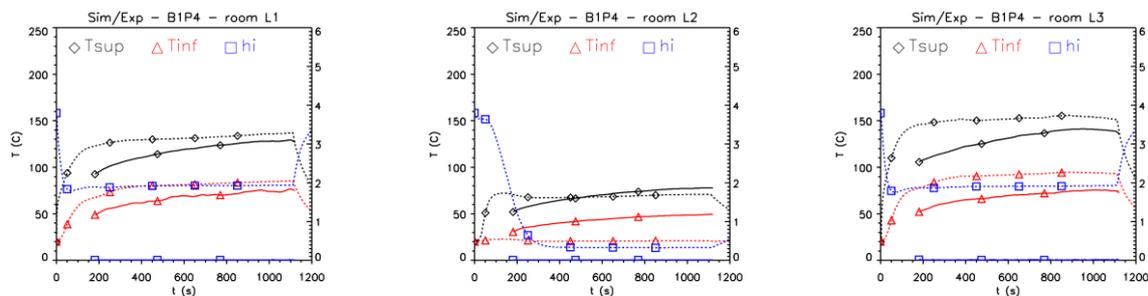
Determination of zone code variables from experimental data

Validation is made on upper and lower gas layer temperatures. Experimental gas layer temperatures are obtained from regression methods applied to mean vertical temperature profile in each room for a given time. Several regression methods are available for processing vertical temperature profiles. In the present work, the method used is the one proposed by Pretrel & al¹⁹ which considers the thermal stratification as two layers, a lower one with constant temperature (the lower temperature) and an upper one with a constant vertical temperature gradient (linear increase of temperature with elevation). This theoretical description is the one that best fits experimental temperature profiles, ie, that minimizes the difference between theoretical and experimental profiles. For each test, experimental upper and lower temperatures as well as the interface height are determined for each time step, in the three rooms and for all tests. The upper layer temperature is the average temperature of the upper layer.

Validation

An example of comparison is presented in Figure 10 for test B1P4 (configuration A with a fire HRR of 277 kW in room L3 and a fire HRR of 210 kW in room L2). Temporal variations of upper (T_{sup}) and lower (T_{inf}) temperatures and the interface height (h_i) in each room obtained from tests and from SYLVIA predictions are compared. The agreement is satisfactory for the upper layer temperature, and this is true for all the tests. Regarding the lower layer temperature and interface height, larger discrepancies between test data and simulations are reported. This is mainly due to the fact that these scenarios lead to small lower layer and consequently to a large discrepancy in predicting its characteristics, thickness and temperature.

Figure 10: Comparison between experiment (plain line) and simulation (dotted line) for the upper lower and interface height (from left to right) for test B1P4 (configuration A) (if $h_i=0$, then T_{inf} is the temperature of the first temperature probe).



Then for each test, the upper layer temperature at $t=1000$ s is compared between test data and SYLVIA predictions, and the whole set of data are presented in Figure 11. Predictions and tests reproduce the same behaviour previously analysed in Figure 6 for the maximum experimental temperature. The average discrepancies between simulations and test data are 13% and 6% for configurations A and B respectively, which are considered as satisfactory.

In addition, the comparison of the calculated upper layer temperatures between the two configurations A and B is also presented in Figure 12. Variations of the predicted upper layer temperature show the same trends as for the experimental maximum temperature. However, the differences observed during the tests for the maximum temperatures between the two configurations are not as pronounced with calculated layer temperatures. With SYLVIA predictions, both configurations give similar results regarding the upper layer temperature. This result indicates that in terms of mean temperature (average temperature of the upper layer), the two configurations are

similar. Differences between the two configurations concern more specifically local variations of temperature especially near the ceiling that cannot be highlighted by the two layer simulations..

Figure 11: Upper layer temperature from simulations (SYL) and tests (EXP) at time t=1000 s in the three room and for configuration A (left) and B (right)

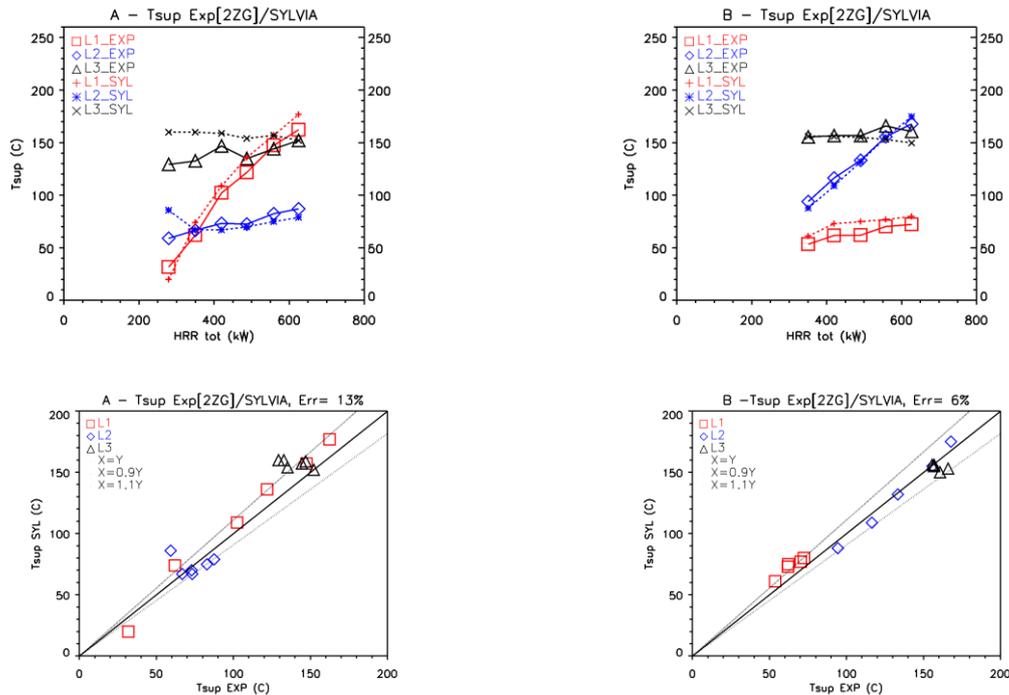
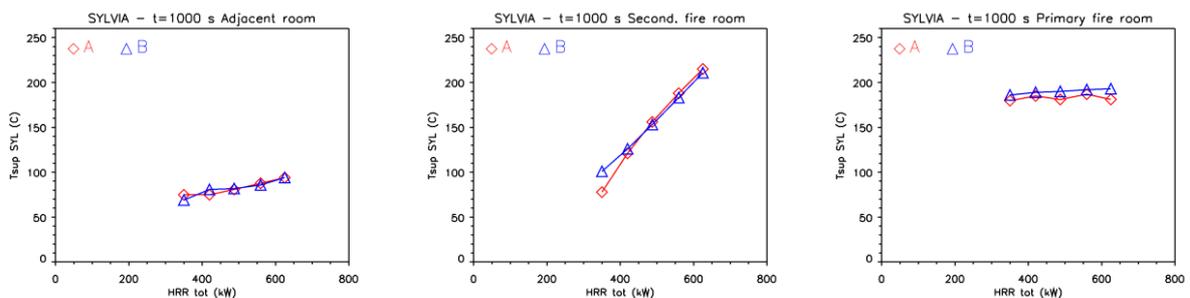
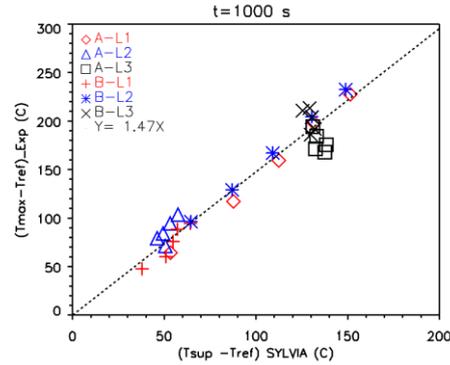


Figure 12: Effect of the configuration on the upper layer temperature predicted by SYLVIA code, from left to right, in the room without fire (L1 or L2), the secondary fire room (L2 or L1) and the primary fire room (L3) versus the total fire heat release rate.



Nevertheless, an interesting result emerges from the comparison between test data and SYLVIA predictions: a correlation seems to exist between the experimental maximum temperature and the predicted upper layer temperature. An issue when performing zone code calculation is the relation between the upper layer temperature predicted and the real maximum temperature that can be expected in the enclosures. As illustrated in Figure 13, the maximum gain of temperature measured during tests ($T_{max}-T_{ref}$) is compared to the gain of temperature predicted by SYLVIA code ($T_{sup}-T_{ref}$). The maximum temperature (near the ceiling) is about 1.47 greater than the upper layer temperature. This ratio certainly depends on the type of thermal stratification reported for these fire scenarios and other stratifications could have given different values. Nevertheless, this analysis leads to a practical criterion that can be considered for assessing maximum gas temperature from zone code calculations in the experimental configurations used for this study.

Figure 13: Correlation between the upper temperature predicted with SYLVIA code and maximum experimental temperature measured in the room



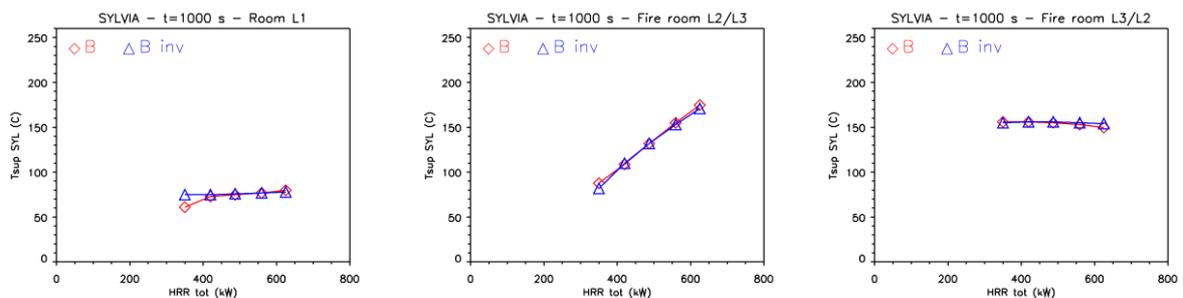
SIMULATIONS OF COMPLEMENTARY CONFIGURATIONS

Based on the previous validation, other multiple fire scenarios are considered only from zone code predictions. The aim of these simulations is to analyse some other configurations in order to see whether similar conclusions can be drawn concerning multiple fire scenarios.

Scenario B inverted

A first configuration is the scenario B in switching rooms L2 and L3 in order to investigate the effect of fire relative positions. This scenario named "B inverted" consists in locating the fire with larger HRR in room L2 and the varying fire HRR in room L3. These predictions aims at investigating if the position of the primary fire has an influence on the results given with scenario B. Results are presented in Figure 14 with a comparison of the upper layer temperature increase in each room. As expected from the previous analysis, there is nearly no difference in the two fire rooms. Whatever the relative position of the two fires regarding the open doorway, the mean smoke temperature (ie. the upper layer temperature) is identical. Differences are only noticed on the adjacent room with no fire. The scenario that leads to the highest temperature in the adjacent room is the one where the strongest fire is contiguous to the adjacent room. Smoke propagation through the doorway is more effective and then a greater amount of convective heat is transported towards the adjacent room. Regarding smoke temperature in the adjacent room, multiple scenarios sorted from the more to the less severe scenario are scenarios A, B inverted and B. Doorways are an efficient means for propagating smoke and the doorway near to the greatest fire source is more favourable for smoke propagation.

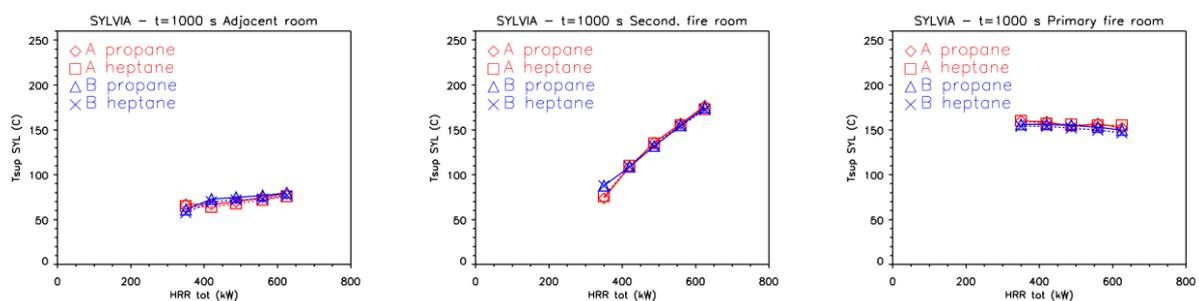
Figure 14: Effect of the configuration (B and B inverted) on the upper layer temperature in, from left to right, the adjacent room with no fire (L1), the secondary fire room (L2 or L3) and the primary fire room (L3 or L2) versus the total fire heat release rate



Scenario A and B with pool fire

A second set of simulations is performed with configurations A and B but using heptane instead of propane gas (used in the experiment). This change in the fuel type aims at considering more realistic configurations rather than propane gas fire suitable when performing parametric analysis with large scale fire tests. Regarding the numerical modelling, the change of fuel implies other parameters for predicting the effect of oxygen depletion on the burning rate. Simulations presented in the validation section are performed with the same fire HRR in each room. Results are compared in Figure 15. Very few differences are noticed between the two set of simulations. The change of fuel does not modify the conclusions presented in the previous section.

Figure 15: Effect of the effect of fuel on the upper layer temperature in, from left to right, the emptied adjacent room (L1 or L2), the secondary fire room (L2 or L1) and the primary fire room (L3) versus the total fire heat release rate



CONCLUSION

The objective of this study was to investigate the behaviour of multiple fire sources in a confined and ventilated set of enclosures. Scenarios with two fires have been considered with various distances between fires. Experimental results obtained from fire tests with propane burner in DIVA facility have been analysed. A comparison with simulation results obtained with the SYLVIA zone code was then proposed in order to validate the predicting tools for such scenarios. In a final part, simulations of other scenarios have been discussed to see whether similar conclusions could be drawn concerning multiple fire sources.

The study highlights that the relative position of fires in case of multiple fire scenarios is of importance for the consequences of a fire event. Scenarios with fire sources located far apart may contribute to reach higher temperatures in adjacent rooms. Fire interactions are weak and heat efficiently propagates in adjacent rooms. Scenarios with close fire sources may contribute to reach higher temperatures in the fire rooms. Fire interactions are stronger and areas where fire places are located may lead to higher temperatures than in cases where the fire sources are far apart.

A second important conclusion concerning multiple fire scenarios relates to local effects. In the experimental configurations used for this study, the differences between the multiple fire scenarios have mainly local effects (maximum temperature near the ceiling for instance). But in terms of global behaviour, the fire event behaves in a fairly similar way as the same fire scenario with one equivalent fire source instead of several sources. In term of layer temperature, the zone code approach is appropriate and IRSN SYLVIA code gives satisfactory results. However, if the local effects are of interest, CFD simulations are necessary.

This study brings also information regarding the relationship between the upper layer temperature given by the zone code prediction and the effective maximum temperature expected during a fire event. In the experimental configurations used for this study, the simulations show that

the maximum measured temperature is about 1.5 times higher than the upper layer temperature predicted with a zone code approach.

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