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Benjamin Betting, Emilien Varea, Carole Gobin, Gilles Godard, Bertrand Lecordier, et al.. Experimental and Numerical investigations of the flow characteristics in confined fires. *Journal of Physics: Conference Series*, 2018, 3rd European Symposium on Fire Safety Science 12–14 September 2018, Nancy, France, 1107 (4), pp.042015. 10.1088/1742-6596/1107/4/042015 . hal-01935655

**HAL Id: hal-01935655**

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Submitted on 24 May 2024

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To cite this article: Benjamin Betting *et al* 2018 *J. Phys.: Conf. Ser.* **1107** 042015

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## Experimental and Numerical investigations of the flow characteristics in confined fires

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### ABSTRACT

Fire compartments are of major concern since they are responsible for fatal accidents. The decision and response times of rescue teams are mainly based on human decisions which result from empirical approaches. Since compartment fires are multi-physical and multi-scale problems, a perfect knowledge of the situation is impossible. A fundamental approach of fire compartments which involves fluid mechanics is of great interest. One of the main issues concerns the transition from located to generalized fire. The most important vehicle leading to generalized fires results in smoke transport. Indeed, temperatures are very high and many species are mixed. In this study, an experimental facility composed of a maritime container is set-up. In parallel, numerical simulations -Fire Dynamics Simulator (FDS) software- based on a LES approach, are used. This dual approach makes it possible to validate the FDS code in ventilated and under-ventilated conditions, considering both the temperature fields and the flow dynamics. The compartment fire allows power up to 1MW. Temperature fields are measured with thermocouples racks, and velocity fields are obtained by large scale Particle Image Velocimetry (PIV). The objectives of the paper are: I) compare and analyze temperature fields from both experimental and numerical data, II) introduce preliminary results on large scale PIV measurements located at the smoke exit. Data are also compared with simulations and III) check the numerical assumptions.

### KEYWORDS:

*Large scale PIV, enclosure fire, numerical simulations, FDS, smoke dynamics, under-ventilated conditions.*



## INTRODUCTION

Nowadays, the decision-making of the emergency services is done during the fire intervention and it is mainly based on a rapid analysis. This analysis comes from the experience gained over the years but also during the training given by the Firefighter fire simulators. However, this type of analysis does not allow for a complete knowledge of the disaster since it is mainly based on an empirical knowledge. The evolution of fire, the appearance of a secondary focus or some thermal phenomena, i.e. back-draft [1, 2] or flash-over, [3, 4, 5], are especially feared by the rescue services. Besides, they are difficult to predict with accuracy. All these factors may lead to fatal accidents.

In order to optimize and secure the intervention of rescue services, the knowledge of fires, dynamics and risks represent a major interest. One of the main aspects remains in determining the smoke dynamics at the openings where fresh air and hot fumes mix. Theoretical knowledge on this phenomenon will improve the understanding of smoke flows, particularly at the outlets, [6]. This particular phenomenon is the so called pulsating fire and has been extensively studied, [7-9]. The direct link between the mass of the flow and the air entrained by the plume justifies the interest in this work [10].

Fundamentally, analyzing temperature, velocity and pressure and their sensitivity in the development of a fire is of first importance, [11]. To study smoke dynamics with non-intrusive diagnostic, PIV in large scale can be used [12, 14]. However, few studies exist on the use of this technique for under-ventilated fires analysis. Indeed, the National Institute of Standards and Technology studied fire dynamics in enclosure at the doorway and in the axis of the fireplace, from the outside [15]. In this study, velocities were measured from the inside, for HRR until 1MW.

Besides, to complement this study, numerical simulations, using FDS code are done. The objectives of this work are to study smoke velocity and smoke dynamics and compare the evolution of the experimental and numerical temperature profiles.

## EXPERIMENTAL AND NUMERICAL SET-UP

### Experimental set-up

To investigate the smoke dynamics characteristics in real fires, an experimental test bench was set-up. The thermal phenomena studied in this experimental test bench are likely to be encountered by firefighters during their missions. This cell is composed of two maritime containers mounted perpendicularly, one is the measure cell and the other one is the test cell, see Fig 1.

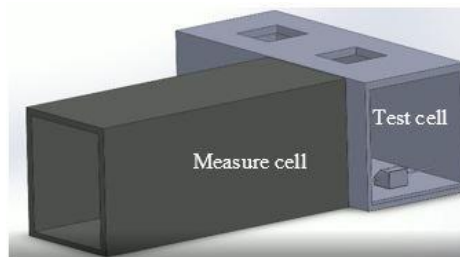


Fig. 1. Experimental set-up configuration.

The standard size of a maritime container is 6 x 2.59 x 2.45 m. These structures have emerged as training tools in rescue services. Moreover, the volume of these containers is close to that of a room of a standard flat, which is of 40 m<sup>3</sup>, approximately.

The fireplace consists in 36 burners fueled with propane covering a 1 square meter surface. This configuration enables to reach a power of 1 MW and temperatures around 800 °C.

Propane was chosen because it produces little soot compared to a real compartment fire. Indeed, it has the advantage of being perfectly controlled and it guarantees the reproducibility of the experiments.

A large optical access of 1 m<sup>2</sup> enables both, the visualization and the possibility to implement advanced laser diagnostics such as Particle Image Velocity (PIV), [16-17]. This configuration is represented on Fig. 2.

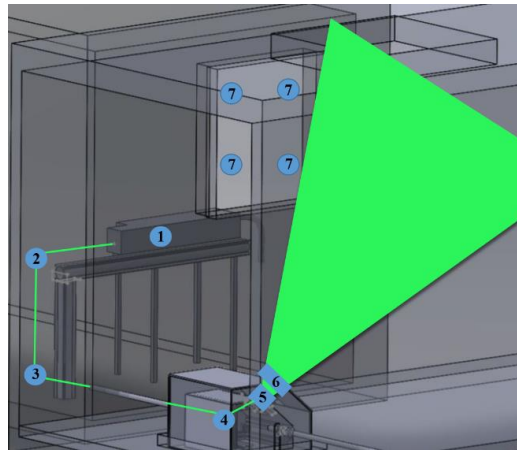


Fig. 2. View of PIV setup.

The laser is represented by number 1, the mirrors by 2, 3 and 4, the optical lenses in 5 and 6 and number 7 shows the position of cameras.

Large scale PIV is a complex task since a compromise between spatial resolution, and field of view exists. To overcome the issue, a special configuration is set-up. Instantaneous, two-dimensional velocity measurements relied on particle image velocimetry (PIV) in which alumina particles are used ( $\sim 50\mu\text{m}$  diameter). These particles are injected through an in-house air supply corona which is positioned below the burner. Special care is given to inject particles without modifying the fresh air injection dynamics. As low as 10% of air to reach stoichiometric condition is used to feed to burner with particles seeded air. The light source is a Nd:Yag laser (Quintel QSmart,  $2 \times 400$  mJ/pulse) combined with a -20mm cylindrical lens to produce a 0.5mm thick laser sheet. Mie scattering from the particles is collected on 4 CCD (Charge-Coupled Device) cameras (JAIRM4200, 12 bits,  $2048 \times 2048$  pix<sup>2</sup>) mounted with 50mm f/1.2 Zeiss lens. A 532 interferential filter reduces noise from ambient light sources. The optical arrangement yields a magnification of 5 pix/mm, calibrated using images of a precision reference grid. Data are recorded using Dantec Dynamics software. Raw images are post-processed with an in-house PIV algorithm developed by Dr. B. Lecordier. A short description is given below. The 4 images are combined on a same image using the reference grid. Distortion and image tilt are compensated. Then a preprocessing is achieved to reduce correlation on identified structures resulting from local soot generation or interfaces due to non-seeded fresh air coming from the opening. Then PIV processing was performed with a cross-correlation technique between pairs of successive images. The size of the PIV interrogation window is 64 pix<sup>2</sup> and a 50% overlap is processed. The time interval between two consecutive images is in the range of 1–2.5 ms.

For temperature measurements, 20 type-K thermocouples of a 1.5 mm diameter, mounted on two shafts of 10 thermocouples placed vertically and horizontally, are installed at the outlet.

### Numerical set-up

Simulations are performed with the FDS code, version 5.5. The numerical domain is represented in Fig 3.

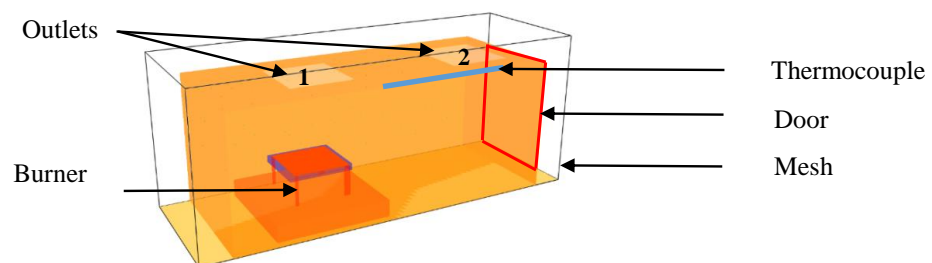


Fig. 3. FDS view of the setup.

In order to optimize the simulation, a convergence study has identified the compromise between resolution and calculation time for different mesh sizes. Simulations have been performed for a physical time of 600 s for four different cell sizes: 2.5 cm, 5 cm, 10 cm and 20 cm. In order to choose the ideal mesh, it was necessary to be

interested in the computation times to obtain the best ratio between reliability and simulation time (not shown here). For these different reasons, the cell size of 5 cm was chosen.

To summarize, the initial conditions used in this work are:

- The enclosure is plunged into a bigger computational domain totally open to take the smoke exhaust and the intake of fresh air into account;
- Ramp fire very fast because the fuel is a propane;
- Consideration of insulation for heat losses (rockwool and Aerated concrete);
- Addition of leaks in order to feed the burner with air which is seeded by particles (20cm<sup>2</sup>).

## RESULTS

### Temperature fields

Simulations are performed for three different powers: 200 kW, 500 kW and 800 kW. The results of numerical and experimental temperature profiles are compared see Fig. 4.

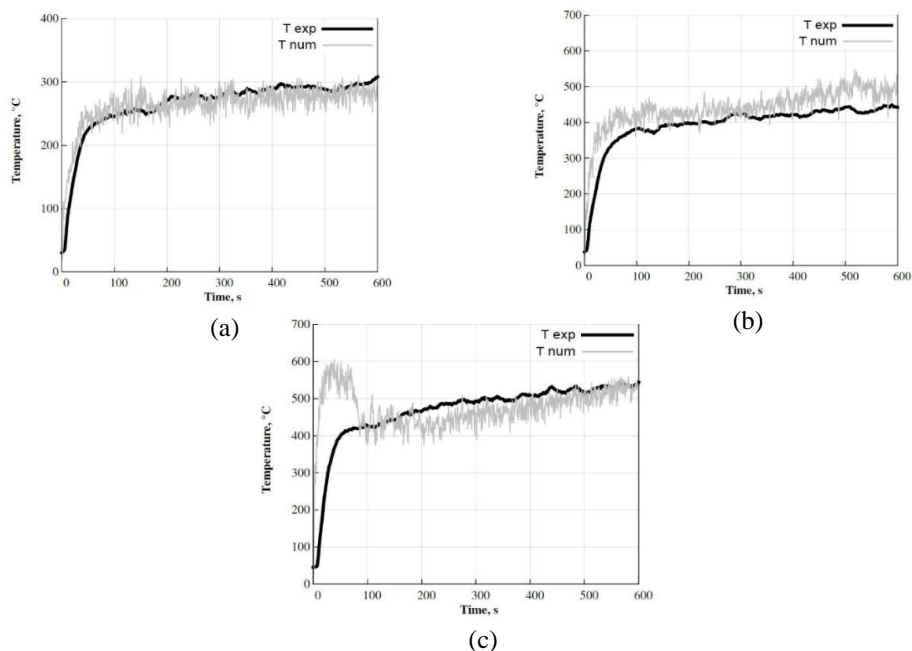


Fig. 4. Temperature profile comparison at 200 kW (a), 500 kW (b) and 800 kW (c).

In Fig. 4 (a), comparison is done for 200 kW. It is observed that the temperature evolutions with time for experimental and numerical results are very similar. The power rises are almost identical, as well as, the temperature values. In addition, the steady state is not reached.

In Fig. 4 (b), the temperature evolutions against time are plotted for a power of 500 kW. Numerical and experimental results have similar profiles. However, it is observed that a slight gap begins to appear between the two temperature evolutions. At 800 kW, see Fig. 4 (c), an important discrepancy between the experimental and numerical results appears at the beginning. Nevertheless, this difference is recovered after a few seconds. This deviation of the numerical data from the experimental results might be due to the range of validity of the CFD code. For all three cases, it can be seen that the numerical temperature profiles are much noisier than the experimental ones. This is due to the fact that, in the real case, the response time the thermocouples do not capture the high frequency fluctuations which results in a low pass filter. This comparison is done to validate numerical assumptions in simple cases. This made it possible to adjust the numerical parameters and thus improve the reliability of the simulations before the velocity measurements.

### Velocity fields

In this study, two configurations are performed, see Fig. 3.



- In the first case, outlet N°2 is open. It's the only opening. Hot smokes have to go out through this opening. Fresh air necessary to the fire development mainly enters the volume by the same way. Indeed, a small amount of particle seeded air is introduced at the bottom of the burner, as described in the experimental part. This case allows studying confined fires. It's called configuration 1.
- In the second case, outlets are closed. The door is open. Hot gases go outside through the upper part of the volume. Fresh air enters the compartment by the lower part. This case is typical of well-ventilated fires. This case is called configuration 2.

In this paper, only instantaneous fields are performed for a power of 200kW. Comparison between numerical and experimental results is done. Results are plotted for configuration 1 and they are shown on Fig. 5.

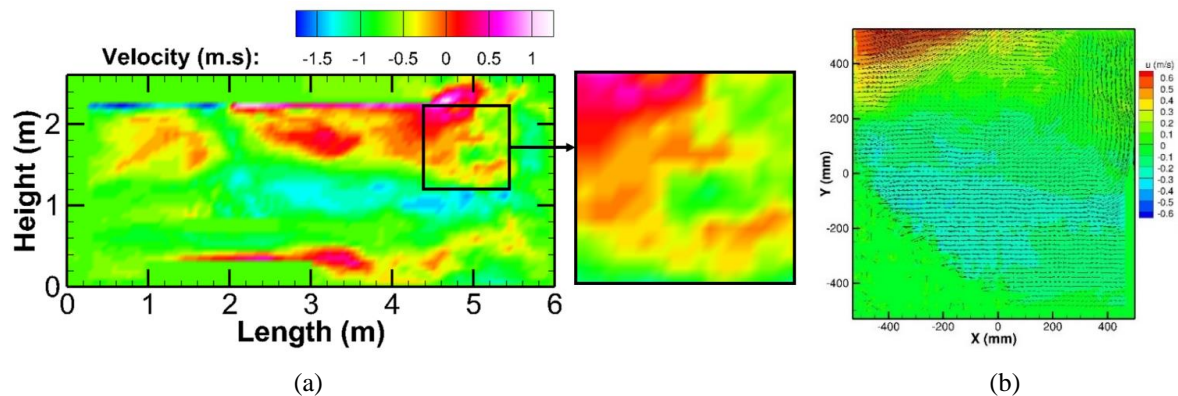


Fig. 5 Velocity fields at 200 kW, numerical (a), experimental (b), configuration 1.

In Fig. 5 (a), we observe global velocity fields in the cell. A zoom is given for comparison with experimental results, visible on Fig. 5 (b). Although slightly overestimated the numerical case, velocity fields are similar. In fact, results of smoke dynamics and hot gas velocity obtained with PIV are correctly simulated with the FDS software. Considering the second configuration, Fig 6a, one can see that the velocity field is divided into two zones horizontally distributed. The first half part sees the smoke with positive velocity corresponding to smoke exit. The second part sees fresh air income. The same behavior is observed in the experimental field. Strong exit velocities are observed at the top left corner, while air inlet with negative velocities appears on the right side. In Fig. 5 (b); we can note the absence of vectors at the bottom left of the image which results from a non-total laser sheet. This point is being improved.

Fig. 6 (a) shows numerical results in configuration 2. As in the previous figure, a zoom is made to observe the same area as for the experimental tests, available on Fig. 6 (b).

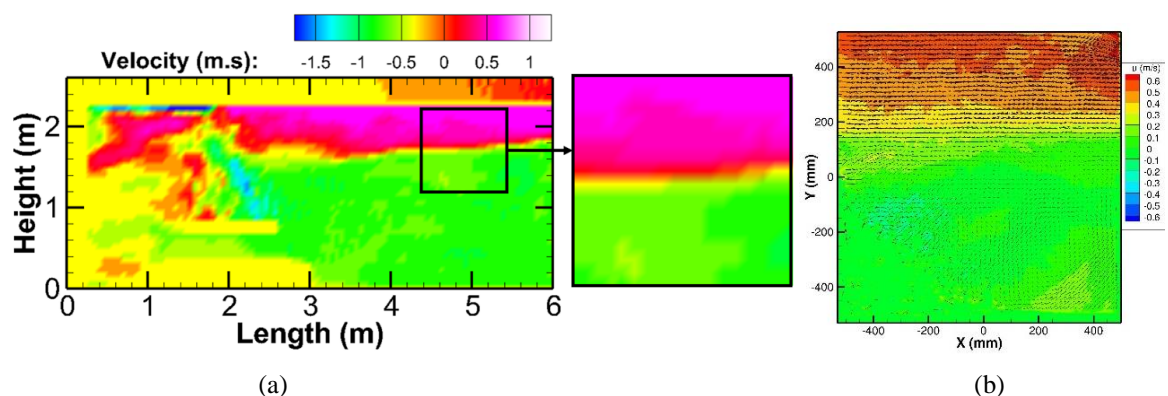


Fig. 6. Velocity fields at 200 kW, numerical (a), experimental (b), configuration 2.

This case is ideal to make a comparison between numerical and experimental results. Indeed, the fireplace is well-ventilated. This allows studying fire with less soot (simpler for PIV measurements) and studying smoke flow with dynamics less complex (simpler for numerical simulations). In this configuration, the results are very close. In both cases, three different velocity fields are observables. They correspond to the hot gases are under

ceiling, neutral plan and fresh air intake the enclosure. Velocity fields are still slightly overestimated in numerical case but faithfully represent the experimental flows.

## CONCLUSION

This work introduces large scale PIV measurement as well as mean temperature profiles and comparison is made with numerical simulations.

Considering temperature evolutions, good agreement is observed for well ventilated conditions up to 500kW. Discrepancies exist for higher configurations where the fireplace is not well ventilated. The main issue may results from FDS code which is not yet fully validated for under ventilated conditions.

In this study, numerical and experimental velocity profiles were compared for powers up to 200kW. These tests are performed in representative large scale fire, in ventilated and confined configurations. Good agreement was observed for both cases. More data are being processed for analysis and comparison of mean and fluctuating velocity fields

This research makes it possible to observe the influence of the compartment on the development of fire. It also allows an experimental and numerical comparison and therefore, to observe the reliability of the FDS code in this configuration. Adjustments are needed, especially for laser lighting to obtain a fields of 1m<sup>2</sup>. Otherwise, average fields of velocity are in progress.

## ACKNOWLEDGEMENTS

Financial support from the French National Research Agency, under the project 'Firediag' is gratefully acknowledged. This project has been funded with the support from the European Union with the European Regional Development Fund (ERDF), FEDER MADNESS and from the Regional Council of Normandie. We thank the computing center CRIANN for the computation time.

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