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EXPERIMENTAL STUDY OF SMOKE MOVEMENT BETWEEN TWO ROOMS CONNECTED BY A STAIRWELL

Samia Haouari Harrak ^{a,b}, Rabah Mehaddi ^a, Pascal Boulet ^a, El Mehdi Koutaiba ^b

^a Université de Lorraine, LEMTA, UMR CNRS 7563, France

^b CSTB - Centre Scientifique et Technique du Bâtiment, France

ABSTRACT

Small-scale experiments were carried out to study the smoke flow induced by a pool fire, in a multi-compartment configuration, consisting of two rooms connected by a stairwell. The stairwell was equipped with removable obstacles simulating the presence of stairs, to assess their influence on the smoke flow. The experimental results highlighted the effects of the obstacles on the flow, namely the disturbance of the distribution of the temperature in the smoke inside the stairwell, and the formation of vortices below the obstacles. A comparison between the experimental data and the numerical results with the zone code CFAST was also performed in order to assess the performance of the code.

INTRODUCTION

Fires in buildings have attracted much attention these last decades due to catastrophic disasters, in particular in multi-storey buildings. In such a situation, the smoke resulting from the fire is often the main cause of death of the occupants. Vertical buildings generally include a stairwell that connects different floors. The stairwell can then serve as a path for the smoke issuing from lower floors and flowing towards upper floors. Therefore, understanding the smoke movement in this kind of geometry is of great importance. Many works have been carried out to study the smoke flow in a stairwell ^{1,2,3}, particularly in the case of high rise buildings ^{4,5}. One of the goals of the present investigation is to understand the influence of stairs or obstacles present in the stairway on the smoke movement. The smoke flow in a stairwell is driven by its buoyancy (owing to temperature difference). However, the presence of obstacles may induce a dilution of the smoke with the fresh air reducing its temperature and thus its buoyancy, which in some cases may cause smoke destratification. This dilution effect is complex and difficult to model with simple correlations or code zones such as CFAST ⁶ for example.

In the present study, the smoke flows in a multi-compartment configuration, consisting of two rooms connected by a stairwell, are experimentally studied at the laboratory scale. The experimental data are compared to numerical results with the zone code CFAST version 7.

EXPERIMENTAL SET-UP

The experimental setup is shown in Figure 1. It is composed of two rooms located one above the other and connected by a stairwell. Two circular vents were placed at the top of the stairwell and the upper room (room 2). The vents were kept open during the experiments. The fire and air supply are located in the lower room (room 1). The dimensions of the experimental model are given in Figure 2. Three removable obstacles are placed inside the stairwell, to study the influence of stairs on the smoke flow. The thickness, length and width of the obstacles are respectively equal to 0.01 m, 0.30 m and 0.15 m. All walls of the experimental model, including the ceiling and the floor, are made of 1 cm thick Polycarbonate sheets, allowing the visualization of flow. A fermacell plate (composed of gypsum and cellulose fibers) of 0.01 m thick, is placed below the ceiling of the room 1 to protect it from high temperatures. The surface area of the plate is equal to the room surface area. The properties of the materials used are given in the Table 1.

Circular pools filled with heptane were used to generate the fires. Four pool diameters (0.045 m, 0.053 m, 0.061 m, 0.064 m) were used to vary the heat release rate of the fire. They were designed with a 0.04 m depth, made of steel with 0.004 m thick walls. A spark ignition system was used to start the fire. An electronic balance was placed beneath the pool to measure the fuel mass loss. By using the heat of combustion of heptane, the heat release rate of the fire can be calculated from the fuel mass loss rate with the following formula

$$Q_t = \chi \Delta H_c \dot{m}_f \quad [1]$$

where \dot{m}_f is the fuel mass loss rate, ΔH_c the heat of combustion of heptane, taken as 44.6 MJ/kg⁷ and χ the combustion efficiency, set to 0.93⁷. The heat release rate Q_t is plotted as a function of time in Figure 3, for each heptane pool diameter (D_{pool}).

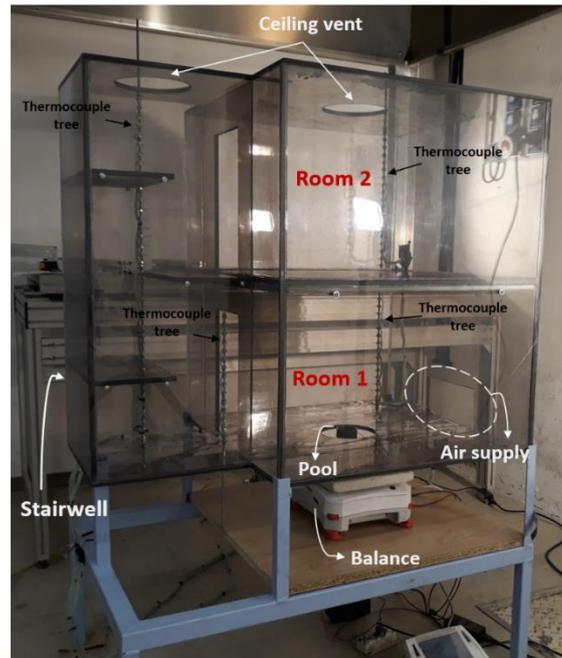


Figure 1: Photography of the experimental setup

Vertical temperature profiles were measured using a vertical tree of K-type thermocouples placed inside each room, at the door of room 1 and inside the stairwell (see Figure 1). The distance between two successive thermocouples was 0.02 m.

1. Physical and thermal properties of the walls

Material	Thermal conductivity (W/m/K)	Emissivity	Specific heat (J/kg/K)	Density (kg/m ³)
Polycarbonate	0.2	0.9	1440	1200
Fermacell plate	0.32	0.9	1100	1150

Using a double cavity Nd: YAG pulsed laser, which emits at the wavelength of 532 nm and a CCD camera, Particle Image Velocimetry (PIV) technique was applied to measure the velocity field of the smoke at the door of the room 1. By combining the velocity fields and temperature profile measurements, the mass flux of smoke was evaluated at the door of the room 1.

RESULTS AND DISCUSSION

A total of 13 experiments were performed. The characteristics of these tests are shown in Table 2. For each heptane pool, two cases are studied: without and with obstacles in the stairwell. The repeatability of the tests carried out with the experimental device was verified by repeating a test (in the case of heptane pool diameter of 45 mm) six times under the same conditions.

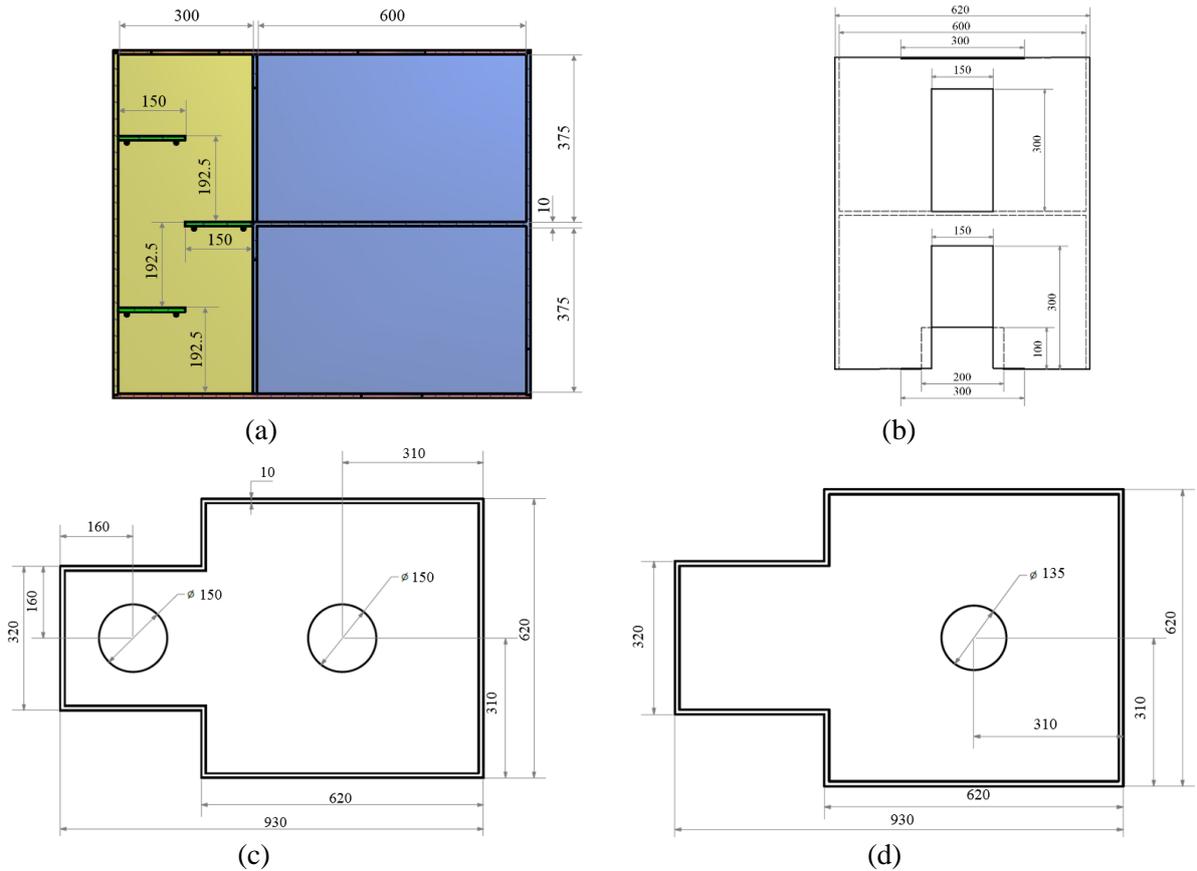


Figure 2: Dimensions of the model. (a) Vertical cross-section through the stairwell and both rooms, (b) Vertical cross-section passing between the stairwell and both rooms, (c) Ceiling, (d) Floor. (The dimensions are in (mm))

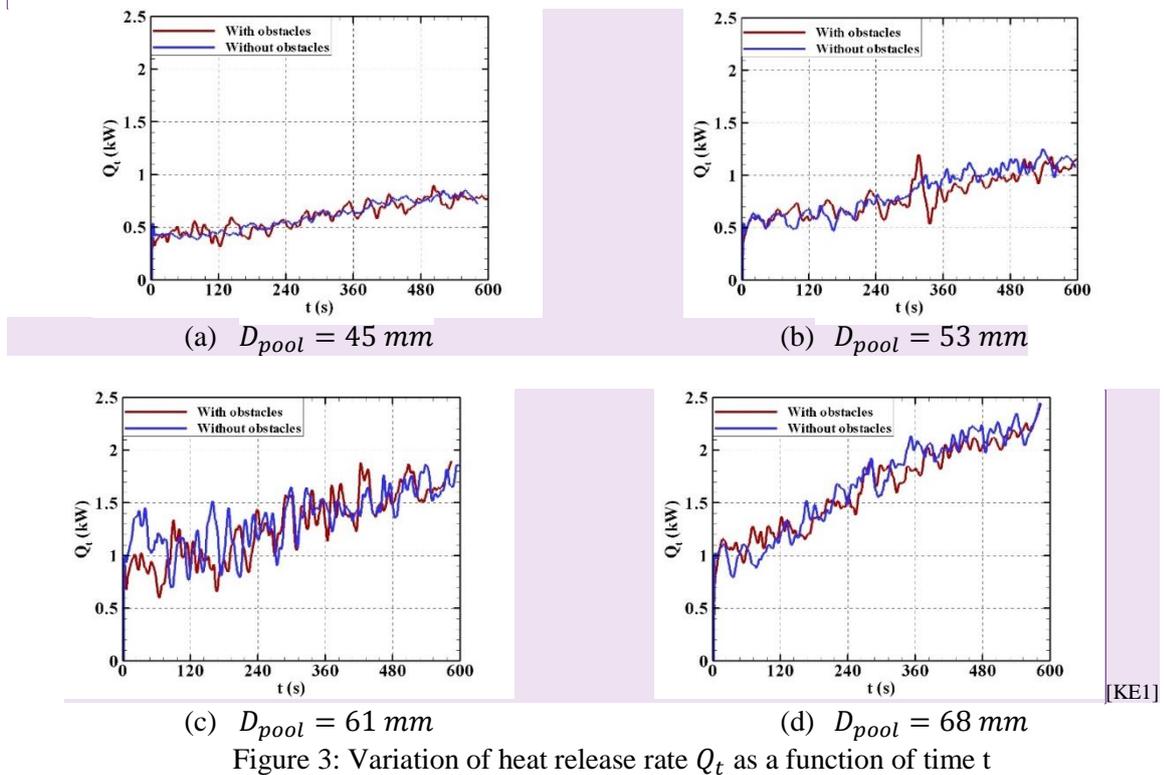


Figure 3: Variation of heat release rate Q_t as a function of time t

2. Tests performed on the model

	Heptane pool diameter (mm)			
	45	53	61	68
Without obstacles	✓ (x 6)	✓	✓	✓
With obstacles	✓	✓	✓	✓

The experiments were simulated with version 7 of the zone code CFAST. The heat release rates evaluated experimentally (see Figure 3) were prescribed in the code. The characteristics of the walls presented in Table 1 were assigned to the simulated walls.

In order to evaluate the results of the CFAST code, the well-known Janssens and Tran ⁸ method was applied to the vertical temperature profiles recorded during the experiments. The interface position z_{int} and the mean temperature of the smoke layer T_{up} were calculated by solving the following system of equations

$$(H - z_{int})T_{up} + z_{int}T_{low} = \int_0^H T(z) dz \quad [2]$$

$$(H - z_{int}) \frac{1}{T_{up}} + z_{int} \frac{1}{T_{low}} = \int_0^H \frac{1}{T(z)} dz \quad [3]$$

where H is the height of the room and T_{low} is the temperature of the lower layer, taken equal to the air temperature measured near the ground.

An example of vertical temperature profiles is shown in Figure 4. It is seen that the vertical temperature profiles recorded inside room 1 highlight the formation of a two-layer thermal stratification in both cases, with and without obstacles in the stairwell. According to the vertical temperature profiles in room 2, we can observe in both cases, without and with obstacles in the stairwell, the absence of a two-layer thermal stratification. The temperature profiles are linear. This is confirmed by the images taken during the experiments showing the total filling of room 2 with the smoke. In the stairwell, it can be seen that the distribution of the temperature in the smoke is uniform in the case “without obstacles in the stairwell”, whereas the presence of the obstacles disturbs this vertical distribution of the temperature inside the stairwell. In all cases we can see that the smoke is hotter in the case “with obstacles in the stairwell”. This can be explained by the fact that the presence of obstacles creates zones of confinement, i.e. the smoke recirculates under the obstacles. Indeed, during the experiment eddies are observed below obstacles using the PIV technique. In fact, the eddies store energy in the model which induces a decrease in the energy at the exit of the system (model on fire) compared to the case without obstacles. Note that the influence of the obstacles on the smoke flow is not taken into account in the zone codes.

Table 3 presents a comparison between the values averaged over the last 120 s of each test, calculated experimentally (for the case with obstacles in the stairwell) to those predicted by CFAST. We choose to present only the results corresponding to the smallest and largest heptane pool. The maximum difference between the interface positions is observed in room 2, it is equal to 26 % of the height of the room, for $D_{pool} = 0.045$ m, and 23 % for $D_{pool} = 0.068$ m. In fact, the zone code predicts a total filling of the room 2 by the smoke. As mentioned in the preceding paragraphs, the vertical temperature profiles recorded in room 2 as well as the recorded images highlight the absence of thermal stratification inside this room.

Regarding the average temperature of the smoke layer, the differences vary, for the smallest heptane pool, between 4 °C (in room 2) and 10 °C (in room 1). As for the relative differences, they vary between 22 % (in room 1) and 48 % (in the stairwell and room 2). For the largest heptane pool, temperature differences vary between 5 °C (in the local 1) and 8 °C (in the stairwell). As for the relative differences, they vary between 6 % (in room 1) and 29 % (in room 2).

Regarding the average temperature of the lower zone, the differences vary, for the smallest heptane

pool, between 1 °C (in the stairwell) and 4 °C (in room 1). As for the relative differences, they vary between 31 % (in the stairwell) and 93 % (in room 2). For the largest heptane pool, the temperature differences vary between 2 °C (in the stairwell) and 8 °C (in room 1). As for the relative differences, they vary between 19 % (in the stairwell) and 76 % (in room 2). We note that the differences in temperature are of the order of a few degrees, while the relative differences are very important.

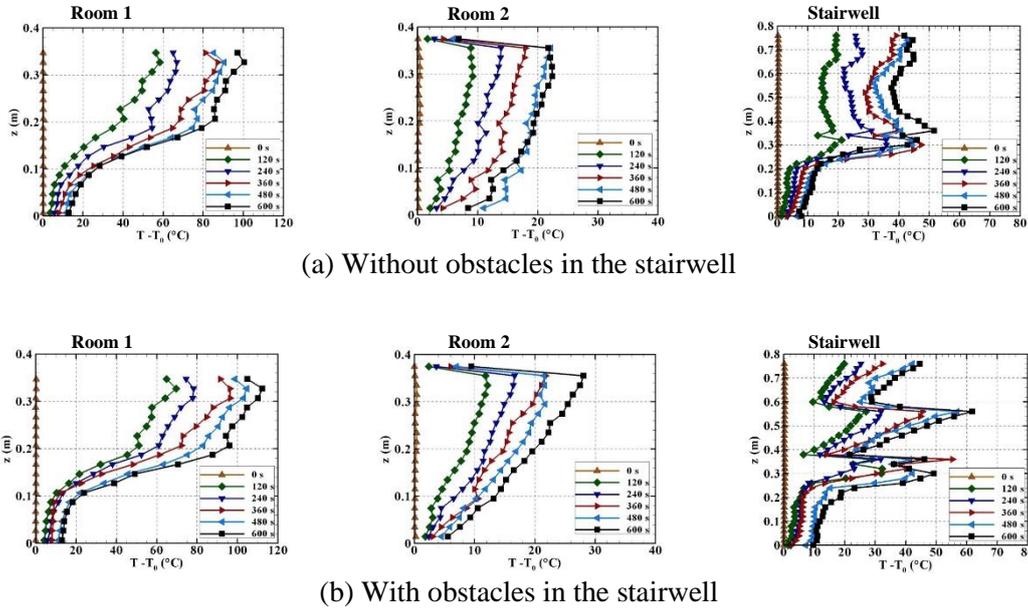


Figure 4: Vertical temperature profiles at different instants. ($D_{pool} = 68 \text{ mm}$)

3. Values of the characteristic quantities of the zones averaged over the last 120 seconds.

		$D_{pool} = 45 \text{ mm}$		$D_{pool} = 68 \text{ mm}$	
		Experience	CFAST	Experience	CFAST
Room 1	ξ	0.46	0.39	0.36	0.39
	$T_{up} - T_0$ (°C)	46.3	36.1	83.7	78.8
	$T_{low} - T_0$ (°C)	4.9	1.2	12	4.3
Room 2	ξ	0.26	0	0.23	0
	$T_{up} - T_0$ (°C)	7.5	11.2	19.8	25.5
	$T_{low} - T_0$ (°C)	1.8	-	4.8	-
Stairwell	ξ	0.33	0.38	0.30	0.40
	$T_{up} - T_0$ (°C)	13.5	20.1	35.9	43.8
	$T_{low} - T_0$ (°C)	2	2.6	8.1	6.6

Figure 4 shows a comparison of the mass flow rates of smoke at the door of room 1 calculated experimentally for the four pool diameters (in cases with obstacles in the stairwell) and those predicted by CFAST. The flow rates presented are averaged over the last 120 seconds of the duration of each test. It is observed that the zone code overestimates the mass flow of smoke at the door. The differences vary between 5.5 g/s and 6.1 g/s. Relative differences range from 53 % to 115 %.

CONCLUSION

In this study, small-scale laboratory experiments were conducted to study the smoke flows in a multi-compartment configuration, consisting of two rooms connected by a stairwell. A heptane pool was used as a fire source in the room located on the first floor. The influence of the stairs on the

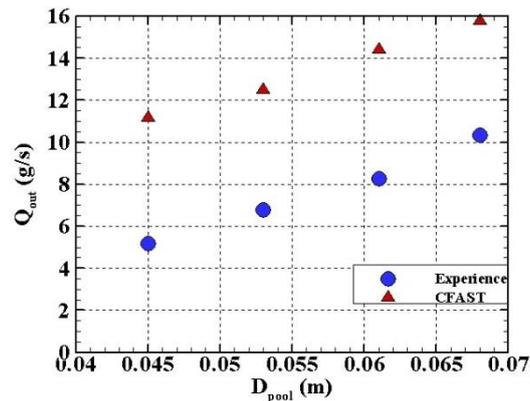


Figure 4: Mass flow rates of smoke at the door of the room 1 averaged over the last 120 s of each test

smoke flow has been studied, by adding removable obstacles inside the stairwell. The vertical temperature profiles and the average velocity fields, observed in the stairwell, highlighted the impact of the obstacles on the flow, namely the disturbance of the temperature distribution in the smoke, and the appearance of vortices below the obstacles. In fact, these phenomena are not taken into account in the zone codes. To evaluate the smoke layer height, the lower and upper layers mean temperature in each compartment, the method of Janssens and Tran⁸ was applied to the vertical temperature profiles. Then, the zone code CFAST was evaluated, comparing the thermal interface positions, the lower and upper layers mean temperature in each compartment. The comparison results showed that the absolute temperature differences between the numerical and experimental results do not exceed 10 °C and the relative differences vary from 2 % to 98 %. The differences between the interface positions observed in the fire room, vary between 1 % and 12 % of the height of the room. In the room located at level 2, the zone code predicts a total filling of the room after a few minutes, this has been confirmed from the smoke flow images and the vertical temperature profiles recorded during the experiments. A comparison of the mass flux of smoke at the door of the fire room was also conducted. The results showed that the CFAST code overestimates the mass flux of smoke at the door from 5.5 g/s to 6.1 g/s, and the relative differences range from 53 % to 115 %.

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