Experimental Study on Pool Fire Behavior and the Ignition Risk of Unburnt Gases in a Reduced-Scale Chamber of Chambord Castle

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1 Introduction

In actual life, fires often present risks to historical and cultural heritage constructions. Preserving historic buildings with cultural value has so become increasingly indispensable. Many devastating fires in recent years have destroyed buildings and entire historic districts around the world. Among the noteworthy events are the 1988 Chiado fire in Lisbon, Portugal; the 2006 Trinity Cathedral fire in St. Petersburg, Russia; and the 2019 Notre Dame fire in Paris, France.

Nevertheless, historic buildings provide specific challenges for fire behavior research linked to their particular architectural characteristics: limited ventilation, the use of highly flammable building materials like wood, and interior venting designs unlike those of contemporary buildings. These architectural features could result in more complex and unpredictable fire scenarios. Although experimental and numerical research on fires in enclosed compartments has expanded significantly and covered areas such as nuclear facilities, multi-compartment scenarios, high-altitude chambers, and residential buildings [1–4], studies specifically addressing fire behavior in heritage buildings remain limited.

In this context, this study aims to investigate the confinement effect on fire dynamics and associated risk across three distinct combustion regimes: well-ventilated, under-ventilated, and severely under-ventilated. A reduced-scale model based on the scaling laws was constructed to replicate a typical room in Chambord Castle. A parametric analysis is realized to examine the influences of fire size and ventilation flow rate. Furthermore, a global approach assesses the potential ignition risk of produced unburnt gases.

2 Materials and methods

The Chambord Castle, a UNESCO World Heritage Site since 1981, is a typical example of French Renaissance architecture in France's Centre-Val de Loire region. Recently, Brunetaud et al. [5] carried out a study on this castle, concentrating on particular zones to assess the natural degradation of the walls' mechanical integrity by 3D imaging and CAD modeling. This previous study also provides geometric data for current research, where the "Queen's Room" (12.0 m in length, 8.32 m in width, and 6.4 m in

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height) in the castle was chosen as a case study to explore fire characteristics in typical castle rooms. A 1/8th model compartment simulating precisely the geometry and dimensions of the queen's room was also created at the GreenSprink laboratory of the INSA Centre Val de Loire.

Figure 1 details the instrumentation setup of the model compartment. The fuel pan is placed on a load cell in the center of the model compartment to monitor the fuel's mass loss over time. Three K-type thermocouple trees are arranged in a specific configuration to realize the temperature measurement in the model compartment. A central thermocouple tree, TC1, is positioned directly above the fuel pan for the flame temperature, and two additional trees, TC2 and TC3, are located at opposite corners of the room for the gas temperature near the inlet and outlet, respectively. Each tree comprises 17 thermocouples to capture the vertical temperature distribution accurately. Heat flux sensors are mounted on the back and right-side walls to assess the thermal exposure to the model compartment's surfaces. A gas analyzer is joined to measure the gas concentrations under the ceiling (close to the outlet). Moreover, the airflow rates before ignition in the extraction duct and admission duct were measured by a hotwire anemometer.

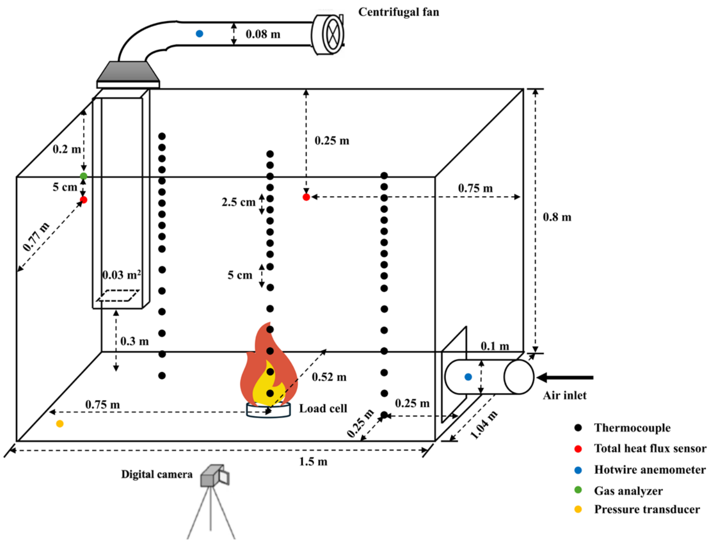

Figure 1: Schema of the experimental setup.

36 fire tests were conducted to assess the impact of varying fire size (D) and ventilation rates on the fire behavior in the model compartment using three air renewal rates of 10, 20, and 30 ACPH (Air Changes Per Hour) as well as four circular pans of 13, 16, 20, and 24 cm. The different ACPH tests with forced ventilation were designed to mimic different levels of window openings and external environmental conditions, such as wind. Meanwhile, n-heptane was selected as the fuel for the current study with a starting mass of 200 g for all tests.

3 Fire behavior in different combustion regimes

The Mass Loss Rate (MLR) and oxygen (O_2) concentrations under the ceiling at different ventilation flow rates are presented in Figure 2–Figure 4. For a 13 cm diameter pan, which consistently results in well-ventilated fires, the MLR reaches a plateau after the growing stage and sustains it until extinction, similar to the behavior of an open fire. The O_2 concentration in the reduced-scale compartment remains above 10%. When the pan diameter increases to 16 cm, fires become under-ventilated. Resembling well-ventilated fires (13 cm), the MLR reaches the peak after the growing stage. However, it decreases to a lower plateau due to the limited O_2 availability, which is insufficient to sustain combustion at the maximum MLR like well-ventilated fires. With pan diameters of 20 and 24 cm, the fire can become severely under-ventilated, resulting in the production of a large quantity of unburnt gases. The MLR of a severely under-ventilated fire initially reaches its peak, similar to fires in under-ventilated regimes (16 cm). However, unlike in well-ventilated or under-ventilated conditions, the MLR continues to decline until extinction rather than stabilizing at a plateau. This behavior occurs because the severely limited O_2 supply is rapidly depleted, preventing the sustenance of a stable pyrolysis rate. In addition, ghosting flames were also observed prior to extinction. Finally, several important observations are worthy of note. First, as the confinement level increases, the magnitude of the MLR decreases, while the O_2 concentration under the ceiling drops sharply. Next, under our experimental conditions (i.e., chimney-like ventilation with a perpendicular low inlet and outlet, representative of a castle room structure), the influence of ventilation flow rate on fire behavior is less pronounced than that of pan diameter.

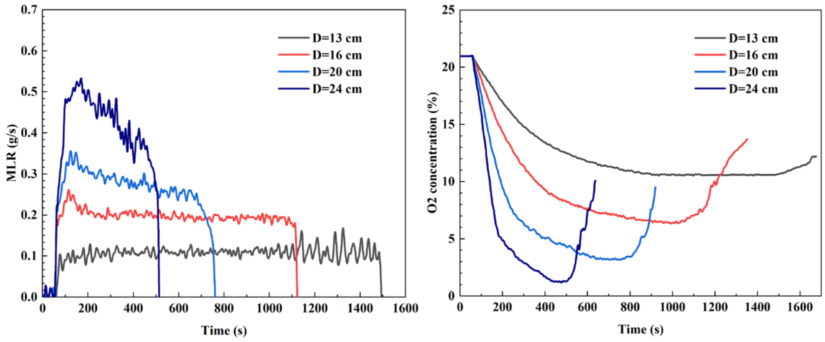

Figure 2: Evolutions of MLR and O_2 concentrations at 10 ACPH. Left: MLR evolutions. Right: O_2 evolutions.

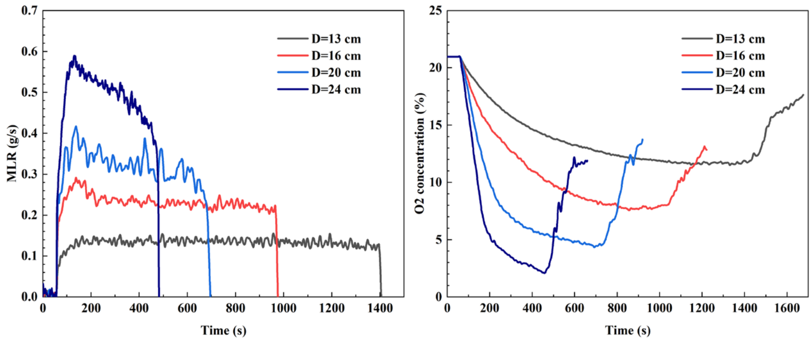

Figure 3: Evolutions of MLR and O_2 concentrations at 20 ACPH. Left: MLR evolutions. Right: O_2 evolutions.

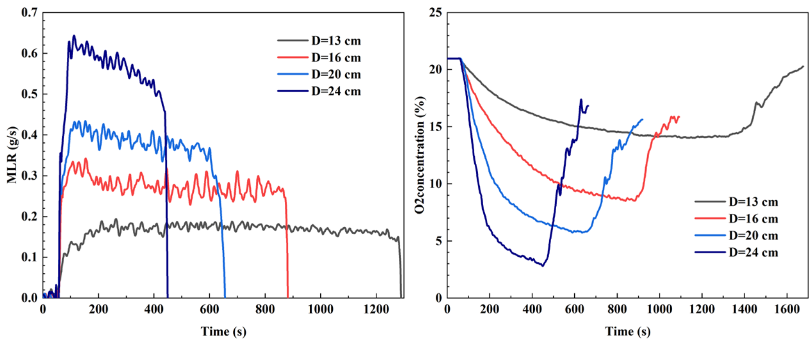

Figure 4: Evolutions of MLR and O_2 concentrations at 30 ACPH. Left: MLR evolutions. Right: O_2 evolutions.

4 Unburnt gases and their ignition risk

Due to the representativeness of the results, we focus on two representative cases: 16 cm at 10 ACPH (under-ventilated) and 24 cm at 10 ACPH (severely under-ventilated). Figure 5 compares CO, H_2, and C_xH_y evolutions between these cases, showing that the larger pool fire (24 cm) generates significantly more unburnt gases due to a higher MLR and incomplete combustion at the same O_2 supply. In contrast, the 16 cm case exhibits lower unburnt gas concentrations, indicating higher combustion efficiency.

The evolutions of major fuel gas fractions reveal that in the 16 cm case, CO is the dominant unburnt product, resulting in a higher LFL and lower ignition risk. Conversely, in the 24 cm case, a higher pyrolysis rate and faster O_2 depletion promote the formation of partially oxidized hydrocarbons, which are more reactive and increase ignition hazards. Since CO, H_2, and C_xH_y are all combustible under vitiated conditions, the 24 cm case presents the highest ignition risk, underscoring the need for more concrete analysis of the potential unburnt gas ignition risks.

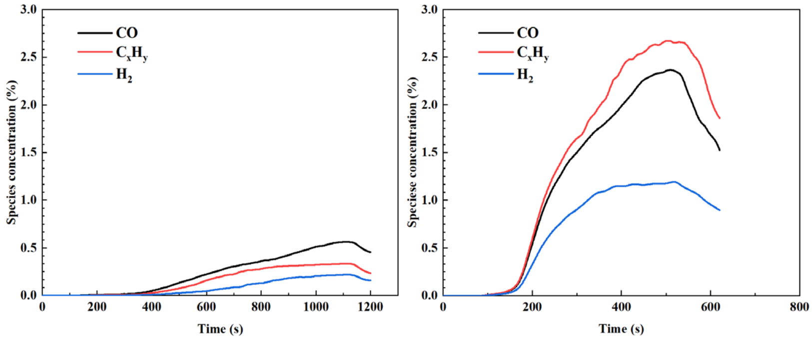

Figure 5: Malor fuel species concentration evolutions. Left: For D=16 cm at ACPH=10. Right: For D=24 cm at ACPH=10.

Based on a global approach proposed by Manescau et al. [6] to estimate the ignition risk of unburnt gas mixtures in confined and mechanically ventilated enclosures during a fire. A simplified ignition model is introduced and updated, assuming that auto-ignition occurs when the gas temperature reaches the Auto-Ignition Temperature (AIT) and the concentration of major unburnt gas mixture exceeds the Low Flammability Limit (LFL). The assessment requires determining the mixture composition and temperature, as well as comparing the unburnt gas proportion with the LFL. For individual gas, the LFL is determined based on the gas temperature, while for gas mixtures, it is calculated considering the molar fraction of major fuel components present in the mixture. For the paraffin hydrocarbon species (CxHy in this study), Zabetakis [7] proposed a correlation to predict its LFL as a function of temperature:

$$LFL_{C_xH_y}(T) = LFL_{C_xH_y}(T_0)\cdot\left[1-\frac{T-T_0}{1300-T_0}\right] \tag{1}$$

For two other major fuel species, CO and H_2, Hustad and Sonju [8] developed other formulas to describe their LFLs:

$$LFL_{H_2}(T) = 5[1-0.00129(T-T_0)] \tag{2}$$

$$LFL_{CO}(T) = 15[1-0.00095(T-T_0)] \tag{3}$$

The values of the AIT and LFL at T_0=25 °C for the three major fuel species are summarized in Table 1. In a fuel mixture, the LFL is determined using Le Châtelier's law [9]:

$$LFL(T) = \left[\sum_i \frac{Xi}{LFL_i(T)} \right]^{-1} \quad (4)$$

Table 1: Thermal properties of major fuel species [7,8].

Fuel type	AIT (°C)	LFL (T_0=25°C)
CO	588	15
H_2	520	5
Heptane	233	1.05

For safety considerations, when unidentified long-chain species are present in gas sample, the LFL of C_xH_y is assumed to be the lowest among the cases considered. Since LFL decreases with increasing carbon chain length, heptane's LFL is used as a conservative estimate in heptane fires. Determining AIT is more complex due to its dependence on chemical kinetics, but like LFL, it generally decreases with carbon chain length before stabilizing. In the absence of a universal law for AIT in mixtures, the lowest AIT among components, heptane in this study, is chosen.

The results of the risk assessment of unburnt gas ignition in the two studied cases are presented in Figure 6. Note that the analysis is conducted only for periods when unburnt gases begin to produce remarkably. Based on our experimental results, the 24 cm pool fire demonstrates a high ignition potential after 300 s, whereas the 16 cm case remains below the ignition threshold despite the temperature slightly exceeding the AIT. This observation emphasizes the significance of enhancing ventilation and tracking unburnt gases., particularly in severely under-ventilated fire scenarios.

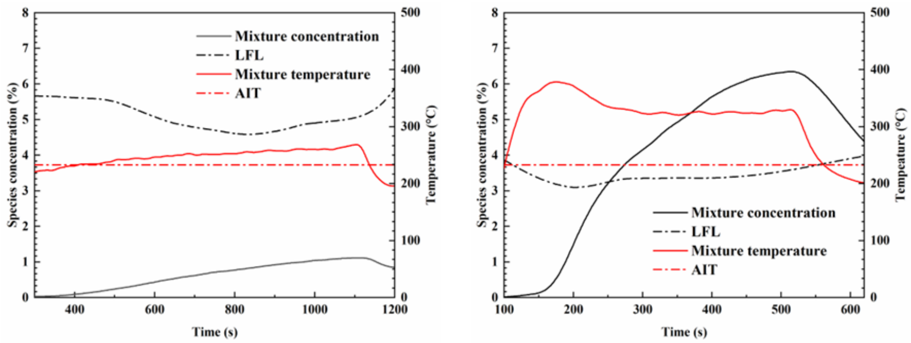

Figure 6: Risk assessment of unburnt gas ignition. Left: For D=16 cm at ACPH=10. Right: For D=24 cm at ACPH=10.

5 Conclusion

This experimental study examines the influence of pool fire size and ventilation rate on fire behavior and the ignition risk of unburnt gases in confined spaces. The findings indicate that fire behavior exhibits considerable variation across distinct combustion regimes influenced by environmental conditions. In well-ventilated fires, the MLR reaches a plateau, and oxygen concentration stays above 10%, facilitating sustained combustion. In under-ventilated fires, the MLR reaches its maximum after the growth stage, subsequently declining to a lower plateau as a result of restricted O2 availability. In severely under-ventilated fires, the availability of oxygen is insufficient to maintain steady combustion, resulting in a persistent decrease in MLR and the buildup of unburned gases. Ghosting flames are also observed prior to extinction. A significant finding is that in the chimney-like ventilation of a castle room, the effect of ventilation flow rate on fire behavior is considerably less pronounced than that of fire size.

Utilizing the concepts of AIT and LFL, a global risk assessment approach for unburnt gas ignition was employed to evaluate potential fire hazards in this confined environment. Two representative cases were analyzed: one measuring 16 cm at 10 ACPH, categorized as under-ventilated, and another measuring 24 cm at 10 ACPH, classified as severely under-ventilated. The results indicate that while the 16 cm case is below the minimum ignition threshold, the 24 cm case shows a significant ignition potential. The results underscore the need for more targeted and effective fire prevention strategies in hazardous scenarios.

Despite these findings, several significant areas still need to be investigated: (1) the impact of local turbulence flow and pressure variations on unburnt gas accumulation requires further investigation; (2) an experimental method for precisely mapping the distribution of unburnt gases during combustion is still lacking; (3) future work will focus on detailed numerical simulations and extended experimental studies including different fuel types and depths to enhance the understanding of fire dynamics in heritage buildings and similar enclosed environments.

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