Experimental study of the dynamic behavior of a flame in a 1 m³ under-ventilated compartment: Application to fire safety.

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Résumé:
Des essais de feu d’heptane ont été réalisés à échelles réduites dans une enceinte de 1 m³, pour laquelle la ventilation était mécaniquement contrôlée. Le but était d’analyser la vitesse de perte de masse du combustible et le comportement de la flamme dans le cas de feux sous-ventilés. La concentration en oxygène dans l’écoulement qui alimente la base de la flamme diminue continument, alors que la perte de masse diminue ou augmente en fonction de la ventilation dans la chambre. Ceci peut s’expliquer par le rôle respectif du transfert de chaleur de la flamme ou de la couche de fumée vers le bac. Un phénomène de propagation et d’expansion de flamme est observé si la ventilation de la chambre est suffisante.

Abstract:
Some fire tests were conducted with heptane and at a reduced scale in a chamber of 1 m³, where the ventilation was mechanically controlled. The aim was to analyze the rate of mass loss of fuel and the behavior of the flame in the case of under-ventilated fires. For all test, the oxygen concentration in the flow which feeds the base of the flame decreases continuously. However the weight loss rate increases or decreases depending on the ventilation in the room. This can be explained by the respective contribution of heat transfer from the flame or the smoke layer towards the liquid fuel. A phenomenon of propagation and expansion of the flame is also observed if the ventilation of the room is sufficient.

Mots clefs: pool fire, under-ventilated flame, smoke, radiation

1 Introduction

Under-ventilated fires are now recognized as an important issue. The ventilation control in the buildings or in the confined spaces of the nuclear industry can lead to fire scenarios during which they consume quickly the air available in the room. The combustion then undergoes into an under-ventilated regime. During this stage of under-ventilated fires, it can remain a significant production of combustible vapors; due to thermal inertia, convective and radiative fluxes on combustible materials remain high. The excess of combustible vapors, which are not totally consumed by the fire, may trigger a deflagration if some air is introduced suddenly into the room. This thermal accident is a potential serious risk which concerns the people and the operational fire services that are close the compartmented fire. It is important to identify the key phenomena that control the mass loss rate of combustible materials which may be present in the compartment. We must also understand the conditions that lead to the extinction of the flame.

Several tests were carried out at small scales in a compartment of 1 m³, which has been ventilated by a mechanically controlled and adjustable system. Heptane was put in two pans of 11 cm diameter, both placed on a load cell in order to measure the mass loss rate. The temperature was observed at different heights. Oxygen was measured at the base of the pans in order to estimate the amount that feeds the flame.

2 Experimental setup

The compartment is a one-cubic meter chamber of equal sides. Its interior walls, ceiling, and floor are covered with 25mm thick refractive ceramic fibers for thermal insulation. Through the air inlet on a side wall near the floor, air can enter the compartment in one of two ways (See Fig.1):
- A 1 cm diameter duct with a hot wire probe to measure air flow.
- An iris diaphragm across which pressure difference measurements allow the determination of air flow.

Smoke exits through a 4.5 cm diameter vent at the ceiling of the compartment on the side opposite to the air inlet. The ventilation of the chamber can be controlled using an electric fan fixed upon the smoke exit. The fuel mass, vertical gas temperature profile at a corner of the compartment and below the smoke exit, pressure inside the compartment, oxygen concentration near the base of the flame, and the air flow into the compartment were measured.

Two fuel pans of 111 mm inner diameter made of borosilicate glass were used for all tests, there were installed side by side. The fuel mass is measured in real time by a Mettler Toledo weighing scale with a resolution of 0.1 g. The weighing scale was placed at the center, under the fire compartment to protect it from heat. A ceramic cylindrical shaft and water seals were used to connect the fuel pan to the scale. This sealing system is similar to the one used in the study by Utiskul et al. [1]. The vertical gas temperature profiles are measured by two arrays of 5 type-K thermocouples. Oxygen concentration at approximately 3 cm away from the flame base was measured by a Testo 350 gas analyzer. A pressure gauge tube was inserted into the compartment at floor level to measure pressure variations inside the compartment. Data from the precision scale, the thermocouples and the air-flow by the iris diaphragm were taken at a scan rate of 300 ms. The gas analyzers and the hot wire probe provided values every 1 s.

The varying fire power in some tests with high ventilation rates produced some pressure variations in the compartment. Since the force felt by the cylindrical shaft can be transmitted downwards to the precision scale, such pressure variations within the compartment can affect fuel mass loss measurements. Corrections have therefore been made to the fuel mass measurements.

3 Results

Tests of n-Heptane pool fires have been carried out for different values of the ventilation parameter. It is defined by the air mass flow rate at the inlet per unit area of the fuel pan and at the ignition time. It was equal to 195, 91.5 and 252 g/m²/s for tests 1 to 4 respectively. The mass loss rate is also expressed per unit area of the fuel pan.

The oxygen concentrations at flame base and close the pan and the fuel mass loss rates are reported in fig. 2 as a function of time. They show that oxygen concentration is continuously decreasing close to the flame, because the air inlet flux is not sufficient to compensate the oxygen consumption by combustion. For tests 1 and 2, the flame left the fuel pan and has been attached again close to the floor between the vertical wall and the liquid pan (to the left in fig. 1). So the oxygen probe was no more in the vicinity of the flame and this is why oxygen concentration dropped so low, at about 10%. The mass loss rate behavior is quite different. Our
experiments show that the fuel mass loss rate trend depends on the compartment ventilation rate. For the low ventilation rate (tests 2 and 3), it decreases with time, and in contrary, for the high ventilation rates (tests 1 and 4), it increases. These variations of the mass loss rate will be analyzed in the next section according to the respective heat fluxes of the flame and the smoke layer on the combustible. For the two fuel pans of 111mm inner diameter, the ‘free burning’ mass loss rate is equal to 11.6 g/m²/s [1]. This value would be observed if the pool fire is not enclosed in a compartment. This could have been observed at the beginning of each test when the effect of radiation of the smoke layer is small. This is not the case for the tests performed in this study as shown in fig. 3. With the ‘free burning’ value of 11.6 g/m²/s, the stoichiometric ventilation parameter can be calculated from the global reaction of the heptane combustion in air, and the result is 220 g/m²/s. By comparing this theoretical value to those used for each experiment, it is clear that the tests 2 and 3 were strongly under-ventilated and test 1 slightly. This is also the case for test 4. The ventilation parameter is slightly greater the stoichiometric value, however fig. 2 shows that the flame was not fed by fresh air.

It should be noted that for all these tests, the flames have been extinguished due to oxygen depletion inside the chamber, and this occurred before that the fuel has been totally consumed. The time of extinction is 250s, 400s, 250s and 400s respectively for tests 1 to 4.

FIG. 2 – Experimental results for all tests, oxygen concentration at flame base at left and fuel mass loss rates at right. Vertical bars indicate the extinction time.

Figure 3 present the temperature of the smoke layer which fills the major part of the chamber, between the flame and the ceiling. The values reported in fig. 3 represent the average between 0.3m above the floor and the ceiling. It is important to note that the temperature of the smoke layer is higher when the ventilation parameter is increased.

FIG. 3 – Average values of the smoke layer as a function of time

Before extinction, the oxygen is reduced continuously into the compartment and the behavior and the shape of the flames are changing. For strong under-ventilated regimes (tests 2-3), flames look like the examples shown in fig. 4. First (left picture), the flame attachment is stable and conical, pulsations are observed in the flame zone at a frequency of about 3 Hz. This process of ‘flickering’ is well known and is due to instability of the fluid inside the flame zone [2]. Then (middle picture) the flame becomes unstructured, its height
and luminosity are reduced. Before the extinction (right picture), the flame can move from the pan (only in test 2), it persists for a few seconds giving what is called a ‘ghosting flame’.

![Images of the flame during the test 2, left at 50s, middle at 150s and right at 230 s just before extinction](image)

**FIG. 4** – Images of the flame during the test 2, left at 50s, middle at 150s and right at 230 s just before extinction

For a moderate under-ventilated regime (tests 1 and 4), the behavior and the shape of the flame can be different during the period just before extinction. Some pulsations become more abrupt, leading to a rapid expansion of the flame zone as seen in fig. 5. After that, the flame becomes more luminous and like a fire ball which rises driven by the effects of buoyancy.

![Images showing an expanding flame during the test 4, the time between images is 33ms.](image)

**FIG. 5** – Images showing an expanding flame during the test 4, the time between images is 33ms.

### 4 Discussion

The behavior of compartmented fires fed by natural ventilation (without a mechanical system) is well known. In particular, the dynamic of under-ventilated cases and their flame behaviors have been analyzed in several studies at reduced scales [3-8]. In these ones, the ventilation parameter is not measured but it is defined by the product $A\sqrt{H}$, where $A$ is the opening surface and $H$ its height. The present study is also performed at reduced scales, however the ventilation is forced. So it is difficult to compare our ventilation conditions to those used in the previous works. Another important point, the present study is focused on the cases for which the extinction occurs. However, some studies [3-5] have shown similar features to those observed in this study: - There exists a lower limit for the ventilation parameter below which there is no sustainable combustion and a flame extinction occurs - Near this limit, oscillating flames are observed - There is a range of values for the ventilation parameter for which the mass flow rate is greater than the ‘free burning’ value.

In addition, we have also observed the phenomenon called 'ghosting flame' as in the works of Sugawa et al. [9] and Pearson [10]. However in these studies and contrary to our experiments, the fuel pan was elevated in the smoke layer and the fuels were different. They observe large horizontal structures of flame which meander in the compartment, while we see vertical flames detached from the pans and near the floor, as shown in fig. 4.

Figure 2 shows that the fuel mass loss rate increases for the highest ventilation parameters (Tests 1 and 4), becoming greater than the ‘free burning’ value (11.6 g/m2/s) some moments after ignition. It remains
constant for the moderate ventilation parameter (Test 2), and decreases at low value (Test 3). It is obvious that the fuel mass loss rate depends on the heat release in the flame and so on the oxygen concentration in the flow which fed the flame. However oxygen concentration near the flame is continuously decreasing for all tests. This result indicates that there is another process which has also important effect on vaporization of the combustible. During the growth of enclosed fires, fuel is vaporized or pyrolyzed using mainly heat fluxes originating from the flame and from the smoke layer [11], these two fluxes having the same order of magnitude [12]. By taking into account the temperature of the smoke layer, as reported in fig. 4, it can be said that the radiation flux originating from the smoke layer is greater during test 1 (or 4), compared to tests 2 and 3. This may explain the different trends of the mass loss rate observed between tests 1 (or 4) and 2-3. However, tests 2 and 3 have similar values of smoke temperature, the different trends observed between tests 2 and 3 cannot be explained by the smoke layer radiation. The explanation could be the decreasing of the flame heat flux towards the fuel surface when the ventilation parameter is decreasing. In Test 3, it has been observed that the flame volume and its luminosity were strongly reduced. In Test 2, this effect is not so important and the fuel mass loss rate did not decrease.

Oscillating flames have been observed in previous studies [3-5], however the expanding flames, as the one in fig 5, are not detailed. The main features of this phenomena are: - it is stronger when the ventilation parameter is close the stoichiometric value – It occurs in the lower part of the flame (see fig. 5) - it is like a short-time deflagration (see fig. 5) which is followed by a longer latency period - it is more or less cyclic with a period of about one second. These flames which expand outside the fuel pan seem to correspond to the propagation of a premixed flame. However this occurs in the vicinity of the diffusion flame located just above the fuel pan. The juxtaposition of a diffusion flame and of a premixed flame represents a complex problem. In some cases, this has been called ‘triple flames’. It has been shown that they intervene in the stabilization of lifted non-premixed flames [13], or in turbulent combustion with large strain rates, when extinction holes develop in the flame [14]. Close to the diffusion flame edge, the competition between the flow velocity and the premixed flame propagation with respect to the unburned mixture can lead to extinction, propagating or ‘standing triple flame’ regimes [15]. In the present study, the speeds above the fuel pan and inside the test chamber are low and the strain rate inside the diffusion flame is not as high as in the previous studies. However, it is suspected that they may be some similarities. One important issue is to know how premixed gas can be produced in the vicinity of the pan and the diffusion flame. The following explanation is proposed and it is illustrated by the scheme reported in fig. 6.

In the central zone of the test chamber, the hot plume of the flame drives an upward flow and a recirculating of smokes laterally and downward. This induces a vitiated flow, which is mixed with fresh air coming from the inlet, and which is used to feed the flame at its base. This is suggested by the oxygen concentration near the flame which is continuously decreasing during the test. Due to this lack of oxygen, some fuel vapors, emitted by the liquid vaporization, are not consumed in the flame zone. So in the mixing which feed the flame, and represented by the hatched zone in fig. 7, there are also combustible vapors, which can ignite if their concentrations are greater than the minimum of inflammability. This ignition is produced by the
diffusion flame and the propagation occurs from the center of the chamber to the side walls. An examination of the set of images given in fig. 5 can give a rough value of the speed of the propagation. It is found equal to about 0.2m/s, which is the same order of magnitude as a premixed flame speed for a poor richness [16].

5 Conclusion

Several fire tests were conducted with heptane and at a reduced scale, in a chamber of 1m³ where the ventilation was mechanically controlled. The different ventilations were chosen in order to analyze cases of under-ventilated fires with extinction. We observe some similarities with other studies carried out at reduced scales but with natural ventilation. The oxygen concentration in the flow which feeds the base of the flame decreases continuously, oscillating flames are observed, and the mass flow rate can be greater than the 'free burning' value for the cases slightly under-ventilated. However, the mass loss rate of the combustible remains constant or decreases if the ventilation in the room is strongly reduced. A phenomenon of propagation and expansion of the flame is also observed. It suggests the presence of a premixed zone near the fuel pan which ignites at more or less regular periods. Further studies are necessary in order to refine the measurements in this zone and to confirm this hypothesis.

References