Determination of ignition risk of unburnt gases in the extraction duct of an underventilated compartment fire

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Abstract

Ignition risk of unburnt gases in the extraction duct of an underventilated compartment fire is studied from 8-cubic-metre room-fire at the Laboratoire de Combustion et de Détonique (LCD), in France. A study of factors that have an influence on the ignition risk at the extraction is made. Two main factors appear: heat release rate and ventilation flow. These factors are studied by changing ventilation flow for different diameters of fire source. Fire tests are also made in order to understand the impact of closing the inlet vent on the production of unburnt gases. Criteria of heat release rate and ventilation flow are determined in order to predict conditions that lead to an ignition risk.

Introduction

Ignition of unburnt gases is a complex phenomenon in which the levels of description cover a huge range, from the details of species produced by fuels up to kinetic consideration and ambient conditions. It can be produced by an auto-ignition or a pilot ignition.

An auto-ignition occurs when gas temperature is higher than the Auto-Ignition Temperature (AIT) of the mixture. There is no way to estimate the mixture AIT but the AIT of several gases have been determined (Mallard and Le Chatelier [1], Zabetakis [2]). Auto-Ignition Temperature mainly depends on the nature of gases (Fig 1). It decreases with carbon chain length up to 200°C for carbon chain lengths higher than six.

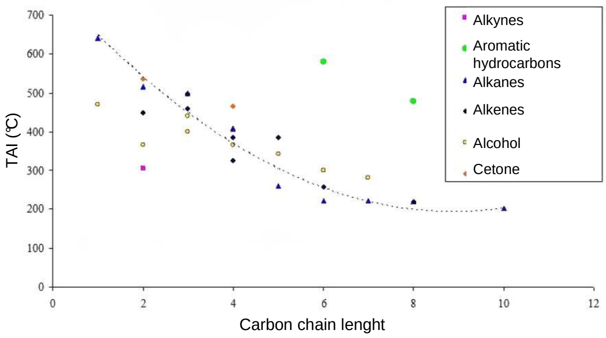

Fig1: Evolution of TAI in function of carbon chain length for different gases, data taken from [3]

To obtain a pilot ignition, a temperature criterion is not necessary because needed energy to ignite the mixture is provided by source energy such as sparks or flame. A minimum concentration of unburnt gases, called Lower Flammability Limit (LFL) is needed so that an ignition occurs. This limit depends on fuels (Zabetakis[2], Babrauskas [3]), pressure (Babrauskas [3]), temperature that is estimated by Burguess-Wheeler's law [4] and oxygen concentration (Lewis and Von Elbe [5]). The Lower Flammability Limit of gas mixture can be calculated with Le Chatelier's law [6].

So ignition of unburnt gases mainly depends on two criteria: gas temperature for an auto-ignition and gas concentration for a pilot-ignition. During an underventilated compartment fire, these criteria are influenced by several parameters such as heat release rate, ventilation conditions, fuels, compartment geometry. Carbon monoxide concentration produced during fire has been measured by several authors (Beyler [7], Tewarson [8], Morehart [9], Gottuk [10]) and the gas transport toward another compartment is studied (Lattimer [11], Mounaud [12], Wieczorek [13]). However, other unburnt gases are rarely quantified and the fuel used in most of these studies is a gas burner that can change the evolution of heat release rate. Moreover there is no study which points out the gas evolution and transport in a ventilation network.

In this work, the quantification of unburnt gases, oxygen and inert species such as azote and carbon dioxide is needed to estimate ignition risk of unburnt gases.

Specific Objectives

During a compartment fire, confinement can produce different phenomena. In case of sufficient ventilation, the fire may grow freely. If the ventilation is inadequate, the oxygen concentration can become insufficient and a large quantity of unburnt gases is produced. Then the fire may continue to burn but at a lower rate driven by the availability of oxygen or even, it may extinguish. When these unburnt gases are removed through an extraction duct which is connected to a ventilation network (Fig 2), a supply of fresh air from others ducts may form a significant amount of a flammable premixed unburnt gases/air mixture able to ignite. In nuclear facilities, this hazard could threaten

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the containment of radioactive matter and generate dispersal.

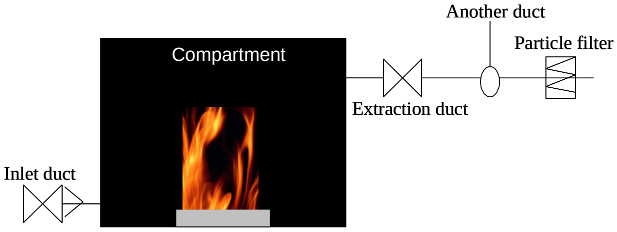

Fig2: Fire in a compartment equipped with a ventilation network

In the present work, the possible occurrence of such event is studied using a 8-cubic-metre room-test at the Laboratoire de Combustion et de Détonique (LCD), in France. Heptane and dodecane fire tests are performed in the compartment equipped with a mechanical ventilation network. The ignition risk of unburnt gases is studied in the extraction duct. The fire products and unburnt gases are removed continuously through this duct and fresh air coming from extraction network enters.

Ventilation conditions and heat release rates are the main factors for this study. The purpose of this work is to study these factors influence on temperature and species production in order to estimate the ignition risk. A series of experiments has been conducted in the room test in order to characterize fire with different ventilation flows. In addition, three pan diameters are investigated to study heat release rate influence on ignition risk of unburnt gases.

Experimental devices

The experimental device is a model of a 100-cubic-metre room. The scale of the main dimension L is 1.43. Scaling the model has been achieved using Froude analogy. The maximum simulated heat release rate Q is around 1MW. Analogy imposes the preservation of the quantity Q^2/L^5 and so the power tested are ranging till about 130 kW.

It is a 8-cubic-metre room-test. Walls are made of reinforced concrete and have a thickness of 0.2 meter. A mechanical ventilation network has a square section of 0.2 meters and mainly delivers a flow of 24 or 40 $m^3.h^{-1}$ (Air Changes Per Hour (ACPH): 3 or 5). Other ventilation flows are tested to study ventilation influence on Heat Release Rate, temperatures and species. Inlet duct is located at the bottom of the room test at a 0.3 meter high and extraction network up to the top, at a 1.7 meter high.

Experiments are performed with heptane or dodecane pool fires. Heptane used contains 71% of n-heptane and has a density of 0.71 $kg.m^{-3}$, a flash point of -4°C and a boiling point of 371.5°C. Dodecane used contains 99% of n-dodecane and has a density of 0.749 $kg.m^{-3}$, a flash point of 74°C and a boiling point of 216°C. In this work, only results of heptane fire are presented. In order to avoid freeboard effects, fuel quantity is determined as a function of pan diameter with the relation: h / D = 11.5%, where h represents fuel height and D pan diameter. The stainless-steel pans are located in the center of the room test, at a high of 0.5 meter, and placed on a load cell to measure fuel consumption as a function of time.

Different sizes of pan diameter (0.10, 0.15, 0.23, 0.30 and 0.40 meter) are used for varying heat release rate. This rate is measured by means of a load cell using Babrauskas'law [3] or calculated on the basis of the oxygen consumption taking account incomplete combustion of carbon monoxide to carbon dioxide. The temperatures in the test-room and in the extraction duct (Fig 3) are measured continuously with chrome-alumel thermocouples of 0.5 mm in diameter that give values with an uncertainty of ±1.5°C. The flow rate of gases in inlet duct and dilution duct is measured with Pitot tubes placed at the entrance of these ducts. Their sensitivities are lower than 1%. In the extraction duct, a laser and a fast digital camera are used in order to determine gas flow rate with Particle Image Velocimetry (PIV) technique. MEDTHERM and CAPTHERM captors are used to measure the radiant heat flux received by walls. Their range of sensitivity is 0 - 0.1 µV.(W/m²). Pressure is also measured continuously by a pressure captor that has a sensitivity of ±2Pa.

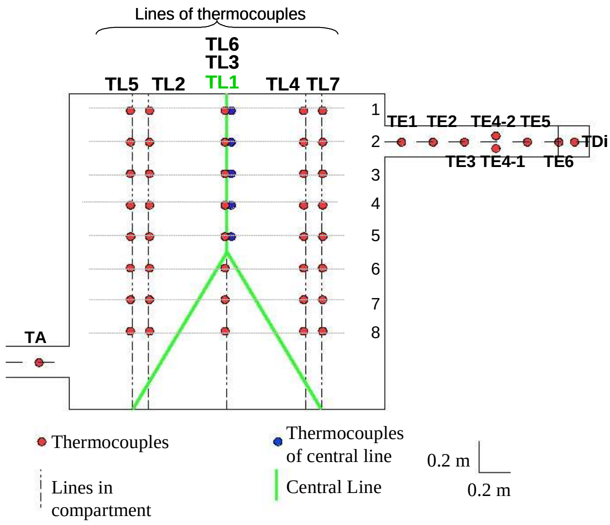

Fig3: Schematic of the compartment and thermocouples position

Continuous measurements of oxygen, carbon dioxide and carbon monoxide are performed in the entrance of the extraction duct by on-line analysis. Local measurements of oxygen, carbon dioxide, carbon monoxide, hydrogen and unburnt hydrocarbons that have a carbon chain length inferior or equal to four such as methane, ethylene, acetylene and propane are performed in the exhaust duct by probe sampling and analyzed in a gas chromatography (Flame Ionization Detector and Thermal Conductivity Detector). Unburnt hydrocarbons that have a carbon chain length superior to four are identified with a mass spectrograph.

Three fire tests for each condition are made to check the reproducibility.

Results and Discussion

The influence of ventilation is studied for several pan diameters, and then different heat release rates, in order to estimate the ignition risk of unburnt gases in the extraction duct.

Small pan diameter fires

A series of experiments has been conducted with heptane pan of 0.15 meter diameter at a ventilation flow varying between 1 and 7.62 ACPH. Heat release rates obtained in these tests are presented in figure 4. In this figure, the heat release rate obtained for this pan diameter during a fire under a hood is also represented.

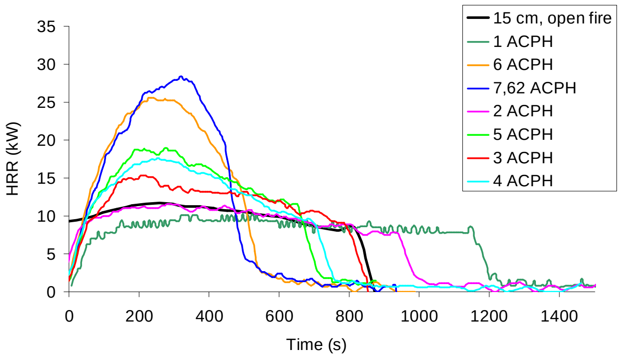

Fig4: Evolution of heat release rates obtained with heptane fires released with a pan of 0.15-meter diameter at different ACPH

At low ventilation flow (1 to 3 ACPH), heat release rate reaches a plateau that is almost the same that the one in open: fires have the same behavior than an open fire and there is not confinement effect. A structure of diffusion flame is watched. When ventilation flow increases, a blowing out effect appears and flames are sloping all the more since ventilation flow is important (cf. fig5). Then the peak of heat release rate is much higher than the one of an open fire.

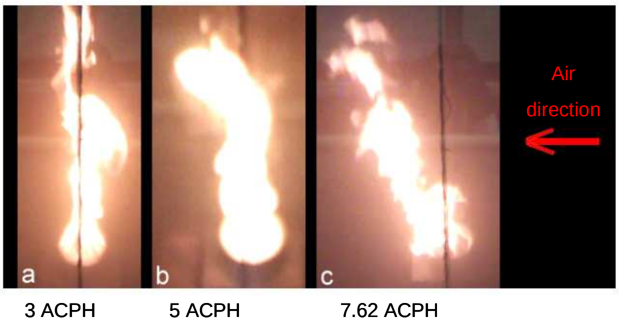

Fig5: Slope of flame at 3, 5 and 7.62 Air Changes Per Hour

Fire of pan diameters equals or less than 0.15 meter gives rise to temperatures lower than 140°C and amount of unburnt gases lower than 0.3%, in the extraction duct. As auto-ignition can only occur for temperatures higher than 200°C for unburnt hydrocarbons that have a high carbon chain length and ignition for concentration higher than 1%, there is no ignition risk of unburnt gases with these diameters.

Medium pan diameter fires

Figure 6 shows the evolution of heat release rate obtained for heptanes fires of 0.23 meter diameter pan at different ventilation flows. The heat release rate of an open fire for this diameter is also presented.

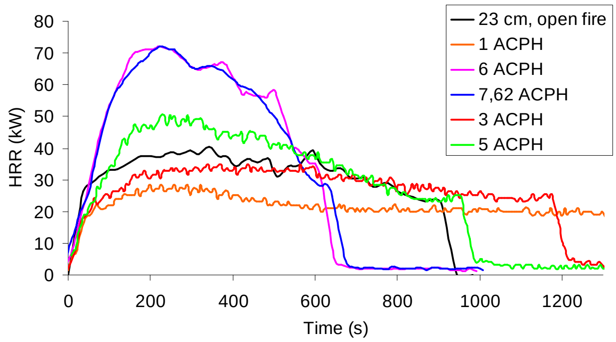

Fig6: Evolution of heat release rate obtained with heptane fires released with a pan of 0.23-meter diameter at different ACPH

Like 0.15-meter diameter fires, plateaus are reached by heat release rates for low ventilation flows (ACPH ≤ 3). There are lower than the one reached by heat release rate in open: it is due to a lack of oxygen. With these ventilation flows, oxygen supply is insufficient to burn fuel at the same heat release rate of an open fire. However these underventilated fires go out by lack of fuel. At higher ventilation flows, a blowing out effect coupled with a confinement effect are observed. Heat release rate reaches a higher value but seems to stay at a steady state level after 5 ACPH. We can suppose that, at an upper ventilation flow, air flow will become too strong: an opposite effect of this blowing out will give a lower heat release rate.

These fires produce maximal temperatures up to 250°C that can lead to an auto-ignition if unburnt gases have a long carbon chain length or if some catalysts such as soot or water vapor are present. However few unburnt gases are produced during these fires and are mainly composed of carbon monoxide that has a high Lower Flammability Limit (12% at 25°C). Then the ignition risk of unburnt gases in the extraction duct is low.

Large pan diameter fires

The evolutions of heat release rate obtained for heptane fire of 0.3-meter diameter pan, at 3 and 5 Air Changes Per Hour, are presented in figure 7. This figure also shows heat release rate obtained during open fire.

In order to avoid damages in the room test with too stronger heat release rates, only these two ventilation flows are tested. The blowing out effect is very low, even for 5 ACPH.

At 3 ACPH, heat release rate reaches a plateau similar to the one of an open fire. But oxygen amount initially present in the compartment and supplied by ventilation flow is not enough to maintain pyrolysis rate. Oxygen is quickly consumed and fire extinguishes by lack of oxygen.

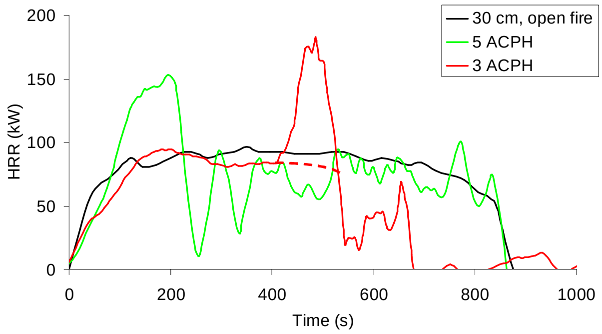

Fig7: Evolution of heat release rate obtained with heptane fires released with a pan of 0.3-meter diameter at different ACPH

The evolution of heat release rate at 3 ACPH presents an important peak: this peak does not linked with an increasing of heat release rate. Indeed, before fire extinction, underventilated flame is a site of strong fluctuations that create a pressure effect on the load cell. As heat release rate is estimated with Babrauskas'law [3] using the derivative of mass loss, these variations are all the more increased on heat release rate. Temperature measured at the beginning of the extraction duct for this test condition is presented in the figure 8. During the heat release rate peak, there is no increase in temperature. As temperatures have usually the same evolution than heat release rate, there is no peak of heat release rate before the extinction. The true evolution of heat release rate is represented on the figure 7 (dotted line).

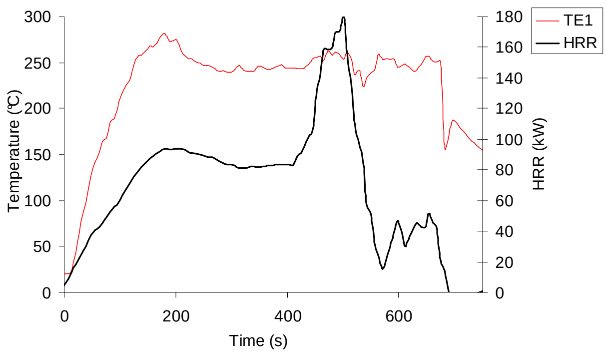

Fig8: Evolution of temperature at the beginning of the extraction duct and of heat release rate obtained with heptane fire released with a pan of 0.3-meter diameter at 3 ACPH

Fires realized at 5 ACPH present a higher heat release rate due to confinement effect coupled with a slight blowing out effect as well as the bigger amount of oxygen that enters in the compartment at this ventilation flow. Like 3 ACPH fires, these fires are underventilated and extinction by lack of oxygen occurs.

With these two ventilation flows, there are auto-ignitions of unburnt gases around heptane pan after the extinction of fire. As auto-ignition is an uncertain phenomenon, the number of these auto-ignitions varies for each test.

These fires produce maximal temperatures in the extraction duct ranging between 275°C and 300°C. These temperature levels are enough to lead to an auto-ignition of unburnt hydrocarbons with a long carbon chain length. Moreover concentrations of produced unburnt gases (hydrogen, carbon monoxide and unburnt hydrocarbon with a carbon chain length equal or inferior to four) are ranging between 1 and 4.5 %. This quantity can lead to a piloted ignition with the presence of source energy. Then the ignition risk of unburnt gases in the extraction duct is important for heptane fire with a pan of 0.3-meter diameter.

Limits of this study

These results are obtained with heptane fire. Same ignition risks with dodecane fire are found at equivalent heat release rates.

Concerning ventilation influence on heat release rate, it must be noted that inlet duct is located at the bottom of the room test (at a 0.3-meter high). The blowing out effect on heat release rate could be different with an inlet duct located up to the top. Moreover, with an inlet duct at the bottom, oxygen goes through the fire and the oxidation reaction is more complete than with an inlet up to the top where oxygen can be evacuated by the extraction duct without going through the fire. More unburnt gases will be expected with a ventilation flow up to the top.

Conclusions

Ventilation conditions

Heat release rate depends on both ventilation conditions and fire size (that can be modified by pan diameter).

The evolution of maximal heat release rate for heptane fire as a function of ventilation flow is represented for different pan diameters in the figure 9. An increase of ventilation flow generates higher maximum heat release rate for all pan diameters. Consequently, there is an increase of temperatures in the compartment and the extraction network, parameter that plays a predominant role in the ignition risk of unburnt gases.

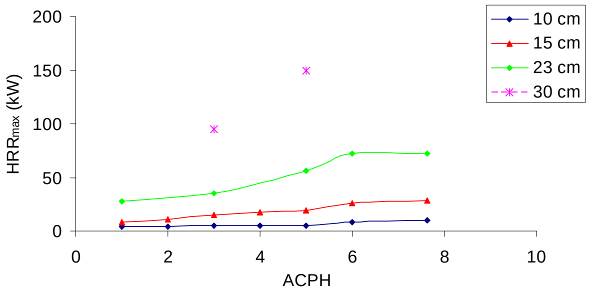

Fig9: Evolution of maximal heat release rate as a function of ventilation flow for different pan diameters for heptane fires

The evolution of maximal heat release rate for heptane fire as a function of pan diameter is presented in the figure 10 for different ventilation flows. The one obtained for an open fire is also represented.

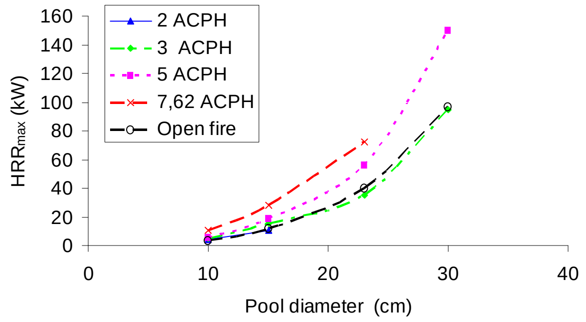

Fig10: Evolution of maximal heat release rate as a function of pan diameters at different ventilation flows for heptane fires

For all ventilation flows, maximum heat release rate increase with the pan diameter. It is noteworthy that fires carried out at 3 ACPH have heat release rates similar to the ones of open fire. Beyond this ACPH, confinement effects and blowing out effects appear and heat release rates obtained are higher than the one in open.

Ignition risk of unburnt gases

Figure 11 shows the evolution of heat release rates of heptane fires conducted with pan diameters of 0.10, 0.15, 0.23 and 0.3 meters at 3 air changes per hour.

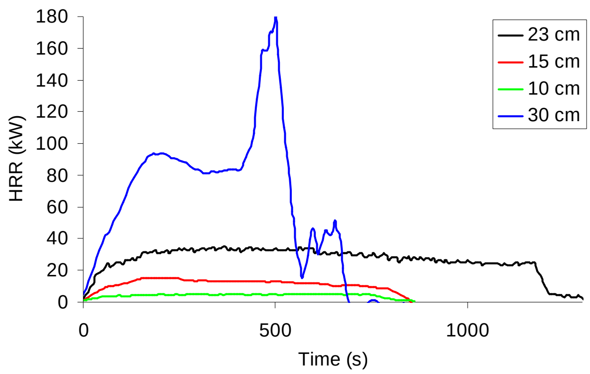

Fig11: Evolution of heat release rate as a function of time for heptane fire of different pan diameters

As previously mentioned, heat release rate is all the more important than pan diameter is larger. It is due to the fact that fuel vaporization increases with pan diameter. Then temperatures in the compartment and the extraction network are more important too. However the oxidation reaction of pyrolysis gases needs more oxygen. As fire is confined, oxygen quantity is limited and becomes quickly insufficient. Then heat release rate decreases and fire can extinguish by lack of oxygen.

For fires with pan of 0.10 and 0.15 meter diameters that are equivalent to fires of heat release rate lower than 250 kW for a 100-cubic-metre room (real scale), oxygen present in the compartment is sufficient to burn all the fuel and fire extinguishes by lack of fuel. The low heat release rate is similar to the one of an open fire except to fires with ventilation flow higher than 5. The result is a negligible unburnt gas production and lower temperatures to generate an ignition risk.

Fires with pan of 0.23 diameter, that are equivalent to fires of heat release rate ranging between 250 and 500 kW for a 100-cubic-metre room (real scale), are borderline cases that present a confinement effect and are underventilated without generating an extinction by lack of oxygen. These fires produce temperatures up to 250°C that can lead to an auto-ignition for long carbon chain length unburnt gases but few unburnt gases are produced. Then the ignition risk in the extraction duct is low.

For fires with pan of 0.3 meter diameter that are equivalent to fires of heat release rate ranging between 700 kW and 1 MW for a 100-cubic-metre room (real scale), an important confinement effect exists and fires are very underventilated, leading to extinction by lack of oxygen. Unburnt gases are produced in important quantity (between 1 and 4.5 % for hydrocarbon with a carbon chain length inferior or equal to 4, for hydrogen and for carbon monoxide). Temperatures are higher than 250°C. An important ignition risk exists for these fires that can be considered as critical cases. Then an analysis of unburnt gases produced is needed.

Nomenclature

ACPH	Air Change Per Hour
AIT	Auto-Inflammation Temperature
D	Pan diameter (m)
h	fuel high in the pan (m)
LFL	Low Flammability Limit (% vol)
Q	Heat Release Rate, noted HRR, (kW)
T	Temperature (°C)

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