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Simulation of ignition risk of unburnt gases in the extraction vent of a room fire

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ABSTRACT

The main objective of this work is to study under ventilated fires. Simulations of a fire in a compartment containing a ventilation network are made with two fire modelling programs, MAGIC and CDI, in order to study the ignition risk of unburnt gases in the extraction vent. They show that an insulating material favours the ignition and that a fire with a low Heat Release Rate (HRR) produces few unburnt gases but with a high HRR, the fire is much shorter. An intermediate HRR will favour the ignition in the extraction vent. A comparison between the results obtained with the two programs is made. This study is a design work for some foreseen fire tests in an 8-cubic-meter compartment at the Institut P', in France.

KEYWORDS: unburnt gases, heat release rate, ignition

NOMENCLATURE

A	area
Cp	thermal capacity
Fr	Froude number
g	acceleration of gravity
h	heat transfer coefficient
H_0	vent opening height
L	characteristic length
$\dot{m}_g$	gaz flow rate
$\dot{m}''$	fuel burning rate per unit area
$\dot{Q}$	heat release rate
S	fuel pan surface area
u	gas velocity
T	gaz temperature

Greek symbols

ρ	density
τ	flow time scale

Subscripts

g	gases
0	vent opening
r	reduced scale room
T	total compartment
∞	ambient

INTRODUCTION

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 (see Fig. 1),

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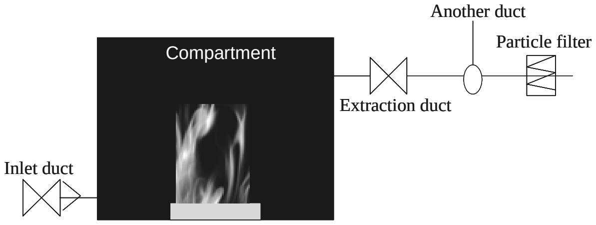

Fig. 1. Fire in a compartment equipped with a ventilation network.

a supply of fresh air from others ducts may form a significant amount of a flammable premixed unburnt gases/air mixture able to ignite.

The purpose of this work is to simulate a fire in a compartment containing a ventilation network with two fire modeling programs, MAGIC and CDI, in order to study the ignition risk of unburnt gases in the extraction vent.

MAGIC [1] is a two-zone model developed and maintained by Electricité de France (EDF) that particularly predicts flow velocities through vents, fire intensity and environmental conditions in the room such as temperature and minimum and maximum unburnt gas concentrations.

CDI (Confinement Dynamique Incendie) is a model developed by Commissariat à l'Energie Atomique (CEA) that allows a compartment design for fire safety. It predicts, in particular, temperatures, flow velocities through vents and fire intensity.

These simulations allow to study the influence of factors such as the use of an insulating material, heat release rate, ventilation flow, fuel volume and the closing of the inlet vent. A critical case that corresponds to the most favorable case to obtain an ignition is determined. A comparison between the results obtained with MAGIC and CDI is realized.

EXPERIMENTS

Models used in MAGIC and CDI

MAGIC uses a two-zone model [2] that considers that combustion products and hot smoke are confined in an upper layer and that air driven at the base of the fire is located in a lower layer.

In the upper layer, an average temperature is calculated using Mc Caffrey's method [3].

$$\Delta T_g = 480.\left[\frac{\dot{Q}}{\sqrt{g.H_0}C_p.\rho_\infty.T_\infty.A_0}\right]^{\frac{2}{3}}.\left[\frac{h.A_T}{\sqrt{g.H_0}.C_p.\rho_\infty.A_0}\right]^{\frac{-1}{3}} \qquad (1)$$

The evolution of species is obtained with conservative equations and species balance. Combustion is governed by pyrolysis rate, oxygen rate and the minimum oxygen concentration needed for fire [4]. Heat release rate (HRR) is calculated using Babrauskas'law [5].

$$\dot{Q}(t) = S.\dot{m}''(t).\Delta H_C \qquad (2)$$

MAGIC determines an interval of unburnt gas concentrations: it calculates a maximum rate of unburnt gases that can be produced during the simulated fire and a minimum rate obtained adjusting pyrolysis rate when unburnt gases are produced. In this study, in the absence of precision, it is the maximum rate of unburnt gases that is used.

CDI is a fire modeling program that uses a simplified code in order to obtain penalized results usable for fire safety. CDI separates the compartment in five zones: flame, plume, a hot zone, an average zone located in the low part of the compartment and a hot undercoat that corresponds to the ceiling jet.

In the hot zone, CDI uses Foote's method [6] to calculate temperatures for mechanical ventilation,

$$\frac{\Delta T_g}{T_\infty} = 0.63.\left[\frac{\dot{Q}}{\dot{m}_g.C_p.T_\infty}\right]^{0.72}.\left[\frac{h.A_T}{\dot{m}_g.C_p}\right]^{-0.36} \qquad (3)$$

and Mc Caffrey's method [3] for natural ventilation. Heat release rate is determined by an analytic equation.

Specific objectives

Investigations on fire compartment require conducting experiments. It is often necessary to quantify temperature, pressure, species concentration and to consider parameter influences such as ventilation flow or heat release rate. Two cases of fire tests can be considered: fire tests in full scale room and in reduced scale room. Experiments in full scale are expensive, which limit the test number. It may be difficult to analyze results in these conditions. With reduced scale room, more tests may be carried out but the scale reduction must respect several scaling laws adapted for studied problem. In many works, Reynolds analogy is used to insure similarity between the prototype and the full scale compartment. However fire requires the preservation of too many groups to ensure complete similarity. Partial scaling is made by establishing dimensionless variables from the conservation equation. Scaling relations for compartment fires have previously been proposed by Heskestad [7], Emori and Saito [8], Quintiere [9] and others. In this work, particular attention is devoted to heat loss.

With constant temperature and pressure from scale to scale, Reynolds and Froude numbers cannot be preserved simultaneously. In this study, fire compartment testing has been conducted at a smaller geometric scale while maintaining the Froude number, $Fr = u^2 / gL$, constant and preserving the relative variation of gas density, with a Reynolds number sufficiently large to make the flow turbulent. Constancy of the Froude number is then ensured provided $u_r = l_r^{1/2}$ that comes from dimensionless variable of momentum conservation. Flow time scale is obtained from mass conservation by $\tau \propto \frac{l_r}{u_r} \propto l_r^{1/2}$.

With the two modeling programs, a cubic compartment of 8 cubic meters is modeled (see Fig. 2). It is a reduced scale room based on a 100-cubic-metre compartment which is cubic and whose wall thickness is 0.3 meter. The overall dimensions of the reduced scale room are scaled geometrically from those of the full scale compartment resulting in this cubic-metre room-test. Scaling Heat Release Rate imposes the preservation of the quantity $\dot{Q}^2 / L^5$. The powers tested are lower than 400 kW which corresponds to a maximum Heat Release Rate of 3 MW at full scale. Heptane pool fires, centered in the compartment, are simulated with several initial conditions. Simulated walls are made up of 0.25 m thick reinforced concrete and floor is made up of concrete. In order to simulate possible leaks at the level of openings, a slit of 1.9 m high by 0.005 m wide is used.

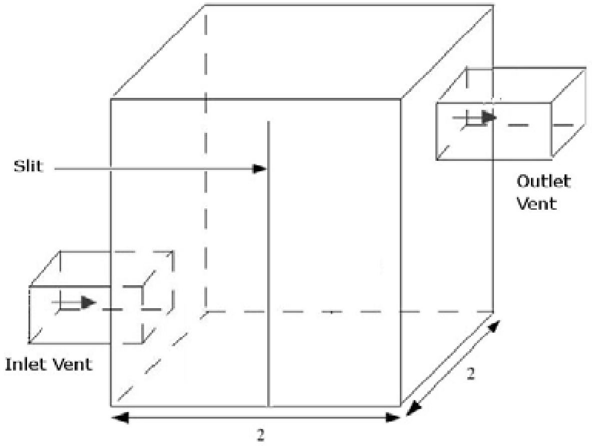

Fig. 2. Schematic of the compartment modeled in MAGIC.

Gases are exhausted through an extraction vent that delivers a flow of 3 at 5 Air Changes Per Hour (ACPH). Inlet and outlet vents have a square section of 0.2 meters. Fires are simulated during a period of 30 minutes.

In some simulations, 0.02 m insulator is used to insulate walls. This insulator has a mass density of 140 kg.m^{-3} and a thermal conductivity of 0.036 W.m^{-1}.K^{-1}.

To estimate ignition hazard, several parameters have to be considered. The different simulations can only deal with three main parameters: the temperature of gases in the extraction vent and oxygen and unburnt gas concentrations.

Firstly, several factors such as heat release rate are tested separately. A reference simulation is used to compare results. During this test, a 10-kg-heptane fire is simulated at a heat release rate of 400 kW, without closing of the inlet vent, in the absence of insulator and with a ventilation flow of 3 ACPH (0.0067 m^3.s^{-1}). This study allows to determine what factors have an influence on the temperature and the unburnt gas concentrations.

Secondly, with these results, a critical case is searched. This case tallies with the one that favors the ignition that is to say with the highest temperature in the extraction vent and the upper unburnt gas concentrations.

Lastly, a comparison with the results obtained with the fire modeling program CDI.

RESULTS AND DISCUSSION

Factors influence on the ignition risk

In order to study the ignition risk of unburnt gases in the extraction vent, five factors are tested: the use of an insulating material, the influence of heat release rate, fuel volume, ventilation flow and the closing of the inlet vent. The fire modeling program used is MAGIC.

Simulations have shown that fuel volume has not an influence on temperature in the compartment and on the unburnt gas rate. It only has an impact on the last of fire.

The influence on the ignition of the use of an insulator is studied. Results show that the use of an insulator on the walls of the compartment has very little influence on unburnt gas rate. Indeed, the Fig. 3 presents the evolution of maximum unburnt gas rate that is the ratio between maximum produced unburnt gas mass and used fuel mass. This evolution shows that unburnt gases are in a similar interval [0; 0.47] g/g. Fig. 4 shows that the presence of an insulator increases temperature in the compartment. The use of an insulator to isolate interior walls favors the hazard of ignition of unburnt gases.

Two ventilation rates are tested (see Fig. 5). The results show that more unburnt gas rate is produced with a ventilation flow of 3 ACPH, with a maximum rate of 0.47 g/g against 0.37 g/g with 5 ACPH. It is due to the fact that a greater ventilation rate produces a dilution of compartment gases more important and provides more oxygen, which favors the oxidation of unburnt gases.

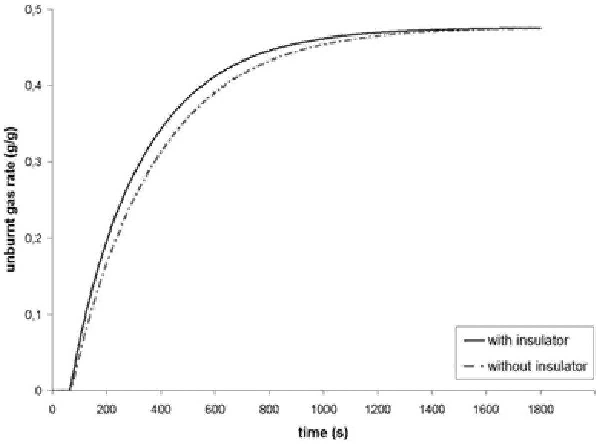

Fig. 3. Model-calculated unburnt gas rate vs. time for a 400 kW fire, without closing of the inlet vent, in the absence of insulator with and without using of an insulator.

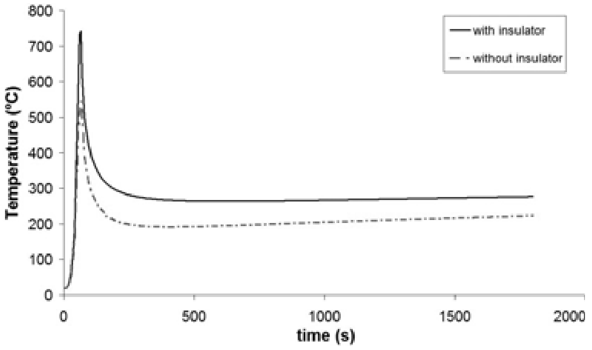

Fig. 4. Model-calculated temperature for a 400 kW fire, without closing of the inlet vent, in the absence of insulator with and without using of an insulator.

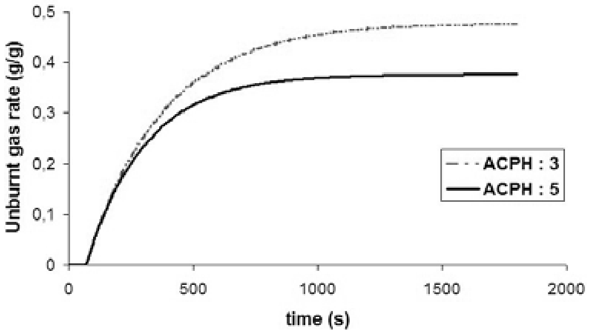

Fig. 5. Model-calculated unburnt gas rate vs. time for a 400 kW fire, without closing of the inlet vent, in the absence of insulator for different ACPH.

Heat release rate has a major effect on temperatures and on the evolution of unburnt gases in the compartment. Two types of fire are observed (see Fig. 6). At high heat release rate, represented by 400 kW on the figure, an important peak is obtained after a quick growth that follows a $\alpha.t^2$ law. This peak is very short and a constant rate of 40 kW is reached. At low heat release rate, represented by 20 kW, there is a constant rate. An intermediate heat release rate gives a smaller but longer peak than with a high heat release rate.

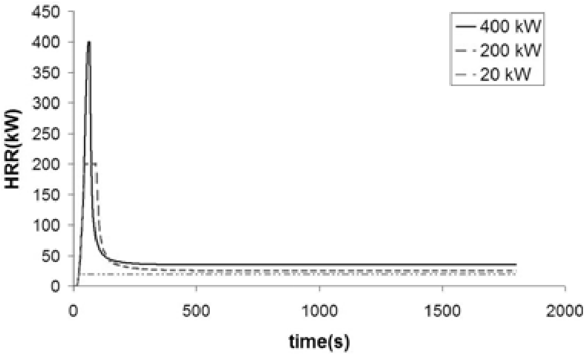

Fig. 6. Model-calculated heat release rate with 3 ACPH, without closing of the inlet vent, in the absence of insulator.

Fig. 7 represents the minimum unburnt gas rate obtained adjusting pyrolysis rate when unburnt gases are produced. Results show that, at low release rate, fire produces an almost non-existent unburnt gas rate, but that unburnt gases are present with a high heat release.

Fig. 8 shows the evolution of temperature in upper layer for three heat release rate: 20, 200 and 400 kW. At low heat release rate, temperature progressively increases but does not exceed 200°C. So an ignition of unburnt gases in the extraction vent seems unlikely at this HRR because their lower flammability limits are upper than these temperatures. At high heat release rate, temperature increases up to a peak of 550°C then decreases and stagnates at 300°C.

This study shows that, with a fire at low heat release rate, temperatures reached during the fire are below the lower flammability limits of major unburnt gases and unburnt gas rate is almost non-existent. So this rate is not favorable at an ignition. On the contrary, with a high heat release rate, temperatures and unburnt gas rate obtained favor an ignition but the last of the intensity peak is too short. An intermediate heat release rate would be used for fire tests in an 8-cubic-metre compartment at the Institut P' in order to have conditions that can give an ignition during a sufficient period.

During a fire in nuclear facilities, a guide of ventilation system is used to stop fire quickly. One of the possible guides consists in closing the inlet vent in order to decrease the quantity of available oxygen.

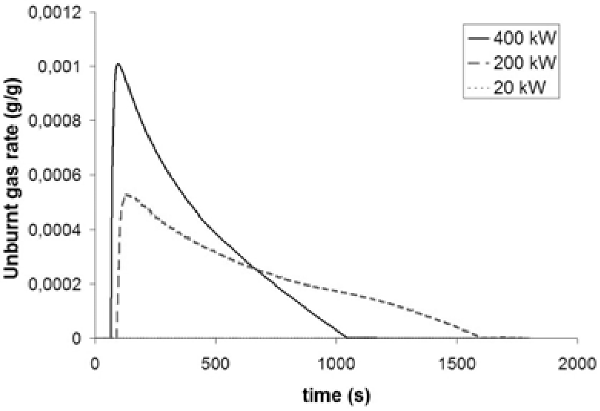

Fig. 7. Model-calculated unburnt gas rate with 3 ACPH, without closing of the inlet vent, in the absence of insulator for different heat release rate.

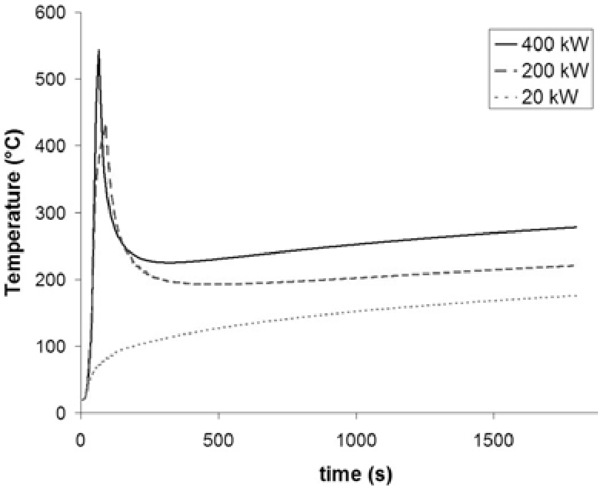

Fig. 8. Model-calculated temperature with 3 ACPH, without closing of the inlet vent, in the absence of insulator for different heat release rate.

Simulations have been made to know the impact of closing the inlet vent on the production of unburnt gases. The closing is tested at several stages of fire. Results show that a closing during the weakening period of fire gives similar evolutions than without closing. Fig. 9 compares the evolution of unburnt gas rates the reference simulation with the one when inlet vent is closed at 30 s, time tallied with the growth period of fire.

It is noted that, after the closing of the inlet vent, unburnt gas rate becomes more important than

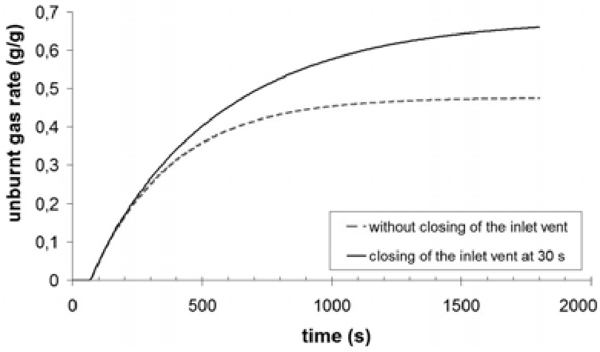

Fig. 9. Model-calculated unburnt gas rate with 3 ACPH, in the absence of insulator with closing of the inlet at 30 s and without closing.

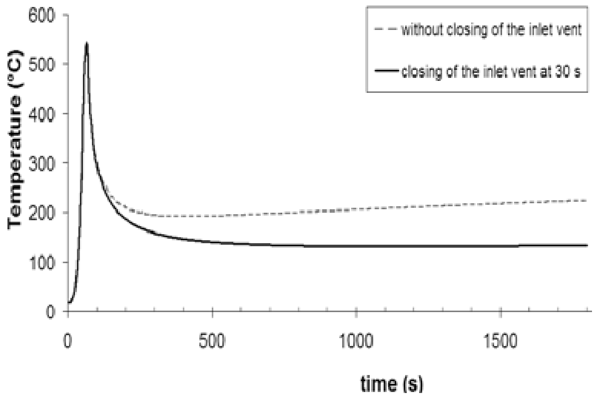

Fig. 10. Model-calculated temperature with 3 ACPH, in the absence of insulator with closing of the inlet at 30 s and without closing.

without closing. It is due to the fact that the quantity of available oxygen is limited and becomes insufficient to react with pyrolysis gases, so there are more unburnt gases.

Fig. 10 shows that, even if the closing of the inlet is carried out during the growth period of fire, similar temperature peaks is obtained. During the weakening period of fire, the closing of the inlet gives lower temperatures in the compartment due to smothering of fire.

The study of these factors shows that the use of an insulator favors the ignition hazard of unburnt gases and that three factors have an important influence: heat release rate, the closing of the inlet vent and the ventilation flow.

Critical case

A critical case, defined as the case that favors the ignition in the junction point in the extraction vent, is determined. A research of the case that gives the highest temperature in the extraction vent and the upper unburnt gas concentrations is done.

The previous part has shown that the presence of an insulator and an intermediate or a high heat release rate favor the ignition hazard. Four simulations are tested: in all of them, the insulator described in section Specific Objectives is used and a heat release rate of 400 kW is simulated. The Table 1 shows what ventilation flow is used and if the inlet vent is closed at 30 s for each case.

Fig. 11 presents the evolution of temperature in the upper layer. Results show that a ventilation flow of 3 ACPH favors temperatures. With 5 ACPH (cases B and D), temperatures after the peak are around 200°C that is below the lower flammability limit of major unburnt gases.

Table 1. Parameters used in the four simulations tested to determine the critical case.

Simulation	Closing of the inlet vent	ACPH
A	Yes	3
B	Yes	5
C	No	3
D	No	5

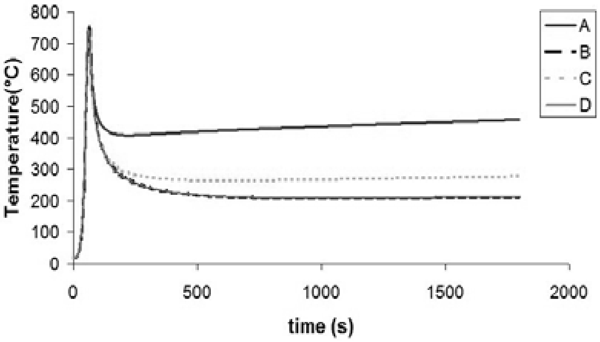

Fig. 11. Evolution of temperature for 4 simulations.

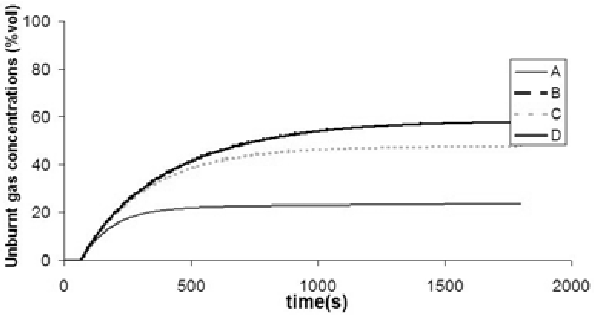

Fig. 12. Evolution of unburnt gas concentrations for 4 simulations.

An ignition will be difficult in this period. Case A with a closing of the inlet vent during the growth period seems to be the most favorable case for the ignition in the junction point of the extraction vent.

Fig. 12 presents the evolution of maximum unburnt gas concentrations for each case. It is noted that cases B and D favor the production of unburnt gases but as temperatures are too low to have an ignition, these cases are not accepted. MAGIC predicts a concentration of unburnt cases sufficient for an ignition with the two other cases but it only gives a gap of concentrations.

This study shows that cases A and C are the most favorable cases for the ignition but foreseen fire tests are needed to have the accurate evolution of unburnt gases and to confirm this trend.

Comparison with CDI

A comparison between results obtained with MAGIC and those obtained by CDI is presented. As CDI does not estimate unburnt gases, only the evolutions of temperatures and heat release rate are compared.

Fig. 13 shows several heat release rates calculated with MAGIC and CDI. At low heat release rate, results are similar. At high and intermediate heat release rates, the two fire modeling programs give the same intensity peak, due to the fact that the same $\alpha.t^2$ law is used during the growth period of fire. During the weakening period of fire, greater heat release rates are obtained with CDI because this software uses an envelope of hyperbola to simulate the general aspect of the HRR.

Fig. 14 presents temperatures predicted by MAGIC and CDI for several heat release rates.

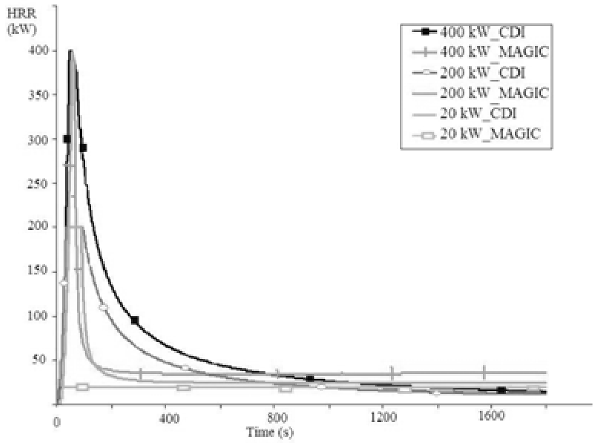

Fig. 13. Comparison between heat release rates predicted by CDI and by MAGIC with 3 ACPH, without closing of the inlet vent, in the absence of insulator.

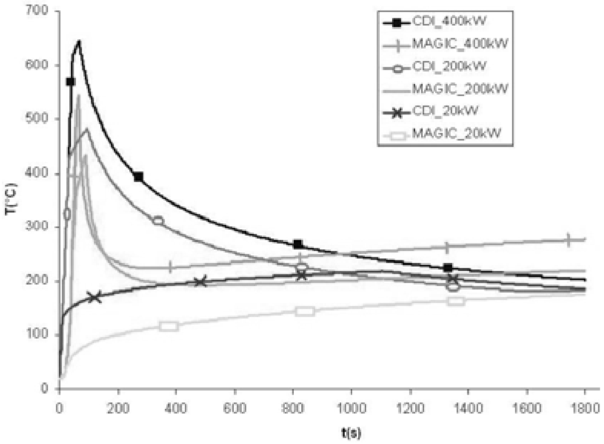

Fig. 14. Comparison between temperatures predicted by CDI and by MAGIC with 3 ACPH, without closing of the inlet vent, in the absence of insulator for different heat release rates.

As CDI uses security coefficients using in fire safety, temperatures in the average zone of CDI tallied with those of the upper layer in MAGIC. At low heat release rate, similar evolutions of temperatures are observed. At intermediate and high heat release rate, the same envelope of hyperbola than with HRR is used in CDI.

It is noted that CDI, as safety software, gives higher temperature than MAGIC. Results with fire tests at the Institut P’ should give results included between these two curves. Higher temperatures are obtained with MAGIC at the smothering of fire due to the slit used in MAGIC to simulate leaks at the level of openings.

Limits of this study

In order to study the ignition hazard of unburnt gases in the extraction vent, the composition and the evolution of gases, and especially unburnt gases, are needed. Yet MAGIC only gives an interval of unburnt gas concentrations. The accurate evolution and the composition of gases are unknown.

MAGIC gives average temperatures in the upper layer and in the extraction vent. However, during fire tests, hot temperatures in a point of the compartment could exist.

Moreover, the slit used in MAGIC to simulate leaks at the level of openings has an influence on temperatures and unburnt gases. Simulations have been done in order to estimate this influence. They show that more the slit is important, more unburnt gas rate during the weakening period of fire is minimized and more the temperature in the upper layer increases.

Lastly, on the level with the extraction vent of nuclear facilities, there is a junction point between other extraction vents that create a dilution. MAGIC does not allow to study this dilution.

CONCLUSIONS

This study is a preliminary work for some fire tests in an 8-cubic-metre compartment at the Institut P', in France.

Simulations with MAGIC have shown that fuel volume has not an influence on temperature in the compartment and on unburnt gas rate but only has an impact on the last of fire. The presence of insulator favors the ignition with an increase of temperature without changing unburnt gas rate. A low heat release rate is not favorable at an ignition because temperatures reached during the fire are below the lower flammability limit of major unburnt gases and unburnt gas rate is almost non-existent. On the contrary, an intermediate or a high heat release rate leads to temperatures and unburnt gas rate favorable for an ignition. Simulations show that a greater ventilation rate produces a dilution of compartment gases more important and provides more oxygen, which favors the oxidation of unburnt gases. Lastly, the closing of the inlet during the growth period of fire gives more unburnt gases but lower temperatures in the compartment during the weakening period of fire.

Critical case, favorable at the ignition in the junction point in the extraction vent, would be a test with an insulator, at an intermediate or a high heat release rate, with a ventilation flow that delivers 3 ACPH.

Comparisons with the software CDI give similar trends. Temperatures measured during fire tests should give results included between the two curves obtained by CDI and MAGIC.

Fire tests in an 8-cubic-metre compartment at the Institut P' will be confirmed these results. During these fire tests, a quantification of unburnt gases will be made and the hazard of ignition in the extraction vent at the junction point between other extraction vents will be studied.

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