Experimental Study about the Influence of Heat Tightness of an Enclosure Fire on Ignition Risk of Unburnt Gases in a Connected Exhaust System

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ABSTRACT

This experimental study was performed from a reduced scale enclosure with a length/height and width of 2 m. In this work, we investigate whether heat tightness of enclosure can change the compartment fire dynamics and pose ignition risk in exhaust system. An external ventilation system provides an air supply rate ranging from 24 to 40 m³/h, corresponding respectively to 3 and 5 Air Change Per Hour (ACPH). A circular dodecane pan with a diameter of 40 cm is placed in the middle of the enclosure. Two situations with and without insulation of the enclosure are compared for several ACPH. The results show that heat tightness of enclosure leads to faster fire growth implying more important peak in heat release rate, and thus more dangerous fire with regarding the ignition risk. Heat tightness of enclosure makes the depression level of the compartment decrease, and consequently the air inlet supply rate decrease too, but the mass loss rate of liquid fuel increase. With heat tightness of enclosure, the fire becomes very-under-ventilated, and the vaporized fuel does not completely contribute to the heat release due to a significant formation of the unburnt gases as hydrocarbons, CO and H₂. It is found that ignition of unburnt volatiles near the exhaust system occurs more easily when the compartment is more heat-tight. Oscillating flames in under-ventilated conditions were observed experimentally due to the ignition/extinction of the liquid fuel pan in a vitiated air enclosure. After the fire extinction, the remaining flames as ghosting flame in the vicinity of the enclosure ceiling were not observed under lowered oxygen vitiation with a mass fraction of around 7%. With a time delay of about 15 min in the current situation, the energy released per mass of oxygen consumed allows to raise the temperature of fuel-air mixture to about 300°C high enough for ignition of the unburnt gases. When the molar fraction of unburnt fuels is above the low flammability limit, any return of air from dilution duct after the fire extinction in a vitiated air enclosure could lead to spontaneous ignition near the extraction duct without needing a pilot flame. Note that heat-tightness of enclosure contributes to a reduction in the ignition delay time at entrance of the connected extraction duct due to a quick accumulation of unburnt fuel gases there. The experimental results from such reduced scale enclosure can be extended to a full scale one by imposing a preservation of the ratio (\(\dot{Q}/L^4\)) between heat release rate (\(\dot{Q}\)) and characteristic length (L). This relationship is derived from dimensionless variable of the energy equation.

KEYWORDS:

risk assessment; ignition risk; fire growth; compartment fires; liquid fuel; heat tightness; extraction duct; dilution; depression
INTRODUCTION
Ignition has gained increasing attention in fire science mainly in industrial scenarios, though knowledge is limited for explosions or gas deflagrations through ventilation system. This phenomenon generally occurs when the fire is ventilation-controlled or during its extinction phase, typically when a compartment containing a fire has a very limited fresh air supply. Liquid pool fires usually generate a significant hazard in an enclosure due to the amount of unburnt volatile gases. The liquids could originate e.g. from leaks from transformers generators or other machinery. Knowing the liquid fire burning rate is the starting point of any fire safety analysis. The factors affecting the burning rates of liquid pool fires in open atmosphere are well known for a wide variety of liquids [1, 2]. However, many liquid pool fire scenarios involve fires in highly confined spaces, especially encountered in the nuclear facilities but also in the current constructions. The burning rate can be significantly different from the ones measured in open atmosphere [3]. These differences are caused essentially by the influence of air ventilation, heat radiation from hot walls and hot gas layer.

In order to contain the potential release of radioactive material and avoid dispersion to the outside, nuclear installations are rapidly moving towards building envelopes more air and heat-tight [4]. Intensive research has been carried over decades on the oscillatory phenomena of unstable flame under confined conditions with mechanically ventilation system [4-6]. The low-frequency oscillating flames were observed [4, 5] with a drastic change in flame behavior in a vitiated air enclosure. There is still a lack of knowledge for complete understanding of an oscillatory behavior but conjectured that issues involved are ignition/extinction of condensed fuel, phenomena leading to a reverse flow in the supply ventilation system and successive combustion of unburnt gases [4, 5]. Only a small proportion of the work has looked specifically the effect of heat tightness of enclosure on the fire behavior, notably the thermal stratification of the unburnt fuel [7].

In a typical ignition scenario, the atmosphere in the extraction duct consists of large un-combusted gases with a concentration generally above the lower flammability limit at elevated temperature. The experimental study of Lassus [8] showed that in a highly confined setting with interconnecting ventilation ducts, an extraction duct is an important pathway for the onset of ignition of a flammable mixture of pyrolysis gases and vitiated air with presence of a dilution duct. Indeed, with a compartment well heat-tight, heat feedback to the surface of liquid fuel is more important in comparison with that less heat-tight [9]. We can expect that the ignition-related risks may become more significant when the enclosure is more heat-tight. In the current study, we verified theoretically and experimentally the influence of heat tightness of enclosure on the compartment fire dynamics and the ignition delay time at entrance of the extraction duct.

EXPERIMENTAL SET-UP
The experimental facility with a length/height and width of 2 m and its geometry are shown in Figure 1(a, b). An external ventilation system consisting of two intake and an extraction ducts, provides an air supply rate ranging from 24 to 40 m³/h, corresponding respectively to 3 and 5 Air Change Per Hour (ACPH). Ducts have a square section of 0.2x0.2 m². The intake was placed closer to the floor at a height of 0.3 m and the exhaust was placed near the ceiling at a height of 1.7 m. Walls of the enclosure are made of concrete (thermal conductivity: \( \lambda_1 = 1 \, \text{W/m.K} \), density: \( \rho =2100 \, \text{kg/m}^3 \), specific heat: \( C_p=0.88 \, \text{kJ/kg.K} \)) with a thickness of 0.2 m; there is always a conductive heat loss through the walls during the fire. The enclosure is considered as perfectly heat tight when the wall and ceiling are recovered by an insulating material as Promatech H ( \( \lambda_1 = 0.175 \, \text{W/m.K} \), \( \rho =400 \, \text{kg/m}^3 \), \( C_p=0.92 \, \text{kJ/kg.K} \)) with a thickness of about 0.035 m.

The stainless-steel circular pan with a diameter of 40 cm was placed in the middle of the enclosure, slightly elevated at a height of 0.3 m. Dodecane is typically used as the fuel load, and a good repeatability was obtained with a difference below 5% for each fire tests. The fuel mass was continuously monitored using a load cell, installed under the pan. Measurements performed include pressure, temperature and chemical species concentrations of gases filling the enclosure. As shown in Fig.1b), the gas temperature was analyzed from seven vertical profiles inside the enclosure, at the extraction duct and the dilution one. Each of the seven profiles comprises eight thermocouples positioned at regular intervals of 0.2 m over the height of the enclosure.

A mechanical ventilation network is used for air supply by using a centrifuge fan at the end of the dilution duct with a fixed speed (cf. Fig.1a). Before activating the fire, a period of 10 minute was included for establishing a depression below atmospheric pressure inside the enclosure. The depression level is a function of the Air Change Per Hour (ACPH) of the enclosure, depending on the resulting outlet volume flow rate of the fan at the end of the extraction duct. After activating the fire, the velocity, the temperature and the pressure at both the intake and
extraction ducts are connected to the fire dynamic. Under the depression condition, the experimental facility is not perfectly airtight mainly due to passage of the thermocouples through the wall. Based on the mass conservation at the admission and extraction ducts, the leakage area around the enclosure is estimated in the order of 14 cm$^2$.

RESULTS AND DISCUSSION

Histories of the relative pressure ($P_0-P$) and the inlet velocity for 5 ACPH at the admission duct are illustrated in Figure 2. Here, $P_0$ denotes the atmospheric pressure, and $P$ the enclosure one. The fire-induced pressure can be said to follow three main stages: 1) activating the fire causes an overpressure inside the compartment which leads to a significant reduction in the inlet flow velocity at the admission duct; 2) with some time delay, the fully developed fire becomes ventilation controlled due to the fire growth, resulting in large fluctuations of the pressure and oscillations of the inlet velocity; 3) during the decay phase, extinction induces a depression peak, followed by a significant increase in velocity of fresh air supplied by the admission duct. Heat-tightness of the enclosure can sensitively reduce the depression level (Fig.2b), and consequently, the air inlet velocity from the admission duct. Therefore, heat-tightness of an enclosure has a significant impact on the dynamic confinement which prevent from hazardous gas leaks.

Fig. 2. Evolution of the pressure and inlet velocity at 5 ACPH. a) with heat loss; b) with heat tightness

A typical evolution of the mass loss rate and the associated HRR at 3 and 5 ACPH with heat loss and tightness is illustrated in Fig.5(a-d). Note that we lack the ability to accurately quantify the HRR by using oxygen calorimetry in such confined facility. Based on the measured mass loss rate $\dot{m}$, the theoretical HRR is derived as $Q = \dot{m}c_L$. The effective HRR is approximately determined from the variation of the oxygen concentration.
$\Delta Y_{O_2}$ at the entrance of extraction duct and the inlet air rate ($m_A$) as: $Q = (Y_{O_2} - r_{in})\Delta Y_{O_2}\Delta H_{L}$. Here, $\Delta H_{L}$ and $\Delta H_{L}$ are the energy released per kilogram of fuel and oxygen consumed, respectively. With heat loss of enclosure (cf. Fig.3a, c), an increase of ACPH from 3 to 5 contributes to an increase of the mass loss rate due to the higher ventilation flow rate over the liquid surface, which enhances liquid vaporization rate via convection. With heat tightness of enclosure (cf. Fig.3b, d), the hotter smoke spreads rapidly towards the liquid base, resulting in a significant increase of the mass loss rate due to the enhanced radiative heat feedback to the liquid surface. The mass loss rate is practically insensitive to an increase of ACPH under the heat-tight conditions due to the dominant radiative heat transfer. In the initial growth phase, burning is fuel-controlled with a stable flame. Followed by the fully developed, post-flashover phase, in which burning is ventilation controlled with appearance of an unstable flame. The lowered oxygen vitiation induces oscillations of the HRR following the trend of the mass loss rate due to an unstable flame. The oscillatory phenomena of the HRR is attributed to the coupling process between the fuel evaporation rate and the inlet flow rate of air, both attached to heat tightness of enclosure. With heat loss of enclosure (cf. Fig.3a, c), the HRR curves show a gradual growing trend with a moderate peak of about 90 kW. The oxygen concentration initially present in the enclosure and the one supplied by mechanical ventilation entrain a sufficiently ventilated fire. The effective HRR corresponds approximately to the theoretical one derived from the mass loss rate because the reaction is almost complete. It is observed that a heat tightness of enclosure leads to the ultra-fast fire growth (cf. Fig.3b, d), and flashover is clearly identified by a rapid increase of HRR from 40 to 140 kW. The ultra-fast growing fire in a very consistent manner becomes progressively oxygen limited, that is to say ventilation-controlled, and the theoretical HRR is higher than the effective one. The extinction due to unstable combustion in a vitiated air enclosure happened early when the wall envelope is heat-tight.

![Fig. 3. Evolution of the mass loss rate and HRR. a) Heat loss at 3 ACPH with extinction due to burn out; b) Heat tightness at 3 ACPH with extinction due to unstable combustion; c) Heat loss at 5 ACPH with extinction due to burn out; d) Heat tightness at 5 ACPH with extinction due to unstable combustion](image-url)
In such reduced scale enclosure, the Dodecane pan of 40 cm in diameter leads to under-ventilated fire, thus generating a large amount of unburnt volatiles as hydrocarbons, CO and H₂. The molar fraction of such unburnt volatiles near the extraction duct is presented in Figure 4(a-d). The aim of this study is to verify if the auto-inflammation risk occurs when the unburnt fuel concentration is beyond the Low Flammability Limit (LFL) at the point of Auto-Ignition Temperature (AIT) [10]. The \( LFL_i \) of each fuel and the \( LFL \) of gas mixtures as a function of the fuel molar fraction \( X_i \) of each fuel composing it are determined as well as a function of the gas temperature as follows:

\[
LFL_i(T) = LFL_i(T_0) \left(1 - \frac{T - T_0}{1300 - T_0}\right)
\]

and

\[
LFL(T) = 100\% \sum X_i LFL_i(T_i)\%
\]

The values of the AIT and LFL at \( T_0=25^\circ\text{C} \) [10] for three fuel species are summarized in Table 1.

| Parameter | CO     | H₂     | Dodecane |
|-----------|--------|--------|----------|
| LFL (T=25°C) | 12.5%  | 4%     | 0.6%     |
| AIT (°C)     | 588    | 520    | 204      |

Fig. 4. Risk assessment of unburnt gas ignition at entrance of the extraction duct. a) with heat loss at 3 ACPH; b) with heat tightness at 3 ACPH; c) with heat loss at 5 ACPH; d) with heat tightness at 5 ACPH

With heat loss of the enclosure at 3 ACPH (cf. Fig.4a), ignition was not observed experimentally due to less important formation of the stratified hotter unburnt fuels layer even the gas temperature is above 300°C high enough for ignition. It is clear that the ignition is not merely dependent on the existence of the fuel-air mixture with a concentration beyond the LFL at the AIT points near the entrance of the extraction duct. As illustrated in Fig.4b, we can see that with heat tightness of the enclosure, starting from 250 s, the molar fraction of unburnt fuels is above the low flammability limit (LFL) at the entrance of the extraction duct. For many minutes, the
energy released per mass of oxygen consumed allows to raise the temperature of fuel-air mixture above the AIT near the ceiling. With a time delay of about 900 s, the auto-ignition would be caused near the extraction duct due to a return of air from dilution duct after the fire extinction at the gas temperature of about 400°C high enough for ignition. The phenomena with ignition near the extraction duct can be characterized by a rapid decrease of unburnt fuel concentration towards a stoichiometric fuel-air mixture and a sharp increase of temperature with a peak reaching a typical flame temperature of 550°C there. It seems that the global equivalent ratio, 0 = $\dot{m}_F$ / $\dot{m}_A$, calculated from the fuel supply rate $\dot{m}_F$, air inflow rate $\dot{m}_A$, and stoichiometric coefficient $s$, higher than 1.5 represents a set of dangerous conditions, as any return of air from dilution duct after the fire extinction could lead to spontaneous ignition near the extraction duct. In Fig.4c with heat loss of the enclosure, occurrence of auto-ignition near the extraction duct was consistently observed at 5 ACPH with a longer time delay of about 1320 s after the extinction at 1250 s with presence of a return of air from dilution duct. As illustrated in Fig.4d, heat tightness of the enclosure contributes to a significant reduction in the ignition delay time to about 780 s due to a rapid formation of the hotter unburnt fuels layer near the ceiling. This is mainly attributed to a sharp increase of the mass loss rate at the initial fire growth stage up to 200 s (cf. Fig.3b, d).

CONCLUSION

In summary, heat-tightness of enclosure can sensitively increase the mass loss rate, and reduce the inlet air flow rate due to a lower depression level inside enclosure, both decreasing the oxygen concentration. This implies that burning is quickly ventilation controlled with heat-tightness of enclosure, forming significant amount of unburnt volatiles. If the concentration of unburnt volatiles is above LFL, and the fire has been established for sufficiently long (in the current study, more than 10 min), there is significant risk of ignition inside the extraction duct without needing a pilot flame. Occurrence of an ignition of the hotter concentrated unburnt fuels at entrance of the extraction duct is attributed to a return of air from dilution duct at the stage of fire extinction which induces a sharp increase of depression level inside enclosure. The experimental results show clearly that ignition can happen early near the extraction duct, as long as the enclosure remains sufficiently heat tight. With heat loss of the enclosure, occurrence of ignition is also identified but with a longer time delay. The current study can be applied to a full scale enclosure fire with a volume of approximately 100 m$^3$. This implies that ignition of unburnt fuel gases may occur in an exhaust system when the HRR is beyond 1.2 MW, corresponding approximately to a global equivalence ratio beyond 1.5. The work is continuing with the aim of improving the evaluation of auto-ignition near the extraction duct by measuring more detailed chemical species and heat flux over the liquid surface.

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