

THEORETICAL CONSIDERATION IN DEVELOPING RIGS FOR STUDYING EXPLOSION CONTROL IN RESIDENTIAL FLATS

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ABSTRACT

There are demands in protecting firemen by reducing the possibility of gas explosion in residential buildings. A method with an experimental rig was proposed to study how explosion can be controlled. The theory concerned will be explored in this paper by reviewing literature results. The technique would then be assessed vigorously.

1. INTRODUCTION

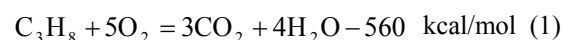
Explosion control on gas leakage in semi-enclosed small compartments should be studied carefully. Such incidents happened frequently throughout the Far East, with over eight cases in about 10 years in Hong Kong.

Feasibility tests by injecting chemical agents into the site will be carried out in a small-scale deflagration experimental rig first. Based on the preliminary results, larger-scale experiments on different explosion suppressants can then be carried out.

A detonation experimental rig will be developed to measure useful data for designing feasible explosion control methods for real-scale scenarios. Verification tests will then be conducted in a full-scale space. Theoretical background of the methodology with reference to the literature will be reported in this paper.

Explosion due to liquefied petroleum gas (LPG) will be considered. LPG is composed of 70% propane (C₃H₈), 10% propene (C₃H₆), and about 15% mixture of butane (C₄H₁₀) and butene (C₄H₈). Generally, it is liquefied in the bottle at a pressure of 0.8 to 1.5 MPa, and a density about 520 kgm⁻³. Upon flowing out in liquid state, it will be changed to gas of volume expanded by 250 times [1-3].

The main combustion reaction is:



In general, complete reactions will require 5.5 times volume of oxygen or 25 times volume of air.

The explosion limits for the mixture of LPG and air is about 2.3 to 64%. When the mixing ratio of LPG to oxygen is within the range 1:45 to 1:6.5, the combustion temperature can go up to 2600°C. The rate of flame spread under a pressure of 1 atm can reach 0.85 ms⁻¹, and its explosion pressure can be as high as 0.8 MPa. Under normal conditions, the shock wave peak pressure ΔP that a person can stand is lower than 0.02 MPa. The pressure ΔP that two layers of brick wall can stand is about 0.045 MPa, and that for a 0.25 m thick reinforced concrete wall is about 0.3 MPa.

The mixture density of fuel and air is about 1.35 kgm⁻³. The volume of the small-scale deflagration experimental duct V can be calculated from the length L and diameter D :

$$V = \frac{\pi}{4} D^2 \cdot L \quad (2)$$

V is 0.14 m³ for this rig.

If the combustion experiment is to be carried out at a pressure of 1 atm, 10 g fuel and 180 g air, or 32 g fuel and 158 g air can be discharged into the duct of 0.14 m³. When compressing the pressure inside the duct to 2 atm, then 20 g fuel and 360 g air, or 64 g fuel and 316 g air can be discharged into the duct to simulate deflagration. If the pressure is further compressed to 3 atm, then 30 g fuel and 540 g air, or 96 g fuel and 474 g air can be used.

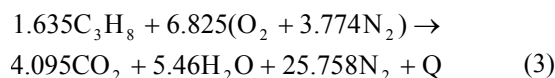
To simulate an explosion with stronger intensity, a larger mixing chamber with a bigger explosion pressure is required [4].

In the designed experimental installation, a mixing ratio of LPG/oxygen between 8% and 15% would be suitable for simulating the actual deflagration, and the maximum pressure is 0.8 MPa.

2. HEAT RELEASE RATE

The heat of explosion for 1 kg of the LPG gas-air mixture (C_3H_8 and air) will be calculated first. The values are then multiplied by the heat of explosion under 1.0, 2.0 and 3.0 atm in the designed installation. Under these three different applied differential pressures of 1 atm, 2 atm and 3 atm, 0.19 kg, 0.38 kg and 0.57 kg of mixture can be discharged respectively into the designed installation [3,4].

The simplified reaction is:



The heat release rate Q of the mixture can be calculated by:

$$\dot{Q} = -\Delta H = -\left[\left(\sum n_j \Delta H_{j,298}^0 \right) - \left(\sum n_i \Delta H_{i,298}^0 \right) \right] \quad (4)$$

Putting in numerical values of $\Delta H_{j,298}^0$ for the j^{th} gas component:

$$Q = -\left[\left(\sum n_j \Delta H_{j,298}^0 \right) - \left(\sum n_i \Delta H_{i,298}^0 \right) \right] \quad (5)$$

Putting in numerical values for Q in MJ/kg gives:

$$Q = -\left[4.095 \times (-393.78) + 5.46 \times (-242) - 1.365(-103.92) \right] \text{ MJ/kg}$$

or

$$Q = 2.792 \text{ MJ/kg}$$

The heat release rates under the three applied differential pressures are calculated to be:

$$Q_{1\text{atm}} = 2.792 \times 0.19 \text{ MJ} = 0.53 \text{ MJ}$$

$$Q_{2\text{atm}} = 2.792 \times 0.38 \text{ MJ} = 1.06 \text{ MJ}$$

$$Q_{3\text{atm}} = 2.792 \times 0.57 \text{ MJ} = 1.58 \text{ MJ}$$

3. TEMPERATURE INSIDE THE EXPERIMENTAL DUCT

Under adiabatic conditions in the deflagration process, and assuming that all the heat released from the deflagration reaction is used to heat up the combustion products, the heat efficiency of reaction under constant pressure is:

$$Q_p = \int_{T_0}^{T_f} C_p dT = (T_f - T_0) \sum n_i C_{pi}^0 \quad (6)$$

or

$$Q_v \approx Q_p = \sum_{i=1}^n n_i \Delta H_i^0 \quad (6a)$$

From the previous calculation of $Q = 2.792 \text{ MJ}$, the combustion temperature can be obtained.

Assume that $T_f = 2000 \text{ K}$ and $T_0 = 298 \text{ K}$, from the enthalpy chart in thermodynamics:

$$CO_2 : C_p^0 = 60.376 \text{ J/mol}$$

$$H_2O : C_p^0 = 51.344 \text{ J/mol}$$

$$N_2 : C_p^0 = 35.984 \text{ J/mol}$$

Putting in numerical values gives:

$$\begin{aligned} (T_f - T_0) \sum n_i C_{pi}^0 &= (2000 - 298)(4.095 \times 60.376 + \\ & 5.46 \times 51.334 + 25.758 \times 35.984) \text{ J} \\ &= 2.496 \text{ MJ} \end{aligned}$$

This value is less than Q of 2.792 MJ.

Again, assuming that $T_f = 2200 \text{ K}$ and $T_0 = 298 \text{ K}$, from the enthalpy chart in thermodynamics:

$$CO_2 : C_p^0 = 60.863 \text{ J/mol}$$

$$H_2O : C_p^0 = 52.623 \text{ J/mol}$$

$$N_2 : C_p^0 = 36.278 \text{ J/mol}$$

Then,

$$(T_f - T_0) \sum n_i C_{pi}^0 = 2.82 \text{ MJ}$$

This value is greater than Q of 2.792 MJ.

Putting in the values:

$$T_r = \left(2200 - 200 \times \frac{2.82 - 2.792}{2.82 - 2.496} \right) K$$

$$= 2186 K$$

4. FLAME SPREADING RATE BEFORE OPENING THE PRESSURE RELEASE OUTLET

In the experiment, the flame area A and the cross-sectional area of the duct are the same. In view of equation (2) on V and L :

$$\frac{A}{V} = \frac{A}{AL} = \frac{1}{L} \quad (7)$$

Assume that α is the turbulent coefficient ($\alpha = 1$ for no turbulence), P_0 is the initial pressure, P_m is the maximum pressure reached, and K_r is the burning rate under ambient pressure, the rate of pressure P changes [5] is:

$$\frac{dP}{dt} = \frac{\alpha K_r A P (P_m - P_0)}{V P_0} = \frac{\alpha K_r P (P_m - P_0)}{L P_0} \quad (8)$$

In the above equation, $\frac{dP}{dt}$ is proportional to P .

When P reaches a maximum value P_m , the rate of pressure rise is also a maximum:

$$\left(\frac{dP}{dt} \right)_{\max} = \frac{\alpha K_r P_m (P_m - P_0)}{L P_0} \quad (9)$$

In this experiment, the length of the duct L is 2.0 m, K_r is 0.5 ms^{-1} and $P_0 = 10^5 \text{ Pa}$, then,

$$\left(\frac{dP}{dt} \right)_{\max} = 1.4 \text{ MPa/s}$$

The burning time t_{\max} is:

$$t_{\max} = \frac{\ln \frac{P_m}{P_0}}{\alpha K_r \left(\frac{P_m}{P_0} - 1 \right)} \cdot L \quad (10)$$

Putting in numerical values gives:

$$t_{\max} = \frac{2.08}{1.75}$$

or

$$t_{\max} = 1.19 \text{ sec}$$

The rate of flame spread is:

$$\frac{dx}{dt} = \alpha K_r \frac{P_m}{P} = \alpha K_r \frac{P_m}{P_0} \left[1 - \frac{x}{L} \left(1 - \frac{P_0}{P_m} \right) \right] \quad (11)$$

As

$$K_1 = \frac{\alpha K_r (P_m - P_0)}{L P_0},$$

then

$$\frac{dx}{dt} = \alpha K_r \frac{P_m}{P_0} - K_1 x \quad (12)$$

Integrating the above gives:

$$\ln \frac{\alpha K_r \left(\frac{P_m}{P_0} \right)}{\alpha K_r \left(\frac{P_m}{P_0} \right) - K_1 x} = K_1 t$$

or

$$x = \frac{L P_m}{P_m - P_0} (1 - e^{-K_1 t}) \quad (13)$$

For $P_0 = 1 \times 10^5 \text{ Pa}$,

$$K_1 = \frac{1 \times 0.5(8-1) \times 10^5}{2 \times 10^5} = 1.75$$

and

$$x \approx 2(1 - e^{-1.75t})$$

The values of x at different time are shown in Table 1.

Table 1: Flame spreading rate

t/s	0	0.5	1.0	1.2	1.3	1.8
x/m	0	1.16	1.65	1.75	1.79	1.92

5. THE DESIGN OF THE PRESSURE RELEASE OUTLET

The pressure release outlet is the most important part of the experimental setup. If there is no pressure release outlet, a destructive explosion will occur. The area of the outlet A_V will affect the variation and maximum value of pressure inside the duct.

The ignition surface is at the front part of the sealed duct, and the pressure release outlet is at the rear end. When the pressure inside the duct has increased to the critical value, the gas at the outlet will reach the speed of sound. Any further increase in pressure will raise the flow rate at the outlet to the speed of sound.

$$a^* = \sqrt{\frac{2\gamma}{\gamma+1}RT_f} \quad (14)$$

and

$$\frac{P_*}{P_0} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

P_* is the critical pressure when γ is 1.4. P_0 will rise to $1.89 P_a$ where P_a is ambient pressure, taking a value of 1.915×10^5 Pa when P_a is 1.013×10^5 Pa. When the pressure inside the duct is larger than P_0 , the mass flowing out at the outlet remains unchanged and the flow rate is:

$$\frac{dm}{dt} = \frac{A_v P}{T} \left\{ \frac{2\gamma}{R(\gamma-1)} \left[\left(\frac{2}{R(\gamma-1)}\right)^{\frac{2}{\gamma-1}} - \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} \right] \right\}^{\frac{1}{2}}$$

for $P > P_*$ (15)

For mixed burning gas, $R = 287 \text{ Jkg}^{-1}\text{K}^{-1}$ and $\bar{M} = 0.02897 \text{ kgmol}^{-1}$, the mass flow rate expressed in mol is:

$$\frac{dn_e}{dt} = \frac{1}{\bar{M}} \frac{dm}{dt} \quad (16)$$

Putting in numerical values gives:

$$\frac{dm}{dt} = 40.32 \times 10^{-3} \frac{A_v P}{\sqrt{T}} \quad (\text{kg/s})$$

$$\frac{dn_e}{dt} = 1.392 \frac{A_v P}{\sqrt{T}} \quad (\text{mol/s})$$

Under isothermal conditions,

$$\frac{dP}{dt} = \frac{RT}{V} \left(-\frac{dn_e}{dt} \right) = \frac{RT}{V} \left(-1.392 \frac{A_v P}{\sqrt{T}} \right) \quad (17)$$

Before ignition in the duct, $T = 293 \text{ K}$ and $R = 8.314 \text{ Jmol}^{-1}\text{K}^{-1}$

$$\frac{dP}{dt} = -198 \frac{A_v}{V} P \quad (18)$$

When $P > P_* = 1.915 \times 10^5$ Pa, the pressure variation with time inside the duct is $\frac{A_v}{V} \approx \frac{7 \times 10^{-4}}{0.14} = 0.005$.

$$\ln \frac{P}{P_m} = -198 \times 0.005t = -0.99t$$

When $T = 2186 \text{ K}$ (after ignition),

$$\ln \frac{P}{P_m} = -389 \times 0.005t = -1.945t$$

The values of t at different $\frac{P_m}{P}$ are shown in Table 2.

Table 2: Values of $\frac{P_m}{P}$ at different time

T/K	$\frac{P_m}{P}$	2	3	4	5	6	7	8
293	t/s	0.69	1.1	1.38	1.61	1.79	1.95	2.08
2186	t/s	0.36	0.56	0.71	0.83	0.92	1.0	1.07

6. GAS RELEASE TIME WHEN THE PRESSURE INSIDE THE DUCT IS LOWER THAN THE CRITICAL VALUE

When the pressure P inside the duct is lower than the critical pressure P_* , the flow at the opening plane A_v is subsonic and the external pressure is P_a . Then,

$$\frac{dm}{dt} = 0.158 \frac{A_v P}{\sqrt{T}} \left[\left(\frac{P_a}{P}\right)^{\frac{2}{\gamma}} - \left(\frac{P_a}{P}\right)^{\frac{\gamma+1}{\gamma}} \right]^{\frac{1}{2}} \quad (19)$$

When $1 \leq \frac{P}{P_a} \leq 2$,

$$\frac{dm}{dt} = 83.53 \times 10^{-3} \frac{A_v}{\sqrt{T}} \left(\frac{P - P_a}{P_a} \right)^{\frac{1}{2}} \text{ kgs}^{-1} \quad (20)$$

or

$$\frac{dn_e}{dt} = 2.883 \frac{A_v P_a}{\sqrt{T}} \left(\frac{P - P_a}{P_a} \right)^{\frac{1}{2}} \text{ mols}^{-1} \quad (20a)$$

When the temperature inside the duct is 2186 K and R is $8.314 \text{ Jmol}^{-1}\text{K}^{-1}$,

$$\frac{dP}{dt} = -354511 \frac{A_v}{V} (p - 10^5)^{\frac{1}{2}} \quad (21)$$

Substituting $\frac{A_v}{V} = 0.005$, integration gives:

$$(P_m - 10^5)^{\frac{1}{2}} - (p - 10^5)^{\frac{1}{2}} = 886.3 t \quad (22)$$

At subsonic outflow, $P_m = 2 \times 10^5 \text{ Pa}$.

From equation (22) for $t = 0$ and $P = 2 \times 10^5 \text{ Pa}$, the t^2 relationship between $p - t$ descends to $P_a = 1 \times 10^5 \text{ Pa}$. The time required t for $P_m = 2 \times 10^5 \text{ Pa}$ to decrease to $P_a = 1 \times 10^5 \text{ Pa}$ is 0.36 s.

Therefore, the working time for the experiment is 1.55 s (1.19 s + 0.36 s). This information is important to provide the correct discharging time of the explosion suppressant after ignition. The total working time has to be taken into consideration in various aspects including the transmission of electric signals, the operation of discharge nozzles, the quantity discharged, and the number and position of the nozzles [4,5].

7. PRESSURE VARIATION INSIDE THE DUCT AFTER OPENING THE PRESSURE RELEASE OUTLET, WITH IGNITION IN THE FRONT

Pressure variation equation given by equation (8) is:

$$\frac{dP}{dt} = \frac{\alpha K_r P (P_m - P_0)}{L P_0} - \frac{R T_u^{\frac{1}{2}} K_v (P - P_0)^{\frac{1}{2}} V_r}{100} \quad (23)$$

Pressure release ratio is:

$$V_r = 100 \frac{A_v}{V}$$

$$P_0 V = n_0 R T_u$$

where P_0 and T_u are the pressure and temperature inside the duct before burning respectively.

$$n_0 = n_u + n_b + n_e \quad (24)$$

where n_0 is the initial mass inside the duct, n_b is the mass burnt, n_u is the mass not yet burnt and n_e is the mass flowing out.

The rate of flame spread is:

$$\frac{dx}{dt} = \left[\frac{P_m}{P_0} - \frac{x}{L} \left(\frac{P_m - P_0}{P_0} \right) \right] \alpha K_r + \frac{x R T_u^{\frac{1}{2}} K_v (P - P_0)^{\frac{1}{2}} V_r}{100 P} \quad (25)$$

The above two equations are applicable to unburned gases under ambient temperature. When the flame front reaches the pressure release outlet, the temperature of the gas released is T_b . The equation at this time is [5,6]:

$$\frac{dP}{dt} = \frac{\alpha (P_m - P_0) K_v A P}{V P_0} - \frac{R T_u K_v A_v (P - P_0)^{\frac{1}{2}}}{V T_b^{\frac{1}{2}}} \quad (26)$$

The rate of flame spread is:

$$\frac{dx}{dt} = \left[\frac{P_m}{P_0} - \frac{x}{L} \left(\frac{P_m - P_0}{P_0} \right) \right] \alpha K_r + \frac{x R T_u A_v K_v (P - P_0)^{\frac{1}{2}}}{V T_b^{\frac{1}{2}} P} \quad (27)$$

Although the integral of $p - t, x - t$ cannot be obtained from the above two equations, it can be seen that:

- The rate of pressure rise $\frac{dp}{dt}$ is not related to the distance that the flame has traveled x .
 - When $x = 0$, the flame spreading rate is $\alpha K_r P_m / P_0$.
 - When $x = L$,
- $$\frac{dx}{dt} = \alpha K_r + \frac{L R T_u^{\frac{1}{2}} K_v K_r (P - P_0)^{\frac{1}{2}}}{100 P} \quad (28)$$
- The rate of pressure rise depends on two terms with and without the pressure release ratio. When $K_v = 0$, that is $\frac{dp}{dt}$ in the sealed duct.

For LPG, when the fuel/air mixing ratio is 5%, $K_r \approx 30 \text{ cms}^{-1}$, α is taken as 1; then when $x = 0$,

$$\frac{dx}{dt} = \alpha K_r \frac{P_m}{P_0} = 0.3 \times 3 = 0.9 \text{ ms}^{-1}$$

where K_r is the burning rate under the reference temperature T_r and reference pressure P_r . Here, the initial value is taken as $P_m = 3 \times 10^5 \text{ Pa}$ at $x = 0$.

When $x = L$,

$$V_r = \frac{A_v}{V} \times 100 = \frac{7 \times 10^{-4}}{0.14} \times 100 = 0.5$$

$K_v = 918 \text{ mol} \cdot \text{K}^{1/2} / (\text{m}^2 \cdot \text{Pa}^{1/2} \cdot \text{s})$ is the coefficient of subsonic flow through the pressure release outlet.

When $x = L$, $P = 6 \times 10^5 \text{ Pa}$, then

$$\frac{dx}{dt} = 0.3 + \frac{2 \times 8.314 \times 293^{1/2} \times 918 \times 0.5 (6 \times 10^5 - 1 \times 10^5)^{1/2}}{100 \times 6 \times 10^5} \\ = 1.84 \text{ ms}^{-1}$$

When $x = L$, $P = 8 \times 10^5 \text{ Pa}$, then $\frac{dx}{dt} = 1.86 \text{ ms}^{-1}$.

When $x = L$, $P = 8 \times 10^5 \text{ Pa}$, $P_0 = 3 \times 10^5 \text{ Pa}$, then

$$\frac{dx}{dt} = 1.45 \text{ ms}^{-1}$$

8. IGNITION AT THE PRESSURE RELEASE OUTLET

If the fire is ignited at the pressure release outlet, the gas released right after ignition is burning gas. At this time, the pressure and flame velocity are:

$$\frac{dP}{dt} = \frac{(P_m - P_0) \alpha K_r P}{LP_0} - \frac{RT_0^{1/2} K_v (P - P_0)^{1/2} V_r}{100} \quad (29)$$

$$\frac{dx}{dt} = \left[\frac{P_m}{P_0} - \frac{x}{L} \left(\frac{P_m - P_0}{P_0} \right) \right] \alpha K_r \\ - \frac{(L - x) RT_b^{1/2} K_v (P - P_0)^{1/2} V_r}{100P} \quad (30)$$

x in the above equation is calculated from the opening end.

When comparing with equations (26) and (27), it can be seen that no matter the ignition is in the front of the sealed duct or at the opening end, the equations for the rate of pressure rise are the same, but the flame spreading rates are different. The second term in equation (27) has an opposite sign with that in equation (30). This indicates that for ignition at the opening end, the rate of flame spread is decreasing gradually. Whereas for ignition in the front closed end, the rate of flame spread is increasing gradually.

9. PRESSURE VARIATIONS INSIDE THE DUCT BEFORE AND AFTER THE BREAKING OF THE OPENING FILM

The opening film will affect the pressure development after deflagration. Upon ignition, the film will not open immediately. The flame inside the duct will develop under the sealed condition. When the pressure is developed to a certain value, the film will break to release gas. The pressure developed is larger when the film is not yet broken. The reaction rate will increase at a faster rate [5,7].

In the experiment under sealed condition, there are two peaks on the pressure-time curve. The first peak appears when the film is broken. Since the pressure increase after the breaking of the film has not grown high enough to compensate for the pressure drop due to gas flowing out through the pressure release outlet, the pressure inside the duct decreases. When deflagration continues to develop, the quantity of gas burnt will increase. The pressure therefore also increases to give the second peak.

The pressure release equation with unconfined outlet is:

$$\frac{P}{(P - P_0)^{1/2}} = \frac{RT_u K_v P_0 L A_v}{VT_b^{1/2} \alpha K_r (P_m - P_0)} \quad (31)$$

Under sealed condition, before the breaking of the film (assume that the instantaneous explosion pressure is P_b), the pressure variation is:

$$\frac{dP}{dt} = \frac{\alpha K_r (P_m - P_0) (P_b + P_0)}{LP_0} + \frac{\alpha K_r (P_m - P_0) (P - P_0)}{LP_0} \\ - \frac{RT_u K_v (P - P_0)}{T_b^{1/2} V} \quad (32)$$

At maximum pressure, $\frac{dP}{dt} = 0$, the pressure release equation under sealed condition is:

$$\frac{P_c + P_b}{(P_c - P_0)^{1/2}} = \frac{RT_u K_v L P_0 A_v}{VT_b^{1/2} \alpha K_r (P_m - P_0)} \quad (33)$$

From the above equation, the maximum absolute deflagration pressure P_c under sealed condition can be obtained.

10. CONCLUSION

Theoretical background of proposed feasibility tests on explosion control on gas leakage in semi-enclosed small compartments were reported. The technique is to inject chemical agents into the site in a small-scale deflagration experimental rig first. Larger-scale experiments on different explosion suppressants can then be carried out. A detonation experimental rig will be developed to measure useful data for designing explosion control systems for real-scale scenarios.

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