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Clean Hydrocarbon Refrigerant Explosion Hazards

Wan Ki Chow[1*], Tsz Kit Yue[1], Yiu Wah Ng[1], Zheming Gao[2], Ye Gao[2]

1. Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Hong Kong, China
2. College of Aerospace and Civil Engineering, Harbin Engineering University, Harbin, Heilongjiang, China
E-mail: wan-ki.chow@polyu.edu.hk (Corresponding author); jack_tkyue@yahoo.com.hk; yiuwahng@yahoo.com.hk; microming01@sina.cn; gaoye66@126.com

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Abstract: Explosion hazards are fire safety concerns resulting from the development of clean hydrocarbon refrigerants (environmental friendly flammable refrigerants) to reduce the emission of substances with high global warning potential. Several clean hydrocarbon refrigerants are flammable with propane. Explosion hazards due to flammable refrigerant leakage from refrigerators put inside a small cupboard may give a concentration higher than its lowest flammability. A small amount of ignition energy can ignite the flammable gas to give combustion. Limiting the pressure development in a small cupboard will result in deflagration, and then transition to detonation. Since the compositions of many of environmental friendly flammable refrigerants are not disclosed and odourless, it is very difficult to assess their hazard upon leakage. This study reveals that the hidden hazard of environmental friendly flammable refrigerants would lead to serious consequences using earlier experimental studies on explosion. This is a big problem taking time to solve. Indoor aerodynamics would affect the mixing between leaked refrigerant with air in the room. Appropriate ventilation should be provided to avoid keeping the heavier explosive gas at lower levels. Different ventilation modes with air inlets and outlets at high and low positions should be considered. Use of environmental friendly flammable refrigerants and the ways in protecting against possible explosion hazards for refrigerators commonly put in kitchen cupboards in small rooms, inter alia, economy-class hotel rooms, small apartments, or subdivided units in densely populated cities, such as Hong Kong have to be watched. At the moment, fire safety management must be enhanced to address the problem.
Keywords: Explosion; Flammable clean refrigerant; Leakage; Small units; Cupboard; Hidden hazard.

1. Introduction

Clean hydrocarbon refrigerants have zero ozone depletion and low global warming potential (GWP). They contain propane (C3H8) which is a flammable clean fuel and has GWP of 3. However, unknown products which are claimed to be clean refrigerants normally operate at a higher pressure in air-conditioning and refrigeration equipment. Propane (C3H8) is the main constituent of clean refrigerants with an explosive concentration range between 2.15 % and 9.6 %. It is non-toxic and has been widely used in domestic refrigerators and freezers. Its operating pressures and temperatures are also fitted for use in air-conditioning equipment, including chillers. They have been in common use since the implementation of environmental protection regulations over a decade ago.

Although the information relating to chemical name, chemical formula, refrigerant data and classification of a large number of refrigerants listed in ASHARE 34 standard is available, the chemical compositions of some products in the market which are claimed to be clean refrigerants are not known. In the absence of explicit guidelines stipulating the fire safety issues related to refrigerants, cost and performance, rather than flammability of refrigerants, become the key factors in the selection of refrigerants [1,2].

Propane is heavier than air. If a leak occurs, it will accumulate at the lowest point and could be collected in an enclosed area. There will be a risk of explosion if the leaked gas comes into contact with a flame, spark or other ignition source. Therefore, flammable clean refrigerants and new options should be watched [3,4]. Although there have been guidelines published by the authorities in Hong Kong about the particular attention on the installation of air-conditioning and refrigeration (ACR) systems and equipment, guidance on solving problems associated with combustion and even explosions [2] involving leakage of clean refrigerants from ACR systems and equipment should be provided.

Three initial research projects [5] on safer use of flammable clean refrigerants were launched by ASHRAE recently. It is good to see planning of reducing the flammability limit of the flammable refrigerants classified as

A2L and A3. However, the explosion hazards [6,7] of clean refrigerants already in use should be watched in this transition period.

It is not so easy to restrict to using only non-flammable refrigerants in the Asia-Oceania areas as in the USA. On the other hand, there are many reported cases of explosion of leaked clean refrigerants. In Hong Kong, a clean refrigerant explosion occurred [8] in a Chinese restaurant of space volume 200 m^3 located on the first floor of a two-storey commercial complex in 2013. Clean refrigerant was suspected to be involved in that explosion incident during maintenance. Relevant guidelines and codes of practice had been published by the authorities in Hong Kong [9-11].

An obvious example scenario is putting refrigerators in a cupboard in a small room, such as economy-class hotel room, small apartment, or subdivided unit. Leakage of flammable clean refrigerant from the refrigerators might give a concentration higher than the lower flammability limits inside the cupboard. A small amount of ignition energy can ignite the flammable gas to give combustion. Limiting pressure release by the cupboard will result in deflagration, and then transition to detonation. Being flammable, additional fire safety concerns shall not be undermined. Experiments on flammable clean refrigerant in a cupboard in this study clearly illustrate the potential hazard and fire safety concerns resulting from the development of new refrigerants to reduce the emission of substances with high GWP.

2. Characteristics of flammable clean refrigerants

Before the Montreal Protocol, chlorofluorocarbons (CFCs) were commonly used in air-conditioning and refrigeration equipment. However, as a result of the Montreal Protocol and subsequent meetings to protect the earth's ozone layer, CFCs and hydrochlorofluorocarbons (HCFCs) as the substitute of CFCs have gradually been phased out because both of them destroy the ozone layer. Despite the non-flammable nature, both CFCs and HCFCs contribute to ozone depletion. As such, the use of clean refrigerants having no ozone depleting properties and lower global warming potential as substitutes becomes common nowadays. However, clean refrigerants are flammable. Unknown products which are claimed to be clean refrigerants normally operate at high pressure in air-conditioning and refrigeration equipment. Although the refrigerant manufacturers continue their efforts to develop new alternative refrigerants for meeting all requirements for zero ozone depletion, low GWP, low toxicity and non-flammability, the issue of non-flammability is still not resolved. Should there be leakage of such type of refrigerant at piping or valve of the plant arising from fault, poor maintenance or improper handling by craftsmen, clean refrigerants in the air-conditioning and refrigeration equipment vaporizes and can escape into the atmosphere resulting in explosion when there is an ignition source in the vicinity.

At present, most of the air-conditioning and refrigeration equipment on the market uses environmentally friendly hydrofluorocarbon (HFC) refrigerants. This type of refrigerant does not destroy the ozone layer, and it also complies with the requirements of current relevant safety and environmental protection laws in some regions. Due to the high GWP of HFC refrigerants, when they are released into the atmosphere, they will have a negative impact on global warming. Therefore, countries reached the Montreal Protocol Kigali Amendment in October 2016 to implement the phase-out of gases with high GWP (including existing HFC refrigerants).

With the adoption of the Kigali Amendment to the Montreal Protocol, many countries have implemented control measures to gradually reduce the use of "high" GWP greenhouse gases by 80 % to 85 % by mid 2030s to late 2040s. There has been an increasingly widespread use of eco-friendly refrigerants with "low" GWP in central air-conditioning and refrigeration systems as well as household appliances around the world in recent years.

New refrigerants are being developed to replace those refrigerants which are no longer in production. Potential replacements include propane and isobutene, and a new category of emerging HFO refrigerants designated as mildly flammable or A2L under the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) flammability and toxicity classifications [8].

In general, providing good refrigeration characteristics and attempt in minimizing the hazards of flammability and toxicity are issues of balance on the development of new refrigerants. Therefore, there are blends of various refrigerants. Some zeotropes with highly flammable hydrocarbons, such as propane, isobutene and propylene, fall within A3 classification but they are marketed as environmentally safe products for replacing non-flammable refrigerants that have no ozone depleting and lower GWP properties. For example, some new alternative refrigerants contain LPG having 100% alkanes with an explosive range between 2.15 % and 9.6 %. Propane (C3H8) is the main constituent of clean refrigerant.

In recent years, some environmentally friendly refrigerants (that is, refrigerants with lower GWP, and some of them may be flammable) have gradually become popular around the world and are used in air-conditioning and refrigeration systems and residential flats in recent years. In this respect, air conditioner manufacturers have begun to adopt lower GWP refrigerants, such as Difluoromethane (R32), which is still slightly flammable.

R32 is a single-component refrigerant (chemical formula is CH2F2). Its ozone depletion potential (ODP) is 0 and GWP is 675. It is much lower than R410A, which is commonly used in household air conditioners having

GWP at 2088 [11].

As stipulated in ASHRAE, and according to the safety classification standard, R32 belongs to the A2L level, that is, it is slightly flammable. Therefore, the fire and explosion hazards of the household air-conditioner equipment using R32 still exist.

The concern over the use of clean refrigerants is the danger associated with explosion and asphyxiation hazards as clean refrigerants contain LPG having 100% alkanes with an explosive range of 2.15 % and 9.6 %. LPG consists of 60 % propane and 40 % butane. It is highly flammable and will easily ignite and explode when its concentration in the air ranges from 2 % to 10 % and when an ignition source is present in the vicinity. As LPG is stored in fuel tank at elevated pressure, any leakage will immediately vapourise and disperse.

3. Explosion hazards

In Hong Kong, air-conditioning/refrigeration system is normally housed in a plant room provided with suitable fire protection equipment, such as fire detection system and fire extinguisher, etc. [9]. It is also under the control of building authority that it shall be separated from the remainder of the building by floors, ceiling walls or partitions having a minimum fire resistance rating, usually not less than one hour [10]. However, from the perspective of fire and explosion hazards, the control of the local authority on the use of refrigerants in air-conditioning and refrigeration control system and equipment is not stipulated in the relevant regulations. Therefore, should there be leakage of refrigerants at piping or valve of a plant room arising from fault, poor maintenance or improper handling by craftsmen, refrigerants can vaporize and escape into the atmosphere. The situation may become complicated when clean refrigerants having flammable characteristic is used in the air-conditioning/refrigeration systems. Under such circumstances, explosion may occur when there is an ignition source in the vicinity.

The explosion hazards of refrigerators or even window-type air-conditioning units with flammable clean refrigerants at positions surrounded by walls or buildings at close distance with inadequate natural ventilation should be watched carefully [3,4]. Leakage of flammable clean refrigerants in small confined space can give big disasters. As the compositions of many of them are not disclosed and odourless, it is very difficult to detect their leakage.

Refrigerators are quite commonly installed in cupboards for better interior design in terms of space or appearance, especially in small hotel units, as shown in Figure 1.

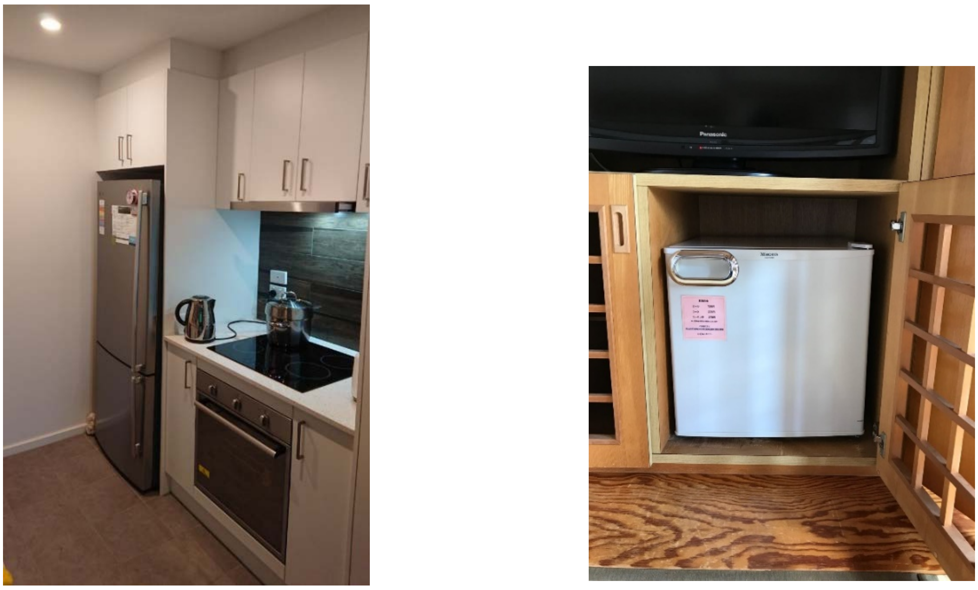


Figure 1. Refrigerators in a cupboard in small units

Flammable refrigerants leaked from a refrigerator may have a mixing ratio higher than the lower flammability limit inside the cupboard. The presence of a small ignition source can ignite the leaked flammable clean refrigerants. In addition, pressure generation would be affected by obstacles [12] and intensified from deflagration to detonation as demonstrated by numerical studies and full-scale explosion experiments [13-15].

Leaked flammable refrigerant from air-conditioning and refrigeration systems and equipment in small units with unknown concentration and probable source of ignition inside an enclosed space is not only a potential hazard to the safety of the occupants, but also to the firefighters. In fact, in many occasions, when a gas leakage incident was reported to the Fire Brigade, there were no signs of fire at the reported location [12], but explosion of the leaked gas might suddenly occur [2,7]. Secondary building fire on leaked refrigerants from a refrigerator and air-conditioning unit in hotel buildings is very hazardous, particularly in small hotel units in very tall buildings. High density of combustibles is stored in smaller units. Upward fire spread in tall buildings can give disasters.

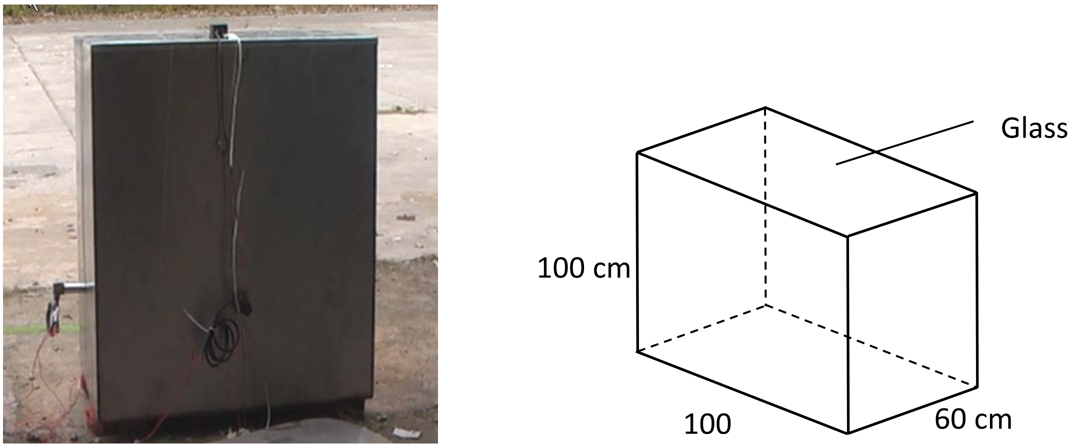
The Fire Brigade should be vigilant and cautious in tackling the gas leakage incidents which have started from leaked flammable refrigerants. They are facing threat of explosion, especially when they are breaking into a locked enclosure or carrying out rescue operation inside an enclosed space which may be filled with flammable gases, as experienced before [16].

4. Simple physical demonstration

Explosion of leaked flammable refrigerant with propane in a kitchen cupboard can be readily demonstrated using a chamber model, as was done previously [17]. This arrangement simulated a refrigerator placed in a kitchen cupboard. The combustible gas concentration distributions, burning temperature and transient pressure were investigated. Experimental data were used in validating a mathematical model for studying the explosion pressure [17].

Better understanding on the probable fire scenarios in small units can be performed in a full-scale burning facility [18]. However, it is difficult to select a site in dense urban areas for full-scale burning tests as land costs are far too expensive. There are also tight environmental protection regulations and real fire tests cannot be done. a site far from the dense urban area should be used for burning tests. In this way, environmental impact of the burning tests can be minimized. Further, there should be water, electricity and heating supply in remote areas which are cold. A facility has been developed in a small town 200 km away from Harbin. There, a full-scale burning hall is designated for the following experiments.

The chamber model was of length 1 m, width 0.6 m and height 1 m as shown in Figure 2 (a), simulating a kitchen cupboard for accommodating a refrigerator. The floor and four walls of the model were made of 2 mm thick stainless steel plates. 31.5 g propane refrigerant was injected into the chamber, giving an average concentration of propane of 3 %. The maximum propane concentration, which occurred at the bottom, was 26 %.



(a) (b)

Figure 2. Chamber model. (a) Photo of chamber; (b) Dimensions

After the leaked propane was ignited, explosion occurred almost immediately. A flame surface was observed in the experiment. The flame surface extended outward from 0 s to 0.467 s after ignition, as shown in Figure 3. In gas explosions, fuel gas and air are mixed in combustible proportions, before ignition occurs. Therefore, combustion, once initiated, will propagate readily throughout the mixture. This kind of combustion is named “pre-mixed” and should not be undermined when the refrigerant leaks from cupboard either with the door opened or semi-opened, especially after an explosion as demonstrated in the previous study [14].

The hidden hazard is clearly demonstrated. This is a big problem requiring time to solve. However, an immediate action is to work out appropriate fire safety management [19] for handling flammable clean refrigerants. Refrigerators should be placed in well-ventilated rooms, rather than housed in kitchen cupboards.

(a) (b) (c)

Figure 3. Burning process. (a) 0.1 s; (b) 0.2 s; (c) 0.4 s

5. Ways to handle explosion hazards

The following points should be watched in handling possible explosion hazards:

1) Overseas standards for clean refrigerants should be scrutinized and justified [1-3] carefully in applying to Asia-Oceania areas. Control on reducing leakage rate of flammable refrigerants and avoidance of having ignition sources cannot be achieved easily, particularly in areas where it takes a long time to develop regulations.

2) More importantly, government authorities have difficulties in implementing the regulation and controlling the use of flammable refrigerants as the market is so huge. Local guidelines must be developed to suit the local demands related to building environments, economy, education and social awareness on safety issues.

3) Flammability of refrigerant is only one of the factors related to the risk of explosion. Research should be extended to work out some explosion risk index with the inclusion of building geometry, obstacles arrangement and leakage amount of refrigerant relative to space volume.

4) Ventilation provision should ensure proper mixing, not to have high fuel-to-air mixing ratio at low level.

5) Fire safety management must be enhanced immediately.

6) Architects and professional persons should include the health and safety of the occupiers and tenants by applying the Construction Design and Management [20] in their projects on new buildings or refurbishment of existing buildings.

6. Indoor aerodynamics

As the amount of ignition energy required for hydrocarbons such as propane or isobutane is very low, hydrocarbon refrigerants in small spaces is an additional hazard. Buildings with air-conditioning and refrigeration systems using clean refrigerants should have fire safety provisions specified by the local authority. The use of hydrocarbon refrigerants has gradually gained more acceptance, at least in several European and South East Asian countries, based on the statistical data so far. However, the low predicted values on risk [21] might be prompted by the low accident frequency recorded from 1994 to 2004. The extensive use of hydrocarbon refrigerants in the past years might change the situation in the very near future. The recent explosion incidents [22-24] including propane refrigerant in 2013 has drawn the attention of the authorities in Hong Kong to formulate relevant guidelines on installation and repair of the refrigerators and household air-conditioning equipment which contain flammable clean refrigerants.

Refrigerant propane leaking from an air-conditioning equipment in a plant room of a small commercial flat with floor area less than 200 m2 might give a concentration higher than LFL in some locations. A build-up of gas concentration may occur [25] because the gas-air mixture, formed during the initial stages of the release, may be re-entrained into the jet or plume rather than fresh air. As a result, the concentration of gas continues to increase with time. If the volume is ventilated with sufficient openings, this concentration build-up can be avoided. A hazardous accumulation of gas-air mixture may occur, therefore, only if the release rate, the necessary volume within which the accumulation builds up, and the ventilation design form an unsatisfactory combination.

Accident analysis suggests that some explosions involving flammable gas took place with a quantity of released gas considerably much less than the lower explosion limit amount [26] required to fill the whole confined space. Inhomogeneous mixing of the leaked flammable gas with air might give a higher propane concentration at some areas. As pointed out above, whether an explosion of the leaked flammable propane occurs or not depends not just on the amount of propane stored, but the degree of mixing with air in the confined space. Room ventilation provision is key to determining the air flow pattern and hence the degree of mixing with air. Since propane is heavier than air,

air inlets installed at high level tend to push propane leaked from the air-conditioning/refrigeration equipment to the ground. A propane concentration higher than LFL can result at the lower levels in Figure 4b.

If the leaked propane refrigerant is ignited, a flame will grow spherically outwards form the point of ignition until it fills the room. The flame consumes fuel and increases pressure. A maximum explosion pressure of roughly 10 bars for hydrocarbons [27] will result in a confined inflagration in a room filled with a flammable gas. Some building structures would not be able to stand such high pressure, as they can collapse even at low gauge pressures of 0.21 bars [28]. The actual maximum pressure, however, might be less than the constant volume explosion pressure due to room openings.

A typical arrangement is selected to study explosions of clean hydrocarbon refrigerants leaking from domestic air-conditioning units. The effects of the following four typical ventilation modes with air inlets and outlets at high and low positions as in Figure 4 are explored:

1) Low level intake, high level exhaust and both with fans.
2) High level intake, low level exhaust and both with fans.
3) High level exhaust with fan and low level intake without fan.
4) Low level exhaust with fan and high level intake without fan.

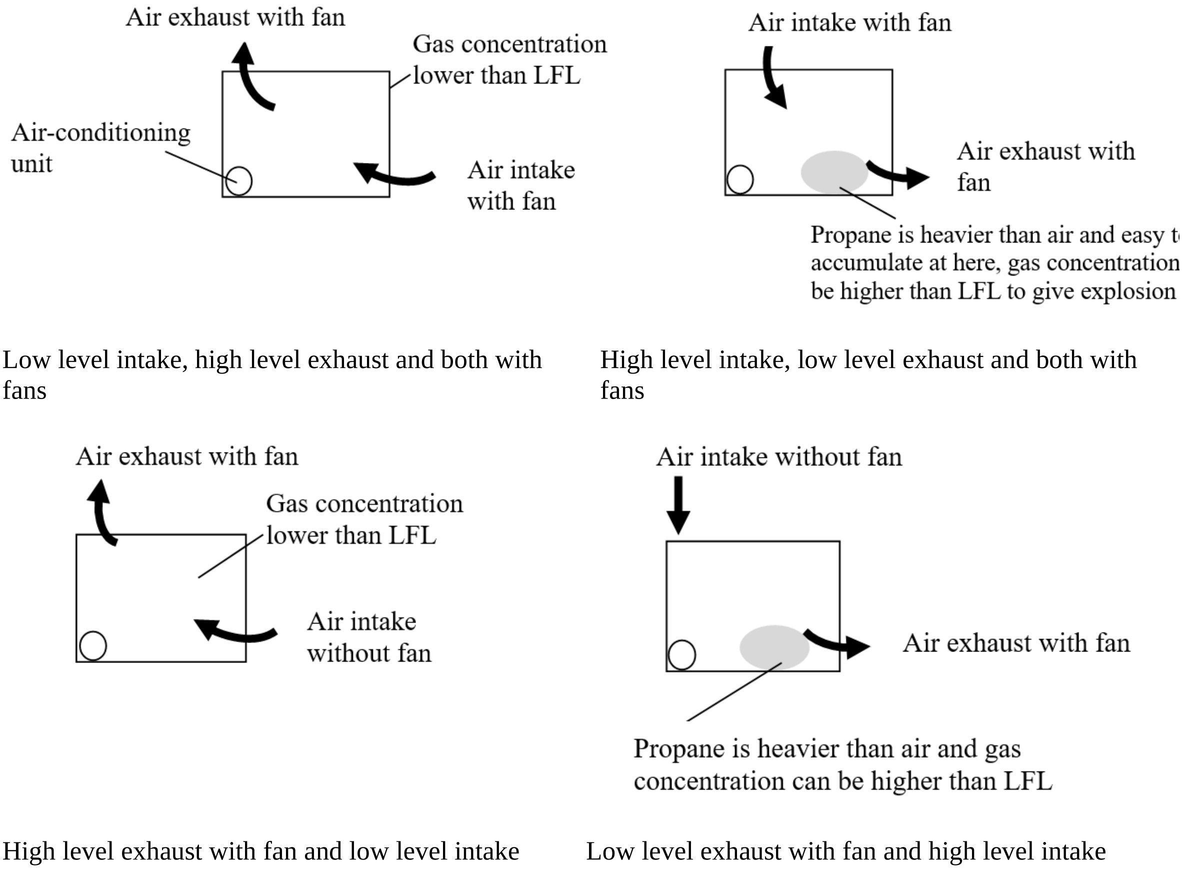


Figure 4. Four common enclosure ventilation modes

Explosion hazards of flammable refrigerants for air-conditioned vehicles in a garage were studied preliminarily by using CFD software Flame Acceleration Simulator (FLACS). A typical double car garage in Hong Kong with a rolling shutter as its entrance was considered in the simulation. Dispersion of hydrogen from the leakage source with an ignition at a higher position was studied [29].

According to ISO 817, propane is designated an A3 safety classification which is within the category of higher flammability [30].

There being a risk of explosion if the leaked flammable clean refrigerant comes into contact with a flame, spark or other ignition source, the requirements on the site for safety, which may be needed because of, but not directly connected with, the refrigerating system and its ancillary components specified in BS EN 378-3:2016+A1:2020 shall be complied with [31].

7. Conclusions

It is very difficult to control the use of flammable refrigerants because there are too many unknown products.

Explosion hazards of flammable clean refrigerants leaked from refrigerators put inside a cupboard are discussed in this study. Experiments on flammable refrigerants in a chamber model illustrated the potential hazard clearly. Refrigerators should be removed from cupboards and relocated in areas with better ventilation.

Research with experimental studies and numerical simulations on explosion involving flammable clean refrigerants are recommended for achieving better facility management and green firefighting.

At the moment, fire safety management must be enhanced.

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