Tunnelling and Underground Space Technology 78 (2018) 35–46

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Experimental scale model study on explosion of clean refrigerant leaked in an underground plant room

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ARTICLE INFO

Keywords:
Explosion
Clean refrigerants
Air-conditioning and refrigeration system
Ventilation

ABSTRACT

Several clean refrigerants widely used in new air-conditioning systems are composed of flammable propane. Leakage of the flammable refrigerant from the air-conditioning systems housed in a basement plant room would pose fire and explosion hazards. However, very few studies have been carried out to study explosion hazards of leaked clean refrigerant in underground spaces. In this paper, a model chamber with two common mechanical ventilation designs in basement plant room was used to study experimentally the hazards. Clean flammable refrigerant was discharged to the model chamber to a concentration level less than the lower flammability limit. Four sets of tests with different ventilation conditions were carried. Concentrations of the leaked refrigerant at different positions in the chamber under different ventilation conditions were measured. Explosion of leaked gas was triggered by ignition. After ignition the transient gas temperature and pressure inside the model were recorded. Results indicate that mixing of leaked flammable refrigerant, and hence the concentrations of the leaked gas, depends on the mechanical ventilation design in the chamber. Improper ventilation provision would result in high refrigerant-to-air mixing ratio at some positions, even though the designed leaked refrigerant concentration is less than the lower flammable limit calculated from a well-mixing model. The results of the present study would contribute to better understanding of explosion hazards due to leakage of flammable refrigerant in green air-conditioning and refrigeration system in basement plant room or similar enclosures.

1. Introduction

Mechanical plant rooms for air-conditioning and refrigeration systems are commonly allocated in underground basement spaces three levels below or even deeper under the ground level (Fire and Safety Department, 2012). Currently, environmentally friendly green air-conditioning systems using propane refrigerant (Granryd, 2001; Yu and Chow, 2006; Baskin et al., 1994; Calm, 2008) are required by regulations in many countries. Propane refrigerant is flammable and may lead to accidental explosions (Lunde and Lorentzen, 1994; Maclaine-cross, 2004; Climate Control News, 2008). Explosions resulting from leaked propane refrigerant have been reported (The Standard, 2013; Chow, 2013; South China Morning Post, 2013; Ming Pao Daily News, 2013) in Hong Kong since 2013. In densely populated urban areas such as Hong Kong, high quantities of combustibles are stored. Even the explosion of a small amount of propane refrigerant could be disastrous as observed in an accident before (The Standard, 2013). Explosion from leaked refrigerants can be much more hazardous in underground spaces as explosion control systems might not be installed. The gas pressure generated cannot be relieved to outside quickly because there are no openable windows or doors as in rooms above the ground. There is an urgent need to better understand (Ng and Chow, 2014, 2015a, 2015b) the explosion hazards of flammable refrigerants leaking from malfunctioning air-conditioning and refrigeration systems housed in underground spaces. With better understanding based on results of research, fire protection systems (Fire and Safety Department, 2012) with explosion control and appropriate suppressing agents can then be designed and specified.

Some studies on the ventilation design to disperse leaked flammable refrigerant were reported in the literature (Colbourne and Suen, 2003a). Experiments were carried out in a specially designed test facility to study the dispersion of leaked refrigerant using tracer gases such as carbon dioxide. From the measured tracer gas concentrations and observed flow patterns, the effects of parameters such as ventilation equipment and installation height of ventilation facility were studied. These results were used to draft guidance on the dispersion of flammable refrigerant in the event of leakage. Design limits of ventilation parameters were also proposed (Colbourne and Suen, 2003b). A

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https://doi.org/10.1016/j.tust.2018.04.010
Received 31 March 2017; Received in revised form 14 March 2018; Accepted 9 April 2018

common guideline is that, even when flammable refrigerant leaks out, the lower flammable limit (LFL) should not be exceeded in the space concerned. Some authorities impose even more stringent guidelines requiring concentration not to exceed about one-fifth of LFL (Ng and Chow, 2015b). Explosion hazard in partially confined areas with very small amount of leaked gas has also been reported in a few studies (Jo and Kim, 2001; Ogle, 1999).

Flammable refrigerants are usually heavier than air and possible to stay at lower level. However, mechanical ventilation with air intake from low level and exhaust at high level would bring gases up. In a room of size 3 m by 1.8 m by 3 m with refrigerant '850 R290' leaking out from an air-conditioner, the average concentration can be up to 3%, falling within the LFL range (2.1–9.5%). As refrigerant R290 is heavier than air, the concentration is distributed unevenly and can be ignited at positions with higher concentration. Therefore, studying the propane deflagration in the scaled room model will provide useful information on explosion hazards.

In addition to the overall allowable concentration (below the LFL) of leaked flammable refrigerant in a room, local flammable gas concentration is also important (Chow, 1995). However, the mechanism and extent of mixing of flammable gas with air depends on the ventilation design. As propane is heavier than air, higher propane concentrations (above the LFL) is found at lower levels in a small flat when fresh air intake is at a higher level. Explosions might occur when there are small ignition sources and such incidents of explosion of flammable refrigerant have been reported (Standard, 2013). The consequences of explosion in enclosed spaces, such as in underground spaces, can be very hazardous (Copur et al., 2012; Li et al., 2013; Feldgun et al., 2014; Mobaraki and Vaghefi, 2015). Better use of flammable refrigerants was raised recently (Kujak, 2017; Chow et al., 2017; National Fire Protection Association, 2018).

In this paper, explosion of propane refrigerant leaking out from air-conditioning systems in a basement plant room was studied using scale models. The effects of the following two typical mechanical ventilation modes called 'extraction only' design (Chow, 2016; Chow and Ng, 2016) were studied with air inlets and outlets at high or low positions Fig. 1):

- High level exhaust with fan and low level air intake without fan.
- Low level exhaust with fan and high level air intake without fan.

A model chamber was constructed with fixed amount of propane refrigerant injected. Possible explosion upon ignition was studied by measuring transient temperature and pressure distribution. Flame spread was observed. The experimental results and analysis are useful for better understanding the explosion hazards of leaked flammable refrigerants under these two ventilation modes by extraction in basement plant rooms housing air-conditioning and refrigeration systems.

2. Experimental method

The model room for experimental study on explosion hazards of leaked propane refrigerant is shown in Fig. 2(a). The model was of 1 m length, 0.6 m width and 1 m height, giving a floor area of 0.6 m^2 and space volume of 0.6 m^3 representing a 3 m * 1.8 m * 3 m room. The mass of refrigerant is about 850 g in a normal air-conditioning unit. The corresponding gas injection mass of the scaled model room is 31.5 g (as shown in Table 1). The floor and walls of the model room were made of 2 mm thick stainless steel sheets. The ceiling of the room was made of 5 mm plexiglass sheet, so that the flame propagation process could be observed from the top.

An opening of area 0.04 m by 0.04 m was provided on the ceiling (12 cm to the shorter edge and 28 cm to the longer edge) and another on the side wall (12 cm to the shorter edge and 28 cm to the longer edge) of the room, for providing mechanical ventilation. The positions of the openings are shown in Fig. 2(a), with a photograph shown in Fig. 2(b).

Propane refrigerant was discharged from two copper tubes of diameter 6 mm, which were located near the center of the bottom of the room Fig. 2(c)). The copper tube penetrated the floor of the model room, and then bent with outlets towards the floor. The distance of the two discharging points was 5 cm, and the height from the bottom was 10 cm. The propane refrigerant supply piping system is shown in Fig. 2(d). There is no other sealing with pressure relief from the vent.

A 200-g refrigerant bottle was used to inject 31.5 g of propane at a mass flow rate 2.69 g/min or a volumetric flow rate 1.5 L/min. The filling up time was 720 s, giving an average concentration of propane of 3%. The exhaust vent area was 0.2826×10^{-4} m^2 or 28.26 mm^2. The average exhaust speed was 0.44 ms^{-1}. Clean refrigerant R290 was used directly instead of tracer gas, because of the small chamber size. R290 is the common name for high purity (higher than 97.5%) propane (C_3H_8) suitable for use in the refrigeration and air conditioning industry. The concentration of propane discharged into the chamber was adjusted to be common design figures calculated from 'well-mix' models (Chow, 1995). The concentrations of the discharged propane at different positions were measured.

Two fans of identical models were mounted respectively on the top and side vents to provide different ventilation modes. According to the ventilation design standards, typical ventilation rates for restaurants are from 6 to 10 air changes per hour (ACH). The air volume required for the fan was 6 to 10 m^3/h. The exhaust fans used were capable of providing such a flow rate.

Propane concentration was measured using gas concentration sensor (MD61) with performance characteristics shown in Fig. 3. As specified in the manual, error range of the sensors for measuring gas concentration is 1.2% with working temperature from 0 °C to 40 °C. It can be seen from the figure that the sensor had a linear characteristic for many types of gases, including propane. The response recovery time is about 10 s. Because of its good linearity, the pure propane gas

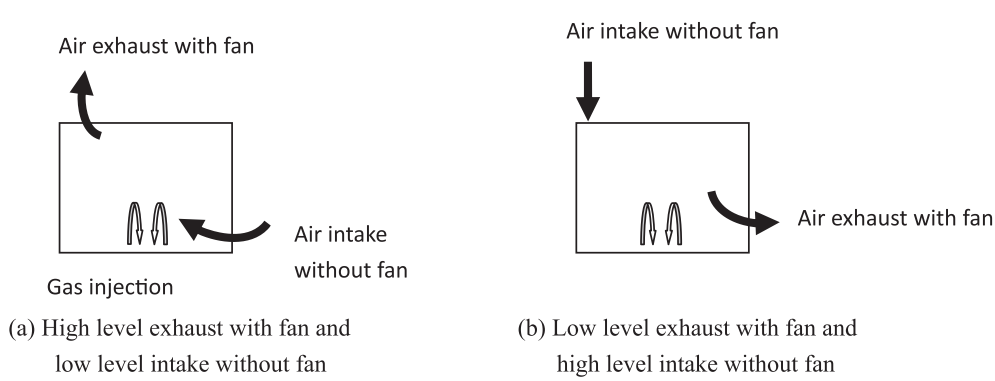

Fig. 1. Two common mechanical ventilation modes.