Compressor Explosion Accident at Pump-Down of Air Conditioners

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Abstract

These days the problem of global warming is becoming more serious and low GWP is demanded for refrigerants used for heat pumps. R1234yf and R32 are promising candidates of new lower-GWP refrigerants; however, they have mild flammability. Therefore, a safety assessment of flammable refrigerants is required.

This study focuses on compressor explosion accidents at the pump-down of separate type air conditioners. Pump-down is an operation to accumulate the entire refrigerant in the outdoor unit by closing the outlet valve of the outdoor unit and compulsorily driving the compressor. If the penetration of air into the refrigerant tube occurs by an operation error, both pressure and temperature inside the compressor would increase. The lubricating oil in the compressor may be self-ignited, and cause diesel explosion.

In this research, we reproduced the diesel explosion and examined its characteristics. The mixture of air, refrigerant and oil were sucked into the cylinder, and were compressed by a compressor, which was simulated by a small-scale engine. R1234yf, R32, R410A and R22 were tested as refrigerants, and PAG oil and POE oil were tested as the lubricating oils. We changed the concentration of the oil, and measured the effect of the oil on the explosion.

It was revealed that flammable range was widely changed by different lubrication oils, which suggested that properties of not only the refrigerant but also the oil were important factors for the accident at the pump-down. The accident probability can be decreased by adjusting the flammability of the lubricating oil.

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Keywords: Pump-down; Compressor explosion accident; Oil; Mildly flammable refrigerant

1. Introduction

Environmental and safety characteristics are important for refrigerants used for an air conditioner, addition to physical properties about cooling capacity and coefficient of performance. From the viewpoint of environment, the refrigerants' ODP (Ozone Depleting Potential) should be zero and GWP (Global Warming Potential) should be low. The GWP of R410A, which is a conventional refrigerant for air conditioners, is so high that new low-GWP refrigerants such as R1234yf (CH_2=$CFCF_3$) and R32 (CH_2F_2) are drawing increasing attention, however, they are known as mildly flammable refrigerants. Table 1 lists ODP, GWP and flammability of typical refrigerants [1-3]. LFL, represents lower flammable limit; UFL, upper flammable limit; BV, burning velocity; and MIE represents minimum ignition energy. In ASHRAE Standard 34, the rank A2L was newly founded for mildly flammable refrigerants, whose heat of combustion is lower than 19 MJ kg^{-1} and burning velocity is lower than 10 cm s^{-1}[4]. In the future, mildly flammable refrigerants are expected to be used in a variety of applications. Therefore, risk assessment of the refrigerants is important. Much research has been conducted on the flammability of low-GWP refrigerants. Kondo et al. revealed that high humidity and pressure may enlarge flammable range of refrigerants by spherical vessel method [5, 6]. Jia et al. and Imamura et al. experimentally investigated leakage of refrigerants from an air conditioner [7, 8].

Table 1. Physical properties of refrigerants

	R1234yf	R32	R410A	R22
ODP	0	0	0	0.055
GWP	<1	677	2090	1760
LFL / vol.%	6.2	13.3	Non-flammable	
UFL / vol.%	12.3	29.3		
BV / cm s^{-1}	1.5	6.7		
MIE / mJ	200	15		
ASHRAE flammability category	A2L	A2L	A1	A1

In this research a compressor explosion accident at pump-down of air conditioners was investigated as a part of the safety research of mildly flammable refrigerants. Pump-down is an operation to accumulate the entire refrigerant in the outdoor unit of a separate type air conditioner by closing the outlet valve of the outdoor unit, and compulsory drive the air conditioner at cooling operation. When the separate type air conditioner is relocated or discarded, it is necessary to pump-down the unit in order to prevent the leakage of refrigerant in the atmosphere. In the pump-down operation, the suction line of the compressor becomes vacuum. If the penetration of air into the refrigerant tube occurs by an operation error of the tree way valve or damaged tubes, both pressure and temperature inside the compressor would increase [9]. It is reported that the lubricating oil in the compressor may be self-ignited and cause diesel explosion [10].

These accidents occurred with conventional refrigerants, such as R22 and R410A, which are categorized as non-flammable. As for the pump-down, it is known that even conventional non-flammable refrigerants still have possible danger. Using mildly flammable refrigerants instead of non-flammable refrigerants changes the conditions or hazards of explosion at accidents during the pump-down. The mechanism and conditions of the accidents related to the pump-down have not been widely investigated. To introduce these mildly flammable refrigerants in the future, it is necessary to systematically examine the phenomena of the explosion during the pump-down, and prepare safety guidelines for the new lower-GWP refrigerants, as compared with the conventional ones.

In this study, the conditions when the mixture of refrigerant, air, and lubricating oil existing in the compressor ignites were measured, and the effects of flammability of refrigerants and the oils were experimentally investigated. In order to avoid a break in the experimental set up, a small engine was used as a simulated compressor because the real compressor would be broken if the mixture is self-ignited.

Nomenclature		
p	Absolute pressure	MPa
Greek letters		
ε	Compression ratio	-
κ	Specific heat ratio	-
Index		
atm	Atmospheric pressure	
max	Maximum	
th	Theoretical value	
'	Normalization	
0	Standard pressure	

2. Experiments

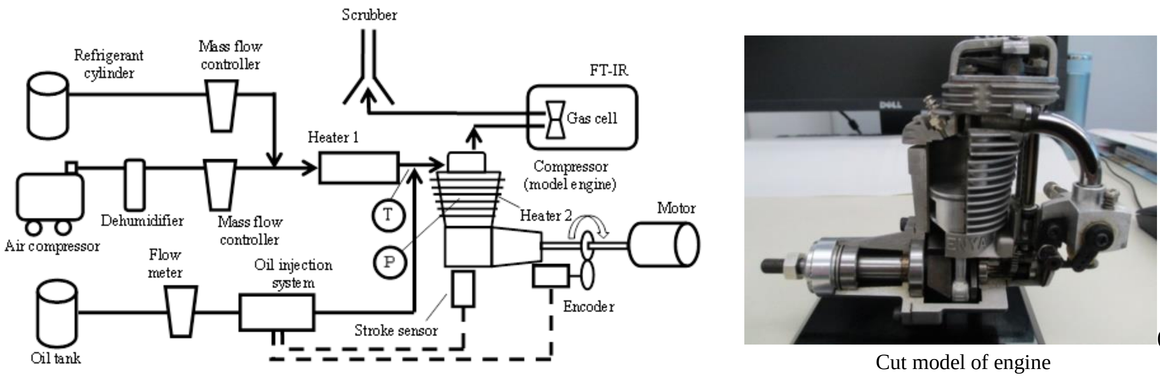
2.1. Apparatus

Experimental apparatus mainly consists of a compressor, an air supply system, a refrigerant supply system, a temperature control system and a lubricating oil supply system. Fig. 1 shows the schematic diagram of the apparatus and cut model of the compressor. A model engine (R155-4C, 4-stroke, stroke volume: 25.42 cc, compression ratio: 16.0, made by ENYA) was used as a simulated compressor, and was driven by a motor connected to the engine's shaft. This is because the real compressor may explode during the experiments same as the accidents. The rotational speed of the engine was changed using the motor. Gears and an encoder were attached to the shaft.

Vapor refrigerant supplied from a refrigerant cylinder was reduced to a pressure of 0.3 MPa, using a pressure regulator. The flow rate was controlled using a mass flow controller (FCST1050LC-4F2-F50L-N2, made by Fujikin, accuracy: ±2%F.S., repeatability: ±0.2%F.S., flow rate range: 2 to 100 %F.S.). The air was compressed to 0.7 MPa, using a compressor, and passed through a dehumidifier. Its pressure was reduced to 0.3 MPa using a pressure regulator. The flow rate was controlled using a mass flow controller (MODEL8550MC-0-1-1, made by Kofloc, accuracy: ±1.5%F.S., repeatability: ±0.5%F.S., flow rate range: 2 to 100 l min^{-1}). The refrigerant and air were mixed and the temperature was controlled by heater 1. Heater 2 was used for equalizing the temperature of the model engine with that of the engine's intake gas.

The pressure of the oil was raised to 150 MPa using an oil injection system (Common Rail Electric Control Fuel Injection System, made by FC Design), and the oil was injected in the form of a spray into the intake port of the engine. The oil quantity per an injection was changed by the injection time.

The gaseous mixture of the refrigerant, the air and the lubricating oil was compressed by the engine. The pressure in the engine was measured using a pressure sensor (6045A, made by Kistler, linearity±0.4%FSO). Considering the thermal behavior of the pressure sensor, the measured pressure was compensated by assuming that the pressure, when the outlet valve was open, was atmospheric. The pressure waveform was also compensated using signals from the encoder on the shaft of the engine, because the rotating speed of the engine became unsteady when the combustion occurred. The exhaust gas of the engine was analyzed using a Fourier transform infrared spectrometer ([FT-IR], FT/IR-4700, made by Jasco, resolution: 0.5 cm^{-1}, S/N: 35000:1). Data obtained from the PNNL were applied to identify the combustion products [11]. These measurements were recorded using a data logger (data logger system NR-2000, made by Keyence, accuracy: ±0.1%F.S.). The sampling rate was set at 40 kHz considering the rotating speed of the engine.



(a) Schematic diagram

(b) Cut model of engine

Fig. 1. Experimental apparatus

2.2. Experimental conditions

In addition to R1234yf and R32 which are the lower-GWP refrigerants, R410A and R22 which are conventional refrigerants were used for comparison. PAG (Polyalkylene glycol) oil and POE (Polyol ester) were used as the lubricating oils. Both of them are used for air conditioners.

Table 2 lists experimental conditions. The gaseous Mixture flow rate was calculated by the number of revolutions and stroke volume of the engine. The mixture was heated to 260℃ in order to burn easily. The temperature of the heater was controlled so that the refrigerant's decomposition does not occur, referring to a research on refrigerants thermal decompositions [12]. The oil flow ratio was calculated based on standard oil flow rate, mentioned later.

Table 2. Experimental conditions

Number of revolutions/ rpm	1500
Gaseous mixture flow rate/ l min^{-1}	18.75
Inlet gas temperature/ °C	260
Oil flow ratio/ -	0.0, 0.7, 1.0, 1.3, 1.6
Injection timing/ degree	90 (at crank angle)

Table 3 lists properties of the lubricating oils. Each information ware provided by production companies, IDEMITSU (PAG oil) and JX Nippon Oil & Energy (POE oil). CHO ratio is mass ratio of carbon, hydrogen and oxygen contained by the oil. Standard flow rate was calculated so that the oil flow rate becomes the theoretical air fuel ratio. The amount of oil inside the compressor is assumed to be independent of the refrigerant concentration during a real accident, so the oil flow ratio was calculated by this standard flow rate at any refrigerant concentration.

Table 3. Properties of lubricating oils

	PAG oil	POE oil
CHO ratio, mass %	61.7 : 10.5 : 26.2	70.1 : 10.8 : 19.1
Flash point, ℃	216	254
Ignition point, ℃	350	408
Theoretical air fuel ratio, kg kg^{-1}	9.54	10.91
Standard flow rate, l min^{-1}	2.295×10^{-4}	3.519×10^{-4}

2.3. Experimental methods

The experimental procedure was as follows:

1) Set the air flow rate at certain value and heat the air at the intake side and engine. Then drive the engine at approximately 50 rpm.
2) Set the air and refrigerant flow rates at the target value after the inlet temperature becomes steady and reaches to the predetermined value.
3) Set the rotating speed of the engine at the target value after the flow rates of the air and refrigerant become steady.
4) Confirm the oil is injected, and then start collecting data using the data logger.
5) Close the outlet valve of the gas cell of the FT-IR and start analyzing the exhaust gas.

3. Results and discussions

3.1. Self-ignition of oil

Figure 2 shows typical pressure changes in the engine when the gaseous mixture of the air and lubricating oil was compressed. The oil was PAG, and the oil flow ratio was 0.0 (without oil), 0.7, 1.0, 1.3 and 1.6. The horizontal axis shows a crank angle of the engine, which reached the top dead center at 360 degree. The plots of the pressure are in 0.5-degree increments.

No combustion was observed when the oil flow ratio was lower than 0.7. The engine ran smoothly, and the pressure rose during compression stroke due to the adiabatic compression. Combustion occurred when the oil flow ratio was higher than 1.0. The pressure rose drastically, and loud noise and strong vibrations were noticed.

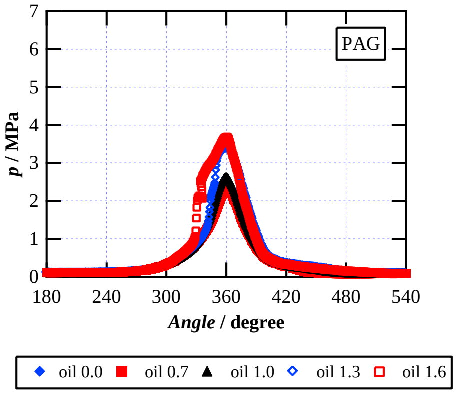


Fig. 2. Change in pressure inside engine against crank angle with different amount of PAG oil

3.2. Self-ignition of refrigerant, air and oil mixture

Figure 3 shows typical pressure changes in the engine when the gaseous mixture of the refrigerant, the air and the lubricating oil (PAG oil) was compressed. The refrigerant used was R1234yf and its concentration was 20%. No combustion occurred when the oil flow ratio was lower than 1.0. Combustion occurred when the oil flow ratio was higher than 1.3. The pressure rose drastically compared with the result without the refrigerant, and bigger vibration and noise were observed. No combustion occurred in any oil flow ratio when the refrigerant concentration was further bigger. These tendencies were similar to the results of R32, R410a and R22.

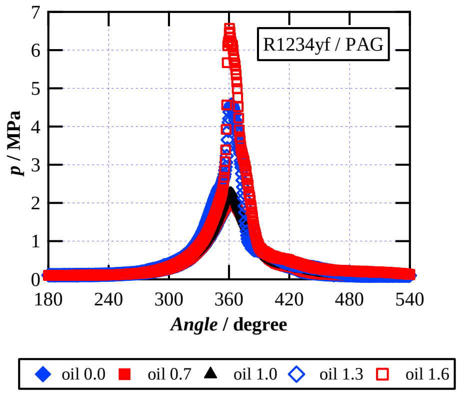
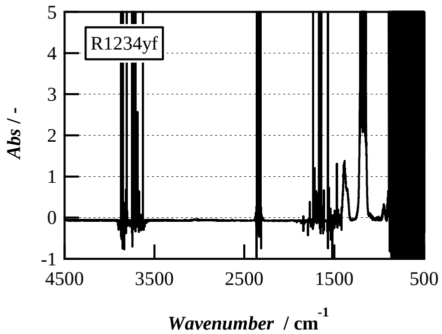
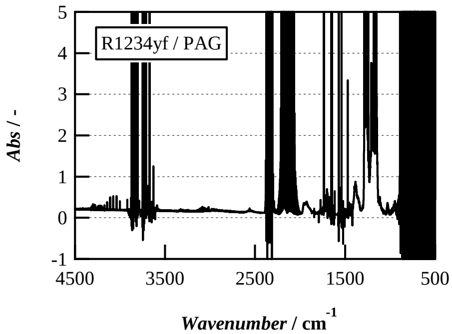


Fig. 3. Change in pressure inside engine against crank angle with R1234yf and different amount of PAG oil

Figure 4 shows typical infrared adsorption spectrum of exhaust gas. The horizontal axis shows wavenumber of the infrared, and the vertical axis shows the adsorption ratio. The refrigerant used was R1234yf and its concentration was 20%. The oil used was PAG oil and its flow ratio was 0.0 in (a) and 1.6 in (b). In Fig. 4 (a), where no combustion occurred, typical R1234yf spectra are observed between 1800 and 1000 cm^{-1}. In Fig. 4 (b), where intense combustion occurred, HF spectra was observed at 4200 to 3600 cm^{-1}, and that of COF_2 was observed at 1980 to 1880 cm^{-1}. HF and COF_2 are the main reactive products of the combustion of R1234yf, which indicate that the refrigerant itself burned and contributed to the intense combustion.



(a) Oil flow ratio: 0.0

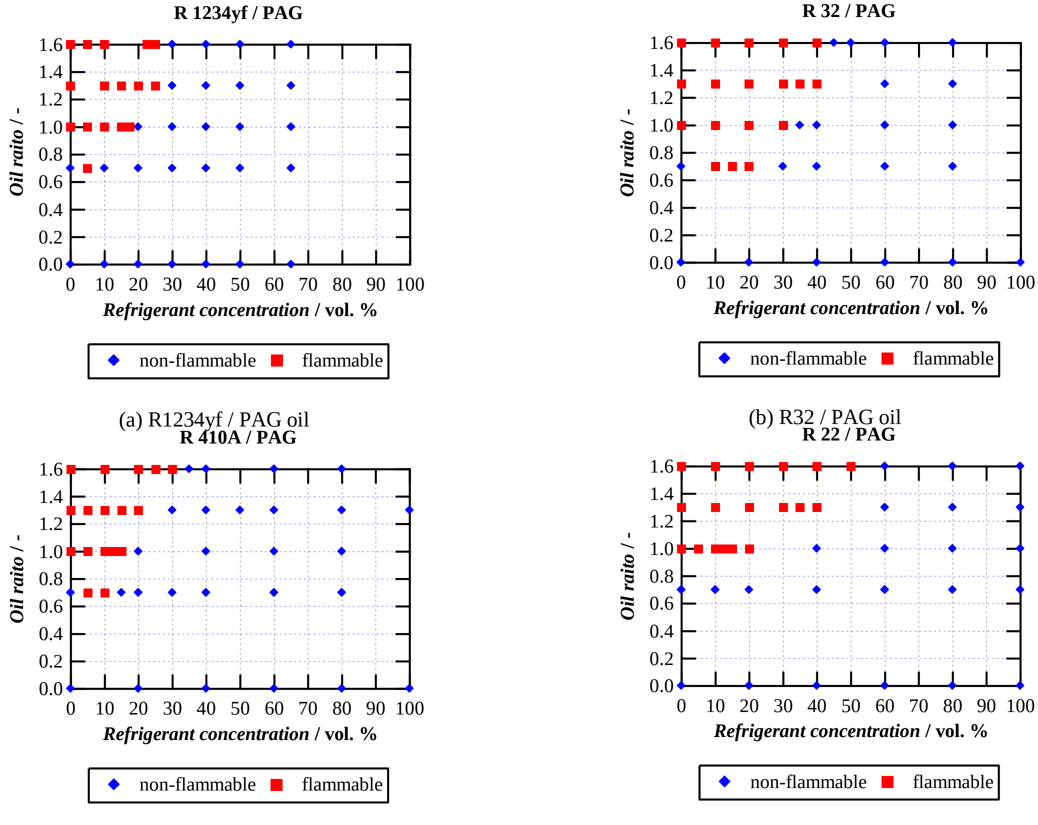


(b) Oil flow ratio: 1.6

Fig. 4. Infrared adsorption spectrum of exhaust gas with PAG oil where R1234yf concentration is 20%

3.3. Flammable range and oil flow rate

Figure 5 shows the flammable range determined by the experimental results obtained with the refrigerants. The horizontal axis shows the refrigerant concentration and the vertical axis shows the oil flow ratio (PAG oil). Red dots represent the condition where combustion occurred, and blue dots represent the condition where combustion did not occur. The figure shows that the flammable range enlarged as the oil flow ratio increased. However, combustion was more likely to occur at lower refrigerant concentrations and higher oil flow ratios.



(a) R1234yf / PAG oil

(b) R32 / PAG oil

(c) R410A / PAG oil

(d) R22 / PAG oil

Fig. 5. Flammable range of each refrigerant against different PAG oil flow ratios

3.4. Comparison between different lubricating oils

Figure 6 summarizes the experimental results with different refrigerants and lubricating oils. The horizontal axis shows the concentration of the refrigerant, and the vertical axis shows the maximum pressure during the cycle. The maximum pressure, $p_{\max}$, was normalized to p_0, which is the maximum pressure when only air was compressed.

$$p'_{\max} = \frac{p_{\max}}{p_0} \tag{1}$$

The theoretical value of the maximum pressure was calculated by assuming the adiabatic compression of a gaseous mixture of the refrigerant and air

$$p_{th} = p_{atm} \times \varepsilon^{\kappa} \tag{2}$$

where p_{atm} is the atmospheric pressure, ε is the compression ratio of the engine, and κ is the specific heat of the gaseous mixture.

No combustion occurred at an oil flow ratio of zero with any refrigerant, which suggests that the existence of lubricating oil is necessary for combustion. For all refrigerants, combustion occurred with low refrigerant concentrations. The dots in the results of the POE oil were located on the left side compared with the results for the PAG oil, which indicates that the flammable range with the POE oil was narrower than that with the PAG oil.

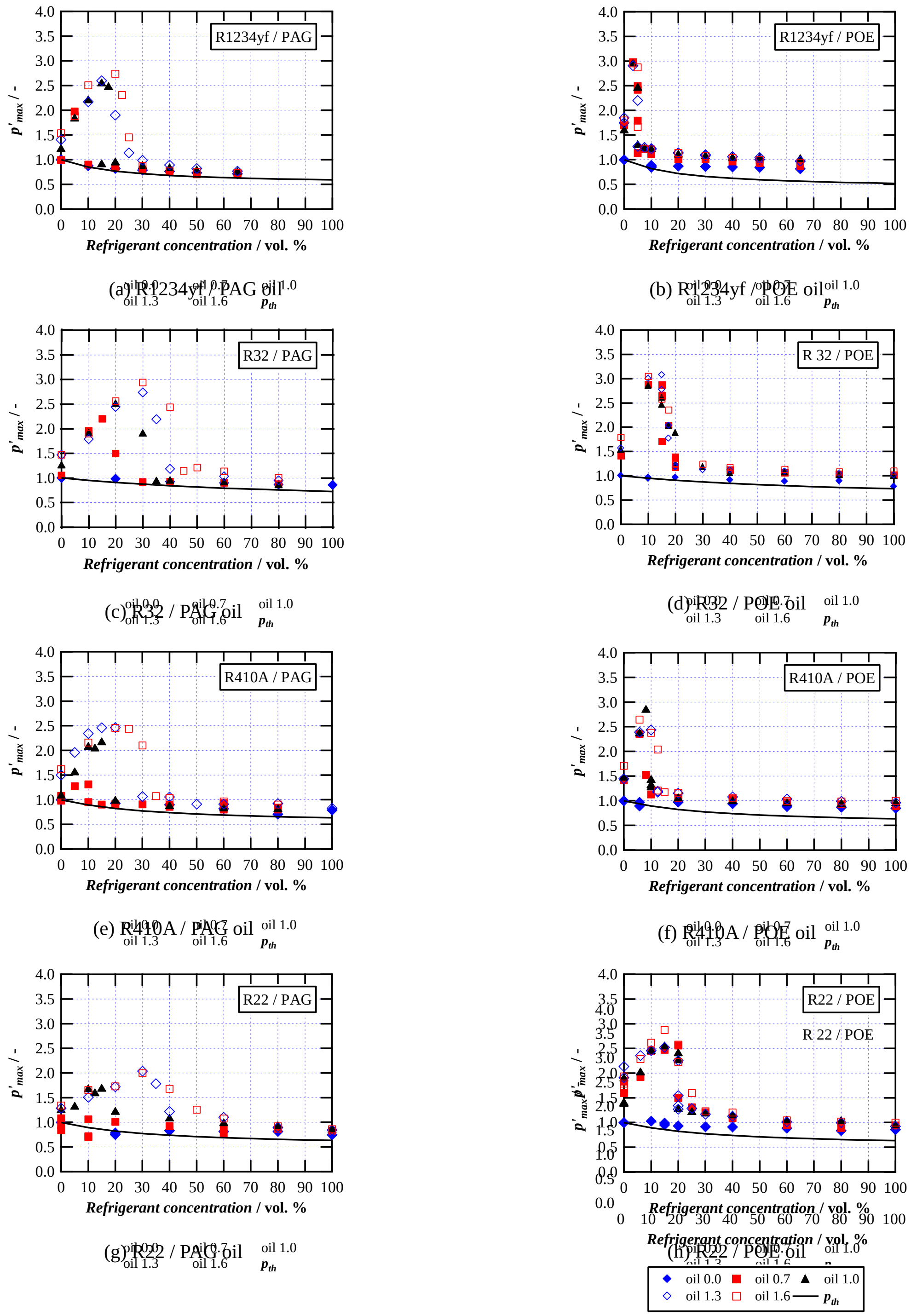


Fig. 6. Maximum pressure against different refrigerant concentrations and oil flow ratios

Table 4 compares the flammable range of each refrigerant with PAG oil and POE oil. The flammable range with the PAG oil is 1.6 to 5.0 times greater than that with the POE oil, which suggests that the properties of the oil are important factors that contribute to accidents during pump down operations, in addition to the properties of the refrigerant. The probability of accidents can be decreased by adjusting the flammability of the lubricating oil.

Table 4. Upper flammable limit (UFL) with PAG oil and POE oil

Refrigerant	UFL with PAG oil / vol. %	UFL with POE oil / vol. %
R1234yf	25	5
R32	40	20
R410A	30	12.5
R22	50	25

4. Conclusion

In this research, the phenomena of diesel combustion during pump down operations were experimentally investigated. An adiabatic compression operation of a gaseous mixture of a refrigerant, air, and lubricating oil was carried out to reproduce the pump down process. The following results were obtained:

1) Accidents that may occur during the pump-down of air conditioners are caused by the diesel combustion of a mixture of air, refrigerant, and lubricating oil.
2) Although the mixture of air and oil could burn under certain conditions, the pressure increase resulting from combustion was moderate unless a refrigerant was added. This result suggests that the refrigerant itself burns, leading to a sudden and significant increase in pressure.
3) The flammable range and the maximum pressure increased as the oil flow ratio increased. This tendency was observed with all refrigerants—R1234yf, R32, R410A, and R22—with the PAG oil.
4) The flammable range may widely vary with the use of different lubricating oils, which suggests that the properties of both the refrigerant and the oil are significant factors that contribute to accidents during pump down operations. The probability of accidents can be decreased by adjusting the flammability of the lubricating oil.

Acknowledgments

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