Study of Combustion Characteristics for R1234yf/R134a Refrigerant Leakage from VCRS Cycle: An Experimental Approach

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Abstract. This academic paper explores the flammability concerns associated with using the refrigerant R1234yf in refrigeration and air-conditioning systems. Since R1234yf is a flammable refrigerant, there is a potential risk of fire and explosion if there is an unexpected refrigerant leakage. The study investigates the combustion properties of R134a + R1234yf (40% + 60%) in the event of hypothetical refrigerant leakage from a test setup. The experimental facility is used to study the thermodynamic behavior of R1234yf in a water chiller. An experimental approach is utilized to investigate the combustion and leakage properties of R1234yf and R1234yf/R134a blends under different initial temperature and mass flow rate conditions. Parameters such as flame shape, temperature, and radiation flux are examined to study the combustion process. The findings of the study reveal that the jet flame would blow off at high temperatures and large leakage mass flow rates. On the other hand, ignition of leaked R1234yf was challenging at low temperatures. The study also highlights that combustion intensity increases between 29 and 58 °C as the leakage mass flow rate increases. These insights could be valuable in guiding the design of fire detection and rescue systems for refrigeration systems that utilize R1234yf.

Keywords: R1234yf · Flammability · Flame height · Radiation flux

1 Introduction

The R134a vapor compression cycle has insufficient heating capabilities due to its thermo-physical properties. The Kigali Amendment, signed by over 170 countries in 2016, requires the gradual phasing down of high GWP refrigerants such as R134a, leading to proposed VCRS systems with low GWP refrigerants [1]. However, concerns regarding reliability and efficiency need further investigation [2]. R1234yf is the best substitute option, but its flammable nature presents safety risks. Risk assessments for R134a/R1234yf refrigerants are necessary due to their A3 and A2 L flammable classifications [3, 4]. An experimental study was conducted to investigate the combustion

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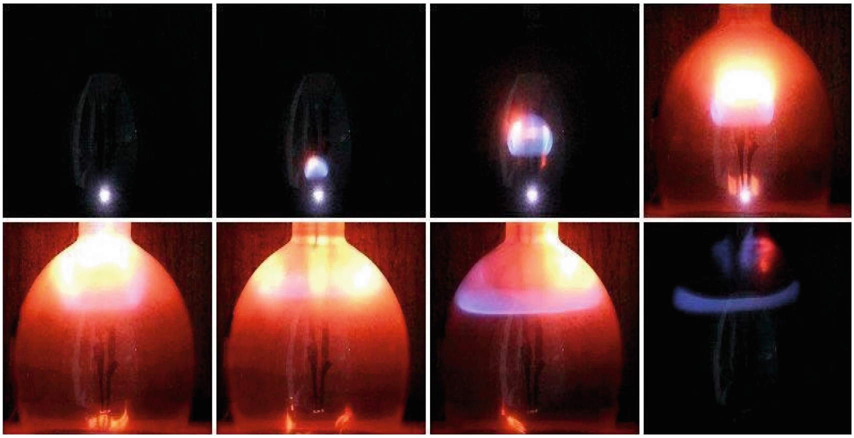

Fig. 1. Flame images of R1234yf near the LFL [6]

behavior of R1234yf as an alternative refrigerant to R134a, providing insight into safe cycle design for a blend of R1234yf/R134a refrigeration systems. R1234yf explosions are milder compared to R32 and methane. Askar et al. experimented with R123yf and other refrigerants in a closed system to detect explosions and flame propagation [1]. Craig D. Needham et al. designed a new mechanism for combustion models [2]. Hanhai Dong et al. studied the effects of initial temperature and refrigerant concentration on the explosion characteristics of R1234yf [3]. J.R. Rowley proposed a new expression for the temperature dependence of LFL [4]. ZijianLv et al. researched the flammability characteristics of R32/R1234yf and R152a/R1234yf [5]. Biao Feng et al. tested flammability limits of R1234yf and its mixtures, and studied flame retardants' effect as shown in Figs. 1 and 2 which represents the LFL and UFL [6]. Zhao Yang et al. studied R1234ze (E)/R161 and R1234ze (E)/R152a [7]. Babushok et al. calculated the burning velocity of refrigerants [8]. Qi Chen et al. developed an experimental apparatus to test the flammability levels of the ternary blend of DME/R1234yf/R134a [9]. Xi Wu et al. reviewed the flammability characteristics of forty-eight HFOs and blends [10]. Mirhadi S. Sadaghiani et al. measured minimum ignition energy and laminar burning velocity for refrigerant/air mixtures [11]. Biao Feng et al. studied the influence of different flame retardants on the flammability of R1234yf [12]. Kang Li et al., investigated the combustion characteristics of R290/R1234yf in a simulated leakage process from an ACHP system and studied experimentally [13].

2 Experiments

2.1 Experimental Test Rig Set-Up

The refrigerant R134a has been forcibly changed in the automotive sector because of the greenhouse effect, and the more ecologically friendly R1234yf will take its place. The characteristic parameters of refrigerants R1234yf/R134a, R1234yf and R134a are compared in Table 1. A unique test rig is set up a indicated in Fig. 3 to determine the risk associated with the usage of R1234yf for a domestic refrigeration system.

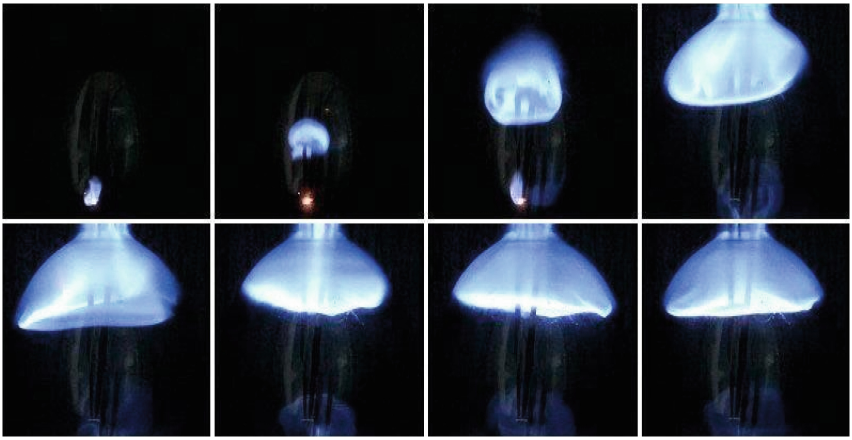

Fig. 2. Flame images of R1234yf near the UFL [6]

Table 1. Refrigerants used in domestic refrigeration systems and their characteristic parameters

Parameter	R1234yf/R134a	R1234yf	R134a
Molecular mass (kg k mol^{-1})	109	114	102
Critical temperature(°C)	98.04	96	101.1
Critical pressure(MPa)	3.652	3.382	4.059
GWP	574.4	4	1430
Safety group	A2	A2L	A1
Formula		$C_3H_2F_4$	$C_2H_2F_4$

The Test apparatus are listed in Table 2 with various parts as shown in schematic diagram. A jet flow combustion system was used to evaluate the ignition energy and flame behavior of R134a/R1234yf, as illustrated in Fig. 3, the system's components include a leaking nozzle, flow meter, radiometers, hot-wire ignition, and gas control cylinder. Thermocouples and pressure sensors measure the temperature and pressure data at four survey locations with an accuracy of 0.25% and a response time of less than 0.2 s. Two radiometers were utilized to observe the thermal radiation emitted by the flame in different directions during the experiment. Instantaneous temperatures of three flammable refrigerants were measured using a K-type thermocouple array at various flame heights ranging from 25 to 100 mm. In addition, a small flame with a volume flow rate of 0.01785 L/min was used to ignite R1234yf/R134a flames to ensure a steady and consistent burning process. Figure 4 shows the original test set up of flame propagation.

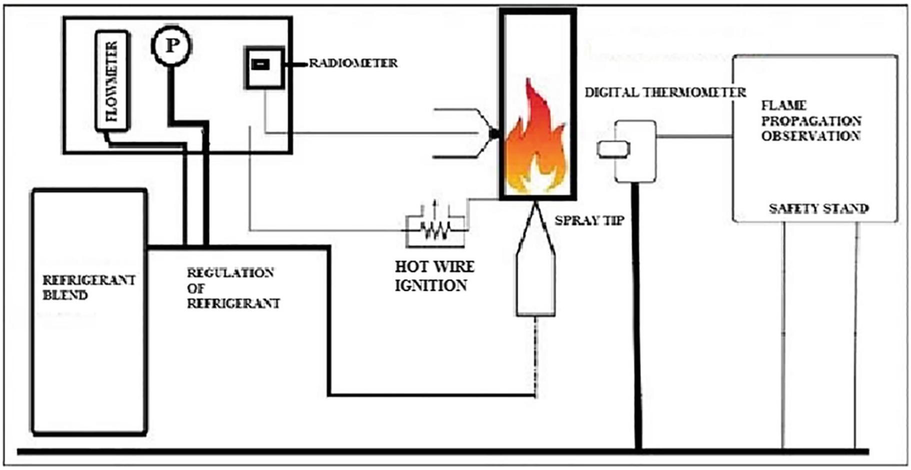

Fig. 3. Schematic for combustion behavior of jet flame leakage.

Table 2. List of Apparatus

S.No	Apparatus
1	Radiometer (5 kw/cm^2)
2	Digital Hand Thermometer (up to 1500 ˚C)
3	Refrigerant blend storage (5 kg)
4	Flow meter (10 LPM)
5	Pressure regulator (600 psi)
6	Hot wire ignition (0–300 ˚C)
7	Spray tip (2 mm)

2.2 Fire Safety Precautions

When handling flammable refrigerants like R1234yf, it's crucial to take proper safety precautions to avoid potential hazards. These include wearing appropriate personal protective equipment, providing adequate ventilation, handling the refrigerant with care, conducting experiments in a controlled environment, using equipment designed for flammable refrigerants like safety stand, and following safety guidelines provided by the manufacturer and relevant safety regulations. By taking these measures, the risk of injury or accidents can be significantly minimized.

Fig. 4. Test rig for flame propagation of R1234yf/R134a

3 Results

3.1 Comparison of Combustion Characteristics

The study compares the flame characteristics of R1234yf and R1234yf/R134a refrigerants under identical volume flow rates of 1.25 lpm at gas temperatures of 30 °C, 60 °C, and 90 °C. R1234yf has a pressure of 0.478 MPa, while R1234yf/R134a has a pressure of 0.314 MPa. R134a is not easily ignitable under normal operating conditions. The flame size of both refrigerants changes with the gas temperature, but R1234yf produces a larger flame compared to R1234yf/R134a. At a volume flow rate of 1.248 lpm, R1234yf achieves the maximum flame height. When gas was observed to heat at a starting temperature of 90 °C. It is the competitive outcome of the effects of temperature-based burning enhancement, flow turbulence, or exit velocity-based instability.R134a/R1234yf has a lower flame height than R1234yf under all considered temperature conditions, although combustion intensity appears to increase as the gas temperature rises based on flame colour. The flame changes colour as the temperature rises, going from red, orange to yellow and white.

3.2 Impact of Gas Temperature and Volume Flow Rate

Figure 5 illustrates the changes in flame shape of R1234yf at different temperatures and flow rates. At a flow rate of 0.5 lpm, a thin flame was observed at the leaking nozzle, which became thinner with increasing refrigerant temperature due to the smaller burning zone. The yellow portion of the flame showed an opposite trend with respect to flame height at the same temperature, decreasing as the flow rate increased. R1234yf/R134 burnt completely with a blue flame at 10 °C, but at 90 °C and 1.5 lpm, it lost its ability to maintain a combustion regime with a hissing sound. The R1234yf/R134a flame was noticeably thinner than R1234yf at 90 °C, and the combustion process appeared smoother. The flame length of R1234yf increased with increasing concentration, but at a flow rate of 2.5 lpm and temperature of 90 °C, an unsteady flame was observed. The R1234yf/R134a flame height was shorter than R1234yf at smaller flow rates. The R1234yf/R134a gas flow was ignited using an R1234yf flame due to the challenge of igniting R1234yf, and it produced black smoke and an unpleasant odour during combustion.

3.3 Flame Height

The study presents a summary of the flame height and flame core height of R1234yf at different refrigerant gas temperatures and flow rates. Flame height and flame core height exhibit different trends with increasing flow rate. At 10 °C, an increase in volume flow rate from 0.5 to 1.25 lpm results in a decrease in flame height and an increase in flame core height, but both heights decrease significantly at flow rates above 1.25 lpm due to intense burning turbulence. Thus, leakage rate in domestic refrigeration systems should be taken into account to prevent refrigerant explosion. Gas temperature has an insensitive effect on flame core height and no monotonic relationship is observed. Flame height increases consistently for R1234yf gas fire from 0.5 to 2.0 min − 1, especially at 60 °C, but it decreases for low and high temperature conditions (30 ˚C and 90 °C) when the volume flow rate exceeds 2.0 min − 1, due to unsteady burning.

3.4 Flame Temperature

The Fig. 5 shows the temperatures of R1234yf/R134a flames at different positions in the range of 0 ˚C to 1000 ˚C, with the highest temperature of the R1234yf flame occurring in the combustion core zone between 100 and 150 mm height. The difference in flame temperature between R1234yf and R1234yf/R134a is due to their distinct combustion behavior, as previously reported. The R1234yf flame exhibited an initial increase in temperature at lower gas temperatures, followed by a decrease after the second thermocouple temperature point. In contrast, the temperature and height of the R1234yf/R134a flame continued to decrease, which was attributed to the fluctuation in the main combustion reaction zone. The researchers speculated that the main burning reaction zone moved towards the exit as the temperature increased due to faster combustion. This resulted in a lower turning point, which was more pronounced in R1234yf. However, both flames have similar temperatures despite their differences.

3.5 Ignition Temperature

The Fig. 5 displays the ignition temperatures of R1234yf/R134a in relation to volume flow rate and gas temperature. It was observed that ignition temperatures remained relatively constant at temperatures of 10˚C, 30˚C, and 60 °C as refrigerant gas temperature increased, with values typically exceeding 90 °C. However, when the temperature was

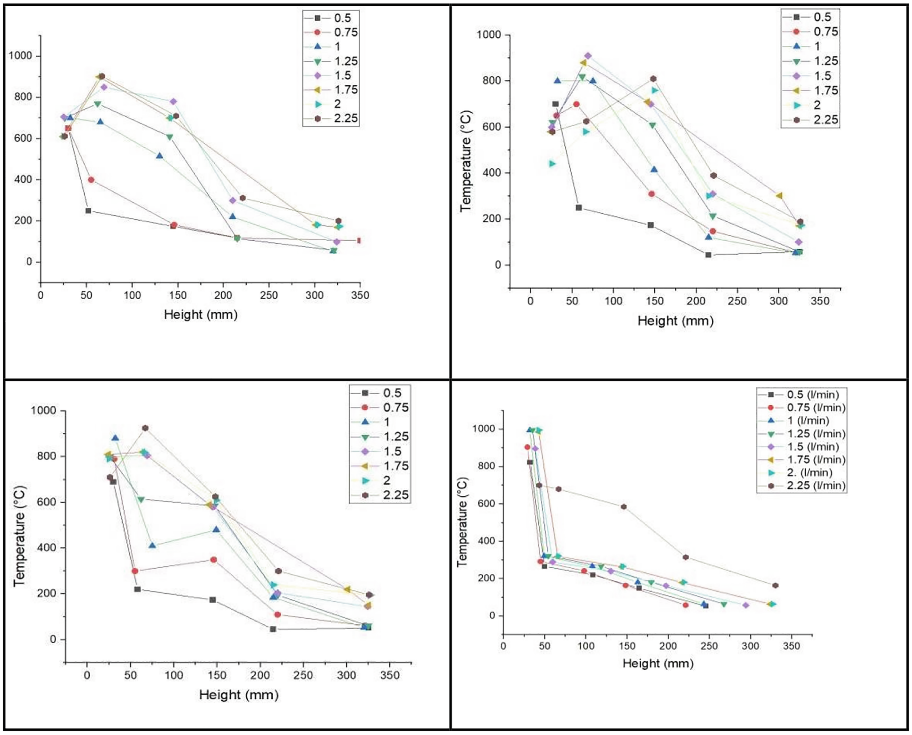

Fig. 5. Flame temperature of R1234yf/R134a, burning under controlled conditions. Leakage at: (1) 20 °C (2) 30 °C (3) 60 °C and (4) 90 °C

increased to 90 °C, the ignition process was found to become easier, except when the volume flow rates were increased. This behavior was attributed to the excess enthalpy produced by the initial temperature, which facilitated the combustion and ignition processes. In contrast, higher flow rates would increase the instability of the gas mixture, hindering ignition. Therefore, managing ignition energy in refrigeration systems could significantly reduce the risk of combustion.

3.6 Radiation Flux

As shown, Fig. 5 and the first row in Table 3 show values at 20 °C temperature. At this temperature, the refrigerant flow rate is 0.5 lpm, the radiation heat flux is 35 W/m^2, and the refrigerant flow rate (again) is 0.5 lpm. The second row in Table 3 shows values at 30 °C temperature. At this temperature, the refrigerant flow rate is 0.5 lpm, the radiation heat flux is 42 W/m^2, and the refrigerant flow rate (again) is 0.5 lpm.

The third row in Table 3 shows values at 60 °C temperature. At this temperature, the refrigerant flow rate is 0.5 lpm, the radiation heat flux is 38 W/m^2, and the refrigerant flow rate (again) is 0.5 lpm. The fourth row in Table 3 shows values at 90 °C temperature. At this temperature, the refrigerant flow rate is 0.5 lpm, the radiation heat flux is 38 W/m^2, and the refrigerant flow rate (again) is 0.5 lpm.

Table 3. Radiation Heat flux obtained under various flow rates at different temperatures

20 ˚C		30 ˚C		60 ˚C		90 ˚C	
Flow rate (LPM)	**Heat Flux (W/m^2)**	**Flow rate (LPM)**	**Heat Flux (W/m^2)**	**Flow rate (LPM)**	**Heat Flux (W/m^2)**	**Flow rate (LPM)**	**Heat Flux (W/m^2)**
0.5	35	0.5	42	0.5	38	0.5	38
0.75	48	0.75	58	0.75	68	0.75	37.5
1	85	1	94	1	62	1	61
1.25	82	1.25	88	1.25	90	1.25	91
1.5	88	1.5	65	1.5	82	1.5	96
1.75	305	1.75	62	1.75	91	1.75	61
2	101	2	51	2	86	2	88
2.25	82	2.25	90	2.25	95	2.25	52

This is due to the flame being close to the leaky nozzle at lower temperatures. The radiation flux of R1234yf/R134a exhibits substantially greater variations when compared to R1234yf. It is observed before 1.25 lpm, the heat flux value of R1234yf/R134a flame grows. According to the results, there is a clear upward trend in the radiation fluxes as the flow rate increases across different temperatures. However, it is notable that the thermal radiation value exhibits a more significant increase than the other types of radiation fluxes (Fig. 6).

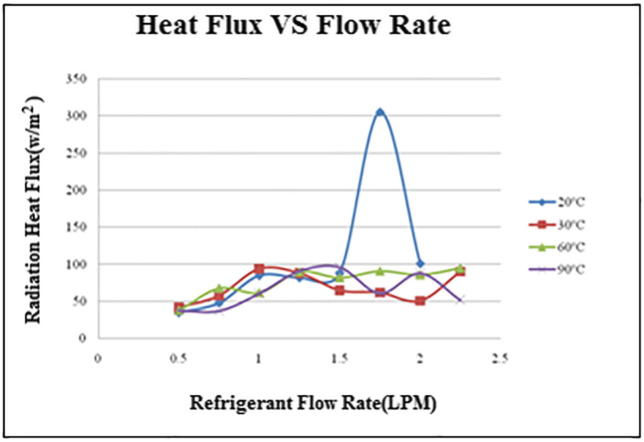

Fig. 6. Relation between Heat Flux and Flow Rate

4 Validation with Previous Works

According to the research conducted by Kang Li et al., [13] the flammability of the R1234yf/R134a blend is lower compared to that of R1234yf alone. The flammability tests carried out in a heat pump showed that R1234yf alone resulted in a fire above 1000 ˚C, while the blend of R1234yf and R134a resulted in a fire around 900 ˚C. Hence, the blend was found to exhibit lower flammability levels compared to R1234yf alone.

5 Conclusion

The combustion characteristics of R1234yf/R134a were investigated experimentally in this study using a model leaking process from a test rig. Based on the vapour compression cycle and combustion facility with R1234yf/R134a proposed, the flame shape, flame temperature, ignition energy, and radiation flux under various volume flow rates and gas temperatures were interpreted and studied. Here is a summary of the findings: When compared to the mass flow rate, the gas temperature had minimal impact on the R1234yf flame height, but a high beginning temperature increased the intensity of combustion. In general, when R1234yf burned, the flame was wider than when R1234yf/R134a was used. The physical form of the flame as obtained here might offer suggestions for assessing fire hazards. It was discovered that the R1234yf burnt vigorously at an initial temperature of 10 °C and at a rate of 1.5 lpm at 90 °C. R1234yf/R134a, on the other hand, could not be ignited without producing blazing fire, along with black smoke and an offensive odour. Additionally, a favorable correlation between flame height and overall refrigerant volume flow rate was observed. For R1234yf, ignition temperatures were typically above 60 °C and were rather constant, with the exception of the high starting gas temperature condition. Additionally, in contrast to R1234yf/R134a, radiation flux for R1234yf dramatically increased with increased flow rate. It was thought that these trends might be helpful for early fire detection and prevention systems for the systems.

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