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Review Article

Performance of Heat Pump Air Conditioning with R1234ze (HFO) as a Refrigerant

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The study shows that refrigerants R1234ze (E) and R1234ze (Z), known for their low global warming potential, are likely to become primary choices in heat pump air conditioning for residential and commercial use. The research evaluates the thermodynamic properties of R1234ze (Z) using experimental, thermodynamic, and numerical analyses. It addresses F-gas regulation requirements and aligns with the Paris Agreement goals by exploring various refrigerants, including R227ea, R114, R236fa, R134a, R1234ze (Z), and R245fa, as potential candidates for evolving industry needs. The analysis indicates that R1234ze (Z) outperforms other working fluids in heat pump applications, with an optimized theoretical coefficient of performance (COP) at a condensation temperature 22 K lower than critical temperatures. However, actual COP deviates due to a significant pressure drop, especially with inadequate volumetric capacity. A key finding is that a substantial portion of the pressure reduction is attributed to mitigating irreversible losses, estimated at a condensation temperature of 70–75°C, emphasizing the complex relationship between pressure and performance. The study suggests that R1234ze (Z) is more suitable for high-temperature applications than traditional air conditioning systems. In a parallel assessment, the initial calculation of the coefficient of performance for R245fa evaluates the reliability of a new refrigeration industry arrangement. Test results for heat pump technology reveal that R1234ze (Z) achieves an impressive COP of up to 3.60 at a buildup temperature of 90°C with a temperature differential of 45 K. This positions R1234ze (Z) as a suitable choice for heat pump applications prioritizing simplicity in system design.

1. Introduction

As per the European Union (EU), to address the issue of supply security, mitigate the effects of climate change, and increase the sector's competitiveness, they set ambitious objectives; around 40% of total energy use is consumed by the building industry, a considerable provider to greenhouse gas (GHG) emissions [1]. The domestic sector accounts for around 26% of total energy consumption in Europe with the majority of this coming from the production of hot water, cooling, heating, and for private residences [2]. By implementing solutions that do not use fossil fuels for building heating and cooling, we may diminish emissions of greenhouse gas and increase the proportion of renewable energy sources (RES). Electrical appliances that can be utilized for this purpose include heat pumps which increase the energy system's efficiency. These devices can be utilized when a new energy plant is necessary for the retrofit of existing structures [3, 4]. High-temperature heat pumps (HTHPs) can be used when heat is needed at high temperatures (90–160°C) and the COP ranges between roughly 2.4 and 5.8 for a temperature rise of 85–140°C, correspondingly [5]. Because single-stage thermodynamic cycles are frequently used in the construction of HTHPs, it is challenging to attain desirable COPs with high-temperature heat output. Studies looking into the use of new refrigerants in the literature have highlighted the essential for the adoption of fluids with low global warming potential (GWP) that demonstrate acceptable system performance at high temperatures [6].

What is meant by the 2013 European Agreement, which aims to gradually reduce the use of F-gases, or fluorinated greenhouse gases, a group of substances that include fluorine? The most widely used F-gases in Europe are HFCs such as R134a and R410A, which are largely employed as refrigerants. The European Union intends to decrease the harmful impact of fluorinated gases on the environment by gradually phasing out the use of refrigerants such as R410A and R134a. The air conditioning sector has been forced to convert to refrigerants with lower global warming potential as a result of a considerable change in recent years. It is fascinating to see how laws have been one of the major factors encouraging national and worldwide investment in new technology. For instance, the demand for F-gas forced HVAC manufacturers to find substitutes for R134a and R410A. We have not yet discussed R134a's alternatives, even though R-32 has drawn a lot of attention as an R-410A replacement with a low GWP. R1234ze and R513A are typically the only options available as R134a substitutes. Depending on the technology they are paired with, both are excellent low-GWP alternatives; however, in this work, we will concentrate primarily on R1234ze and the benefits it provides. The HFO refrigerant R1234ze has a relatively low GWP of just 7. As a result, it ranks as one of the most useful methods for guaranteeing minimal environmental impact and legal compliance [7]. While R1234ze has a much lower GWP (7 compared to 1300 for R134a), it significantly improves the efficiency of chiller operations. Given the stricter environmental standards, these two qualities undoubtedly make this refrigerant a future-proof choice. Another interesting finding is the emphasis on the following concept in the HVAC literature when comparing R1234ze with R134A.

A modified screw profile is incorporated into the new compressor design for the best performance with R1234ze and R134a refrigerants. By using this newly developed compressor, the chiller unit's cooling capability is significantly increased while preserving its compact size. R1234ze is utilized in some traditional medium-pressure refrigerant applications, such as heat pumps, water-cooled chillers, and CO_2-cascade industrial cooling systems. R1234ze is a greener and more energy-efficient alternative to more traditional refrigerants such as R404A. R1234ze is categorized as a refrigerant as somewhat flammable. The refrigerant is classified as nonflammable for handling and storage when the temperature is below 28 to 30°C because it does not interact with the air to create flammable combinations, and R1234ze is a common component of refrigerant blends [8].

R1234ze (E) and its isomer R1234ze (Z) are used as refrigerants in HTHP in industrial applications such as beverage concentration, food sterilization, wood drying, solvent recycling, and petrochemical refining. It is possible in a variety of industrial applications heat pumps can raise the waste heat source temperature to a more useful higher temperature. Using a heat pump system instead of an electric heater or a traditional combustion system can save fuel and reduce CO_2 emissions. Few refrigerants used in heat pump systems have high global warming potentials (GWPs). For example, R245fa, the working fluid for industrial heat pumps and organic Rankine cycles, often has a GWP of 1030 to 100. R1234ze (Z) with very low GWP (GWP 100 10) and identical thermodynamic properties has been recently proposed only to replace R245fa. R1234 (E) 6 with GWP 100 is proposed as an alternative to R134a (GWP 100 = 1430). The advantage of using this refrigerant is that R1234ze (Z) is produced as a by-product of the production of R1234ze (E).

For HTHP pumps, a comparison and evaluation of 250 potential refrigerants at 160°C was carried out. The most important factors in this article to consider, when evaluating refrigerants are COP, which is the opposite of specific compression displacement (SCD), volume, and the minimum temperature required to prevent liquid condensation.

The selection of future refrigerants is intricately tied to environmental and safety considerations, as well as evolving regulatory restrictions. The impact of these factors on the decision-making process is significant, leading to a reduction in the number of viable options. Initially, a pool of 163 potential refrigerants was under scrutiny, but as a result of current and anticipated future restrictions, this number has been streamlined to approximately 20 per case. The overarching goal is to identify substances with lower global warming potential (GWP) and adhere to stringent environmental standards. Thermal properties also play a crucial role in this selection process. The ability of a refrigerant to operate within specific thermal parameters, such as the evaporation pressure within a vacuum range or the low-temperature heat pump's (LSHP) capability to sustain transcritical conditions, greatly influences the feasibility of a substance. Broadening the conditions under which these refrigerants can operate would expand the range of substances under consideration [9]. The global adoption of heat pumps is on the rise, playing a pivotal role in the worldwide shift towards renewable energy sources. Consequently, the efficiency of heat pumps, a critical aspect of their performance, is gaining increasing importance. This research complements and extends previous studies on the characteristics of heat pumps and presents numerical results and experiments related to the use of refrigerants R1234yf and R1234ze (E) in systems with and without internal heat exchanger (IHX) implementation which provides a comprehensive comparison of results. In addition to efficiency, various parameters of the heat pump were analyzed, including mass flow rate, outlet temperature, volumetric efficiency, compression performance, cooling and heating performance, and heat exchanger pressure drop. In summary, the heat pump system utilizing the R1234ze (E) refrigerant demonstrated a higher coefficient of performance (COP) compared to the system using R1234yf, regardless of the presence of IHX. When an IHX was integrated into the cycle, the COP values were consistently 2.61% to 4.99% higher when employing the R1234ze (E) refrigerant compared to R1234yf. In cycles without IHX, the COP values for R1234ze (E) surpassed those of R1234yf by 4.77% to 10.73%. It is essential to note that the heating capacity values with R1234yf were found to be higher than those achieved with R1234ze (E). This detailed analysis not only highlights the efficiency differences between the two refrigerants but also explores various crucial parameters, offering valuable insights for optimizing and applying heat pump systems in diverse scenarios [10].

Trans-1, 3, 3-Tetrafluoroprop-1-ene, also known as R1234zeE, is an HFO refrigerant with a carbon-carbon double bond and a very low GWP [6]. R1234ze molecule has two isomers: R1234ze (Z) and R1234ze (E), each with slightly different properties (see Figure 1). While R-1234ze (E) has about 50% higher volumetric capacity than R-1234ze (Z), R-1234ze (Z) has a higher boiling point (10°C) connected with a higher temperature (153.7°C). Because of this, R-1234ze (Z) can only be used in special uses including high-temperature heat pumps, but R-1234ze (E) will do more similar to R-134a and will be cheaper to apply for the system and compressor size [11].

2. Environmentally Friendly Impacts of Refrigeration

The findings of some logical research [12], which showed the impact of specific mixtures, including chlorinated refrigerants, such as R11 and R12, on the destruction of the ozone layer, were the important primary concern about the harmful ecological effects of refrigeration and air conditioning. The investigation also identified the gaps between the entrance of the chlorinated compound at ground level and its picture separation inside the atmosphere. Therefore, in order to stop the depletion of ozone, immediate action is needed to regulate the release of chlorinated chemicals into the atmosphere. This later evolved into a global accord based on the Montreal Protocol on substances that deplete the ozonosphere [13], which triggered the replacement of ozone-exhausting compounds, particularly refrigerants, and kicked off the recovery of atmospheric ozone depletion. The use of HFC and HCFC refrigerants, which replaced CFC in many modern applications, was also encouraged by the Montreal Protocol. According to the Amendment of the Montreal Protocol, there has been a universal agreement to restrict the export of HFC compounds [14]. HFC compounds are governed by laws in a few countries, including those in the European Union. Regulatory requirements are leading to the replacement of HFC chemicals with alternatives that have lower GWP values (among the various properties required for refrigerants). Therefore, the future production of low GWP options will increase to a greater extent; in Figure 2, HCFC and CFC mass consumption values are taken from reported data [7]. The lower and upper bounds of the reference scenarios in developing and developed countries serve as bounds for the shaded regions for GWP-weighted consumption in B and RF in C. The consumption presented in terms of $GtCO_2$ equivalents per year in B is the total consumption of each HFC compound multiplied by its individual GWP (100-year period) [15].

Consumption, emissions, and RF values for updated HFC baseline scenarios from 2000 to 2050 are shown in Figure 2. Consumption and emissions are adjusted for CO_2 equivalents by using GWP for more than 100 years [12]. As shown in the figure, the upper and lower bounds of the HFC range are due to changes in population growth and GDP and the baseline scenarios. The low and high points of the emerging markets range both based largely on GDP are placed after A1 and A2, respectively. The range for industrialized countries is A2 for the higher end and B2 for the lower end mainly due to population per capita chlorofluorocarbon demand as per the market infiltration which is projected to saturate developed country markets in the next 10 years and developing country markets around 2040 at its highest level in hydrofluorocarbon scenario. Global HFC consumption in terms of GWP increased significantly from 2012 to 2050 especially in emerging countries to 6.4 to 10 $GtCO_2$-eq per year (Figure 2(b)). By 2051, consumption in emerging countries will exceed that of industrialized countries by 800% and by a larger margin in 2020 due to larger populations and faster GWP expansion. By 2050, total HFC emissions in terms of GWP will be between 5.8 and 8.8 $GtCO_2$-eq per year, closely tracking consumption but lagging a few years (Figures 2(a) and 2(b)) [15]. While HFC emissions increased steadily and exceeded those of CFCs and HCFCs after about 2020, total direct CFC and HCFC emissions in terms of GWP decreased between 2000 and 2050 (Figure 2(a)). The baseline scenario predicts that, on a mass basis, global HFC consumption will be 2.3 to 3.5 times higher in 2050 compared to its peak in 1989. Calculated global HFC emissions according to the GWP function for the new reference scenarios will be much higher in 2020 than that of SRES (Figure 1(a)). Equivalent SRES emissions in 2050 will decrease by a factor of four, from 1.3 to 2.5 $GtCO_2$-eq per year (14, 27). As noted in the introduction, lesser SRES levels are expected based on experience and recent market data; specifically, the main reasons for higher emissions in the updated baseline scenarios are the higher starting point for HFC consumption as well as the use of high GWP HFCs. Then, the revised scenarios predict that HFC-125 and HFC-143a will be used in some applications contrary to SRES's expectation that HFC-134a will be used in the majority of applications [14]. R-410A and R-404A are the two main components of HFC-125 and HFC-143a. Emissions are given a higher weight because these mixtures have a higher GWP than HFC-134a. Based on emissions of HFC components calculated from atmospheric concentrations recorded through 2007, it is expected that the use of R-404A and R-410A in emerging countries will follow the pattern in industrialized countries [6]. Atmospheric measurements used to calculate GWP-weighted HFC-125 and HFC-143a emissions in 2007 produced values of 0.076 and 0.073 $GtCO_2$-eq per year, respectively. These values are 2-3 times higher than the SRES values of 0.030 $GtCO_2$-eq/yr, respectively. These upper values cause the 2052 projection starting point to be above the SRES level and all subsequent values to increase. The GWP-weighted HFC-134a emissions calculated from experimental atmospheric concentrations are 0.20 $GtCO_2$ eq/yr, slightly lower than the 0.30 $GtCO_2$ eq/yr [15–17].

3. Evaluation of New Refrigerants

Regarding their suitability for usage during a specific use, refrigerants are routinely evaluated. A material must meet certain criteria in order to be useful as a refrigerant. It should initially have appropriate synthetic, physical, and

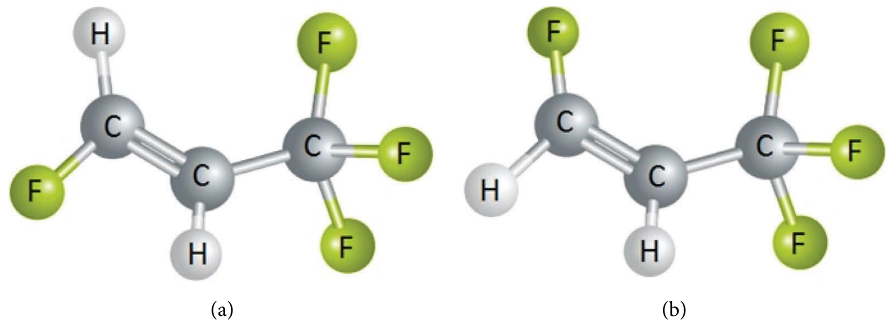

Figure 1: The HFO-1234ze isomers [11]. (a) HFO-1234ze (E). (b) HFO-1234ze (Z).

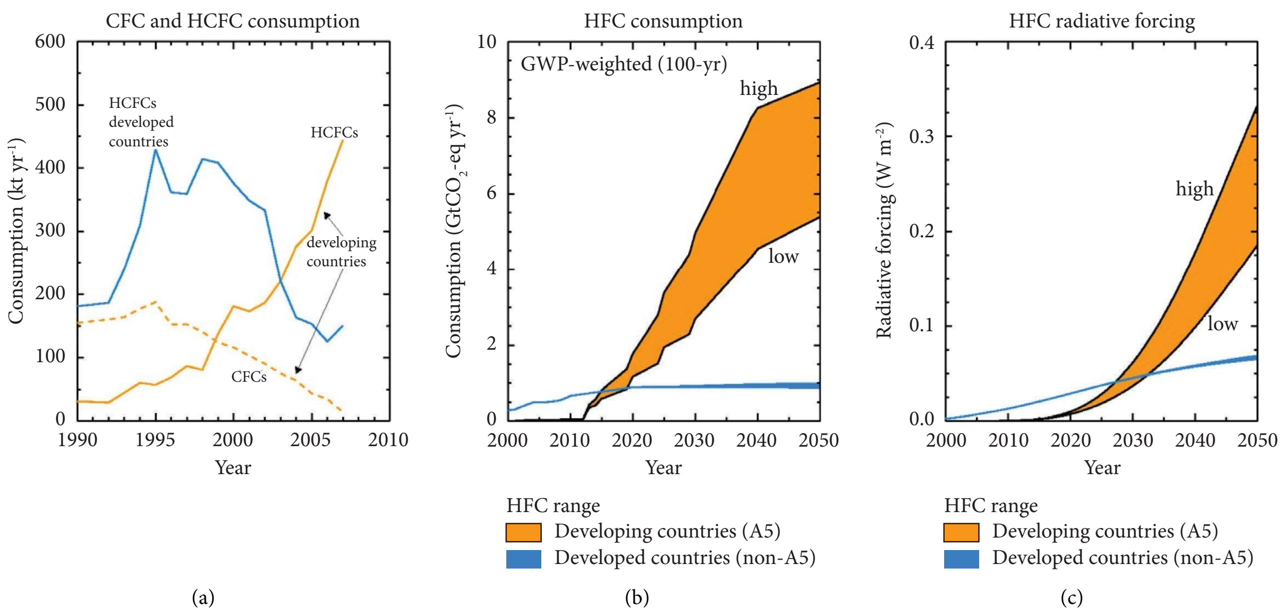

Figure 2: Consumption of CFC and HCFC (a), HFC (b), and HFC RF (c) for the duration of 2000–2050 in growing (A5) and evolved (non-A5) nations [12].

thermodynamic characteristics for the specific structure. In addition to monitoring the conditions, it must be safe to use the refrigerant and maintain natural safety. When the first two requirements are satisfied, additional models are usually used as examples because they have good energy performance, high productivity, and appropriate limits. According to Qiu's observation, recent inspections looked at some tentatively determined information on several significant thermodynamic and transport parameters of HFO and HCFO refrigerants and their mixes. The finish of the examination is solitary. R1234yf and R1234ze (E) are widely researched as far as both thermodynamic properties such as basic point (CP), soaked weight, weight, temperature, volume in single-stage locales, isobaric heat (cp), centric factor (ω) and transport properties, such as warm conductivity (λ), dynamic or kinematic viscosity (μ/ν), and characteristic marvel (σ) [18–20].

In Figure 3, a second concern highlighted is the flammability or high flammability associated with many low-to-no-GWP refrigerants. This characteristic raises additional safety considerations during manufacturing processes and handling, necessitating heightened awareness and training.

The third concern discussed in the figure pertains to community impacts around facilities engaged in the destruction or abatement of F-gases. Troubling evidence from India underscores the potential adverse consequences of HFC-23 destruction projects. These activities were found to become polluting and potentially toxic due to improper treatment and disposal of hazardous feedstocks, including chloroform and sulfuric acid. In one project, accusations were made regarding the dumping of hazardous wastes directly into community watersheds. Allegations further suggested that the thermal incineration process led to the creation of hydrochloric acid and hydrogen fluoride, releasing sulfur

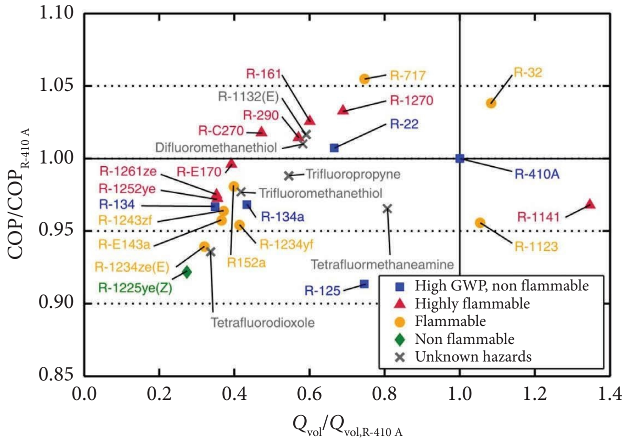

Figure 3: Volumetric capacity and COP of selected low-global-warming potential fluids [20].

dioxide, carbon monoxide, and nitrous oxide. Groundwater tests confirmed elevated levels of many pollutants, exceeding permissible limits, at village wells. Oily films were observed on the water, and chloride toxicity affected crops, manifesting as white crusts on local soils. Additionally, community residents experienced endemic health issues, including eye irritation, skin pigmentation disorders, rashes, joint pains, and decreased fertility. This comprehensive analysis underscores the environmental and health risks associated with certain F-gas destruction projects and the importance of proper handling and disposal practices [20].

4. Short GWP Refrigerant and Cycle Simulation

Figure 4 on the T-s and P-h diagrams shows the calculations for R1234ze (Z) at condensing temperatures of 110°C and 135°C and the causes of the variations in sunken losses. Figures 4 and 5 show how the pressure drop due to the temperature gradient of the refrigerant flow through the evaporator decreases as the temperature of the heat source water increases. The overall system is affected by a reduction in pressure loss. Figure 5 shows how the bulk capacitance increases with temperature up to 150°C. The increased volume capacity is the cause of the lower circulation mass flow under the specified high-temperature conditions. The reduced vapor flow rate is also a result of the denser refrigerant vapor [21]. LDP for permanent loss is reduced due to the reduced pressure drop, especially in the intake manifold. According to Domansky's assessment, as the condensing temperature increases, the throttling causes a slight increase in loss for the irreversible process in the expansion valve. A rise in molar heat capacity usually causes an increase in throttling losses in expansion valves. However, the total irreversible loss of R1234ze (Z) decreases at high temperatures. As indicated, the case study shows that the low-GWP refrigerant R1234ze (Z) is more suitable for future industrial applications than air conditioning or refrigeration systems, as it can achieve a higher COP at condensing temperature exceeding 100.

Figure 6 shows the volumetric capacities and theoretically calculated COPs for the fully reversed Rankine cycle for R410A, R134a, R245fa, R1234ze (E), and R1234ze (Z). Each refrigerant has a specific condensing temperature that maximizes the COP, which is often 20 K below the critical temperature. It almost exactly matches the findings by researcher McLinden, who concluded that a higher COP of about 0.7 is produced by a reduced condensation temperature. Among the selected refrigerants, R410A has the lowest COP but the highest volumetric capacity at condensing temperatures up to 72°C at the same condensing temperature; R1234ze (Z) has a higher COP than R1234ze (E).

Figure 7 shows the COP of the evaporator concerning six different refrigerants and it was found that the average COP of three mixtures of M1, M2, M3, and R152a, R1234ze (E), are composed of R152a and R1234ze (E) (having ratio of 65 : 35, 45 : 55, and 50 : 50) by mass, respectively. As drop-in alternates of R134a in a vapor compression system were hypothetically analyzed, the three mixtures M1, M2, M3, and R152a were about 5%, 3.4%, 2.5%, and 2.0% higher than R134a at condenser temperature of 45°C and 60°C about 9% and 6%, respectively, more than R134a by 5% and 4%. The compressor consumes very little electricity which is mostly to blame, while R1234ze (E) and R134a had almost comparable coefficients of performance (COP), and it was found that the COP of the R1234ze (E)/R152a blend was higher than that of R134a as the COP of R1234ze (E) was nearly that of R134a in the blend with the lowest COP. As the condenser temperature increases, the COP differences between R134a and R152a, M1 and R134a, and M2 and R134a as well as between M3 and R134a increase. Consequently, at higher condenser temperatures, COP is expected to increase with R152a, M1, M2, and M3. Both condenser and evaporator temperatures show a positive and negative relationship with COP [22, 23].

R1234ze (E) has the best efficiency in the condensing temperature range of 29 to 39°C and maintains a COP value of at least 3.9 over a wide operating range, while R1234yf exhibits a higher COP which is shown in Figure 8. The maximum COP was achieved by R1234ze (Z) and R1233zd (E) when the condensing temperature increased from 38°C to 78°C. Except for R1234yf, the COP values for the refrigerants are close to or greater than 88% of the maximum COP value. The volumetric heating capacities of some refrigerants are also contrasted and the volumetric heating capacities of R1234ze (E) and R1234yf are obviously higher than those of other refrigerants and are at least twice that of R1234ze (Z) [24].

5. Theoretical Simulation

5.1. Selection of Refrigerants. The low-GWP HCFO and HFO refrigerants R1224yd (Z), R1234ze, R1336mzz, and R1233zd (E) are all examined in Table1. The outstanding starting temperature of 182.1°C at a realistic weight of 30 bars is one of the benefits of R1336mmz (Z). It has an environmental continuation of only 22 days, a wealth class of A1, a GWP of 2, an ODP of 0, and a GWP of 2. R1336mzz (Z) is marketed by Chemours under the name Option MZ. It is ideal for

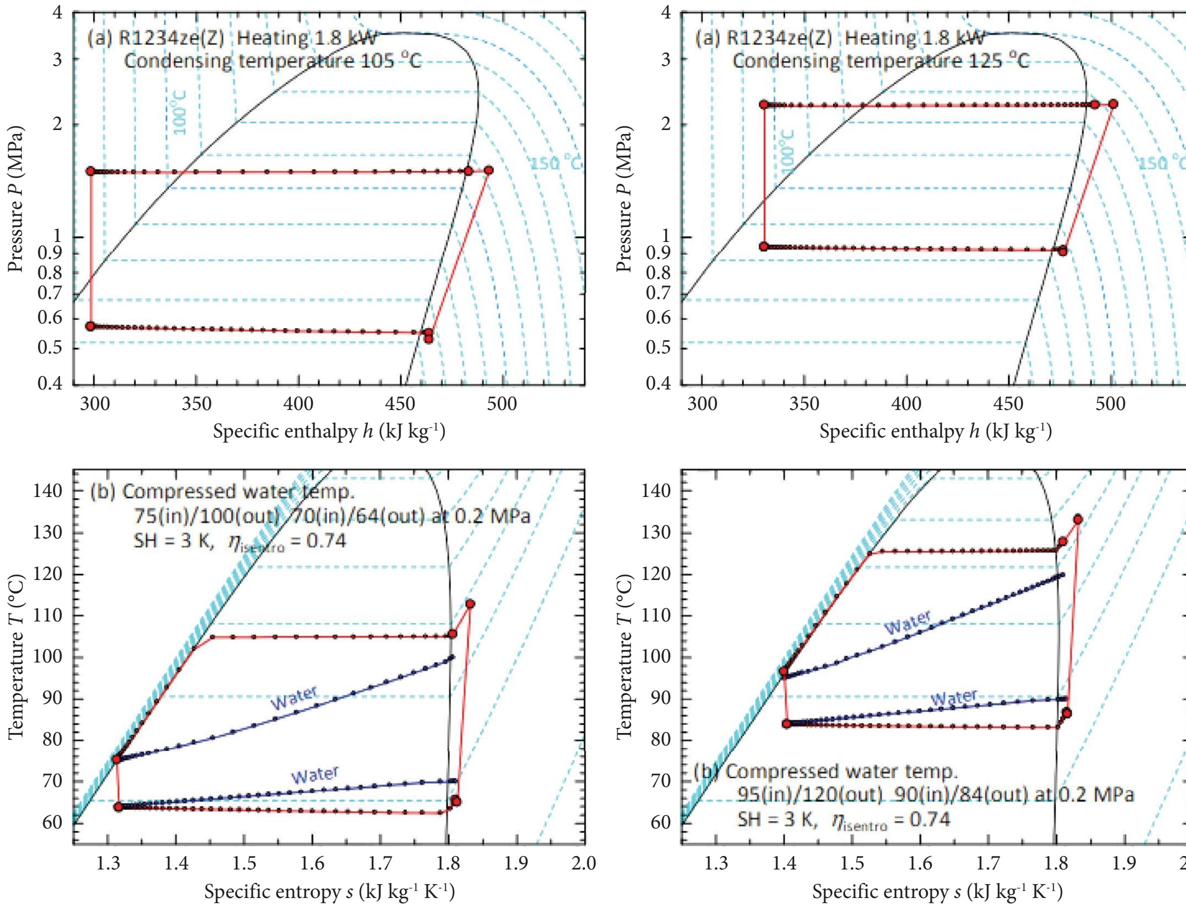

Figure 4: (a) P-h diagram and (b) T-s diagram. Simulation results for R1234ze (Z) at condensing temperatures of 110°C and 135°C [20].

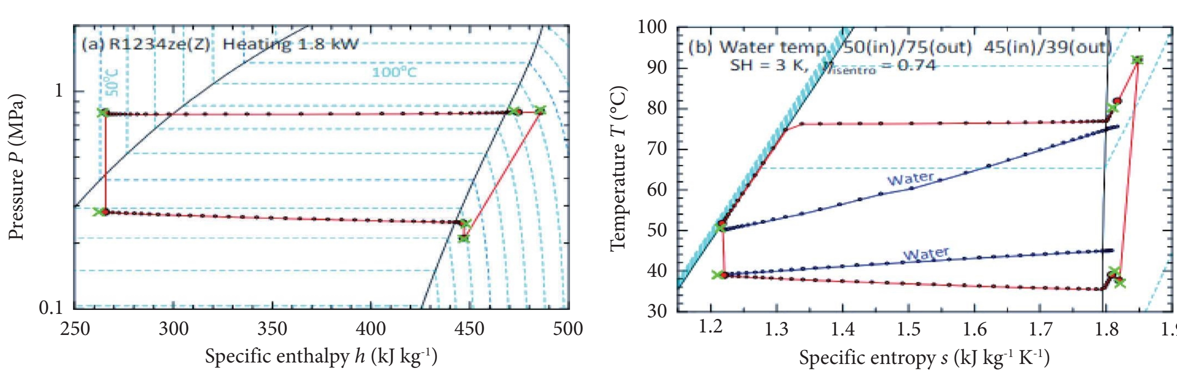

Figure 5: Simulation result of R1234ze(Z) for heating load of 1.8 KW heat pump at compensation temperature of 82°C; crosses and circle symbols represent measured and simulated points. (a) P-h diagram and (b) T-s diagram [20].

waste heat recovery processes, natural Rankine cycles, and the aging of brume because it is stable up to 261°C (23). Testing in the lab has shown that the faces of Bobby, Sword, and R245fa are remarkably similar. Polyol ester oil painting (POE) is completely miscible over a range of temperatures and structures, making it a highly trusted oil painting [26]. There is a pitifully small quantum of information about R1234ze (Z), which has an abecedarian temperature of 140.1°C and an abecedarian weight of 35.3 bar [27]. Its combustibility is calculated using the A2L method and has a GWP lower than 0.9. In HTHP operations, R114 is portrayed as a lucky dropping redundancy for R1234ze (Z) [28]. Honeywell's Solstice, which is offered as R1233zd (E), is suggested for HTHP operations. Its initial temperature is 170.3°C, and its initial weight is 36.1 bars. Despite the chlorine content of R1233zd (E), its ODP is negligible (0.00040) compared to the brief barometric lifetime of 51.3 days [19].

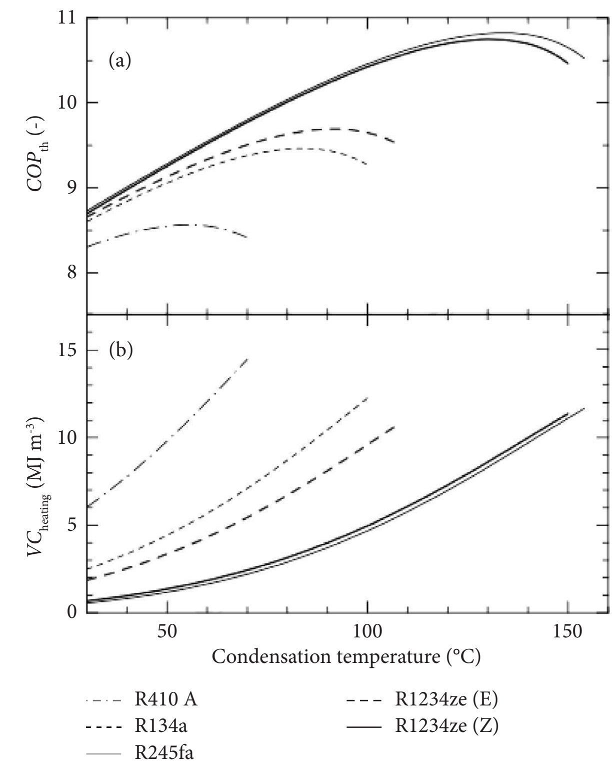

Figure 6: Results of the thermodynamic analysis using the ideal reversed Rankine cycle. (a) Theoretical COP and (b) volumetric capacity [17].

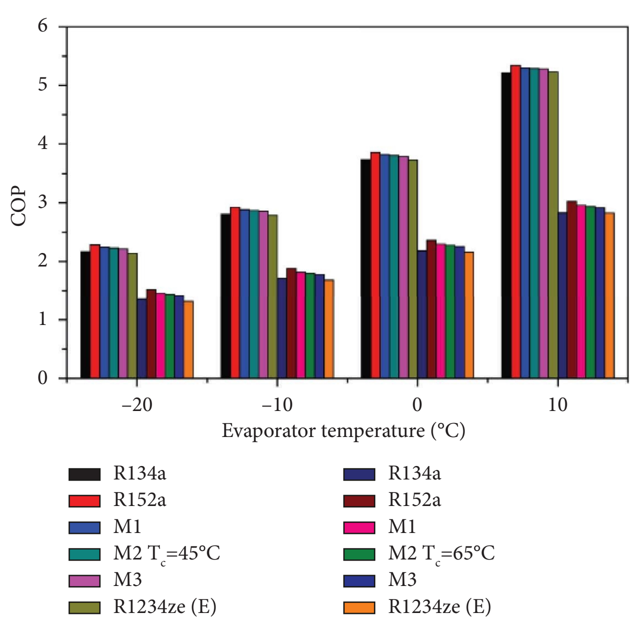

Figure 7: COP variation with evaporating temperature [22].

According to ASHRAE's 2016 classification of safety groups, the normal boiling point (NBP) is at 1.013 bars, where M is the molecular weight; however, the refrigerant is close to the market. Estimated deals worth per kilogram refrigerant (based on an 11 kg container, pricing from PanGas, Climalife, and Solvay, October 2017) [18].

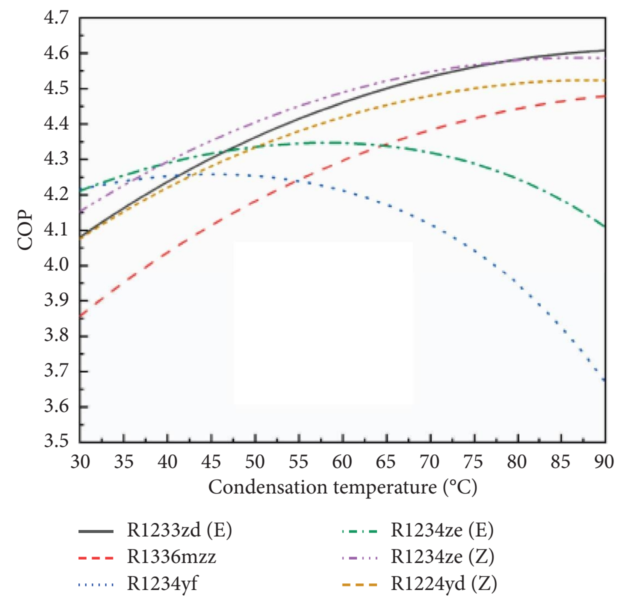

Figure 8: COP variation with condensing temperature of various refrigerant [16].

Fresh A1 noncombustible HCFO refrigerant R1224yd (Z) is mostly used in diffusive chillers and waste heat recovery heat pumps. Using 1224yd as the refrigerant, AGC Asahi Glass intends to launch a commercial product in 2017 (AGC Chemicals 2017). The GWP of R1244yd (Z) is less than 1, and its ODP is almost zero (0.00012, with an expected air life of 21 days), which has little effect on the terrain. Its physical qualities are very near to the R1233zd (E) and R245fa borders. It is also miscible with canvases and has similarities to the development of commonly used essences, such as polymers and elastomers. R1233zd (E) is comparable in price to R245fa (62 EUR per kg) and R365mfc, costing about 50 EUR per kg (80 EUR), respectively). R1224yd (Z) and R1336mzz (Z) are close to the request overview, but prices for the refrigerants are not yet available [25].

6. Simulation for the Performance of the System

To evaluate the thermodynamic performance and many thermodynamic states of the selected refrigerants for this article, a system simulation for an idealized heat pump cycle using an internal heat exchanger was performed as shown in Figure 9. The existing heat pump cycle has a simple configuration, and it operates in the subcritical range and requires only a small amount of equipment. The natural refrigerants R744 and R718 are excluded from the theoretical study because they require a special cycle design with multistage or critical ceiling operation. HTHP is often used as an important ingredient in publications related to industrial applications. Several novels deal with the subject of this essay and discuss it. Brunin examined the operating areas of compression heat pumps using dissimilar fluids and refrigerants. The heat pump output temperature is plotted against the temperature modification concerning the heat pump outlet and the heat source input to show the operating range of the model based on the limiting parameters for

Table 1: Different refrigerants properties of HCFO and HFO suitable for heat pump operation [25].

Type	Refrigerant	Biochemical formula	T_{crit} (°C)	P_{crit} (bar)	ODP (−)	GWP 100 (−)	SG	NBP (°C)	Mol. (g/mol)	Price (EUR/kg)
HCFO	R1224yd (Z)	CF3CF=CHCl	166.5	36.2	0.000	1	A1	18.0	148.5	n.a
HFO	R1336mzz1 za	CF3CH=CHCF 3 (Z)	169.9	29.0	0	2	A1 A2	34.1	165.1	n.a
	R1234ze (Z) b	CF3CH=CHF (Z)	149.8	35.3	0	<1	L	9.9	115.0	n.a
HFC (for comparison)	R365mfce	CF3CH2CF2C H3	186.9	32.7	0	804	A2	40.2	148.1	80
	R245faf	CHF2CH2CF3	154.0	36.5	0	858	B1	14.9	134.0	62

COP, volumetric heat capacity, and low and high pressures is used to specify application areas. Van de Bor proposed a method that is based on the ratio between the temperature rise and fall of the process fluid. To calculate the financial performance of a heat pump the various parameters are to be considered such as mechanical, compression heat pump, and heat absorption [18].

7. Refrigerant and Its Properties

7.1. R1234ze (E) Pure. R1234ze (E), a still relatively new liquid, has been the subject of much research to determine its properties and thus its thermal and energetic behaviors. To create properly functioning refrigeration and air conditioning components and systems, precise thermophysical properties are required. These investigations can provide information about specific measurements of certain properties to evaluate the accuracy of various equations of state (EOS) and even modify them. A density measurement system based on a vibrating tube densitometer has been presented by Cannistraro et al. [29] for use at pressures up to 100 MPa and temperatures between 285 and 365 K. R1234ze (E) has uncertainties guaranteed expansion with a maximum of 0.23% by using a vibrating wire viscometer to measure viscosity at saturation pressures up to 30 MPa and temperatures from 255 to 380 K. Experimental data for R1234ze (E) have an average absolute deviation of 0, 59%. Meng et al. [30] tested the triple value of R1234ze (E) and the results were very similar to those found in the popular literature. The equation of state is a thermodynamic equation that relates the state variables such as internal energy, temperature, pressure, specific heat, and volume to produce fluid parameters. Nicola et al. [31] first used the Peng–Robinson-based EOS to measure the thermodynamic properties of R1234ze (E) and other fluorinated olefins. For R1234ze (E), Akasaka used a completely new thermodynamic property model for typical errors for isobaric heat capacity for liquid and vapor and vapor pressures are 0.2%, 0.5%, and 5%, respectively [27]. He then presented a new EOS that was not suitable for the critical region but was suitable for pressures up to 15 MPa in the case of R1234ze (E) and temperatures between 240 K and 420 K [32]. The average errors are 0.1%, 0.2%, 3.0, 0.05, and 0.1% for liquid density, vapor density, heat capacity of liquid, and speed of sound, respectively, in the vapor phase and vapor pressure. Accurate property calculations are possible thanks to improvements in R1234ze (E) properties and property calculations found in the REFPROP-enabled fluid database [19]. In Alavianmehr's revised Tao–Mason EOS, 34 points R1234ze (E) has the lowest deviation which is 0.36. Akasaka [33] explained the thermodynamic properties of R1234ze (E) using the BACKONE molecular system and PCSAFT EOS. Due to changes in their thermophysical properties, as shown in the figure, R134a should not be supplemented or retrofitted. The compressor can operate with R1234ze (E) at lower pressures because its vapor pressure is 28% to 24% inferior to that of R134a (Figure 10). Due to its lesser liquid density, from 4.7% to 1%, R1234ze (E) requires fewer refrigerants than R134a (Figure 11).

The vapor density of R1234ze (E) is about 20% lower. Although 7.37% viscosity of liquid R1234ze at 343 K liquid has a slightly lower at lower temperatures. This will help reduce pressure loss in pipes and HFO components. In addition to what has been said, it also highlights the significant reduction in GWP (1300 vs 4) and low flammability of R1234ze (E) [34]. The planned replacement for R134a in mobile air conditioning (MAC) systems is R1234yf. However, because it is flammable, it encounters resistance similar to what happened with R1234yf [27], and R1234ze (E) cannot be used due to its flammability (Figure 12).

8. Multistage Compression Heat Pump Systems

Figure 13(a) shows a schematic diagram of a two-stage vapor compression heat pump system, illustrating the operating configuration based on the following principles:

(1) It is then mixed with medium-pressure steam from the flash tank.

(2) Higher stage of compression: The mixed vapor undergoes a higher stage of compression to produce a gas at high temperature and pressure. This gas exchanges heat with water in the condenser and turns into liquid refrigerant.

(3) Subcooling: The saturated liquid refrigerant is further cooled in a subcooler. By the upper stage expansion valve, the high-pressure refrigerant, from the subcooler, is throttled and converted to a medium-pressure liquid and gas mixture.

(4) Separation in the flash tank: The mixed refrigerant is separated into liquid and gas phases in the flash tank while maintaining an intermediate pressure. Medium-pressure vapor refrigerant is combined with exhaust gas from the lower compression stage.

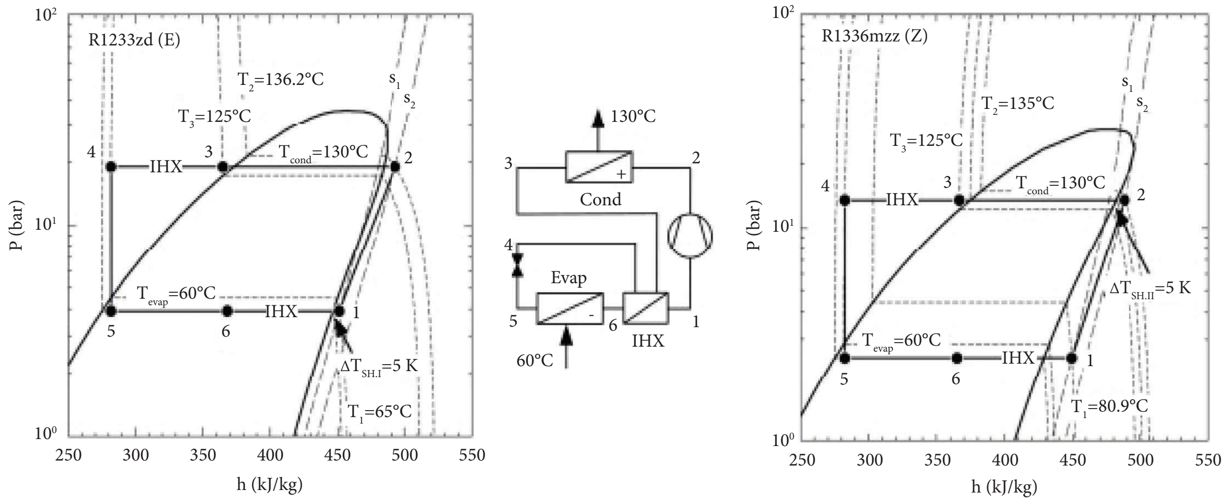

FIGURE 9: log (p)-h diagrams of R1233zd (E) and R1336mzz (Z) at 130°C condensation and 60°C evaporation temperature for internal heat exchanger (IHX), where I = 5 K at compressor input and outlet) and 70 K lift are used to simulate the operation of a heat pump system [18].

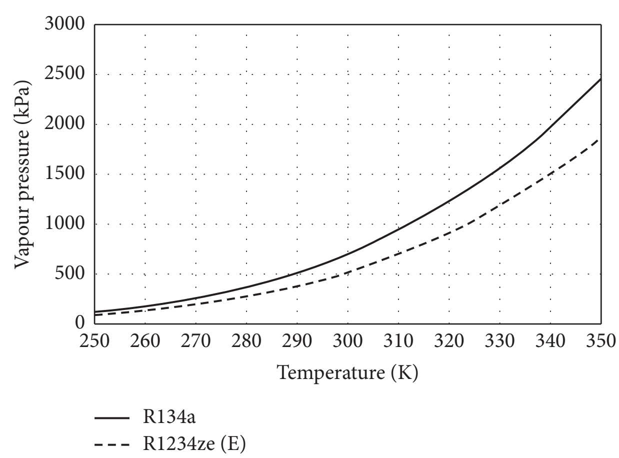

FIGURE 10: Assessment among R1234ze (E) and R134a at unlike temperatures based on vapor pressure [27].

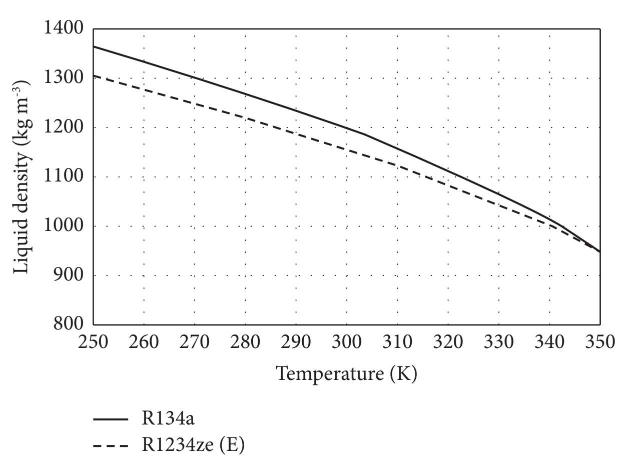

FIGURE 11: Evaluation among R1234ze (E) and R134a at unlike temperatures based on liquid density [27].

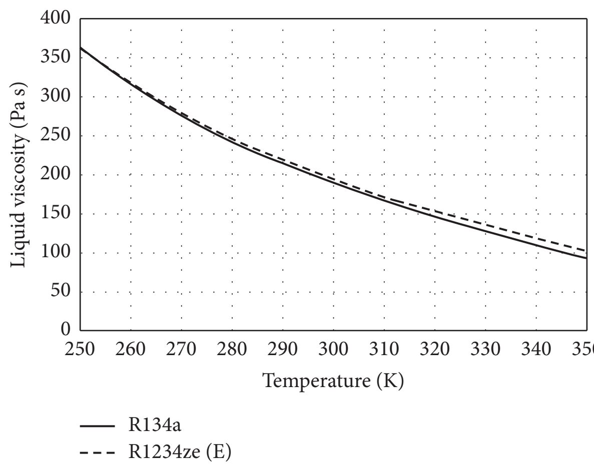

FIGURE 12: Judgment among R1234ze (E) and R134a at dissimilar temperatures based on liquid viscosity [27].

(5) Lower stage compression: Liquid refrigerant is throttled through a lower stage expansion valve to produce a low-pressure and low-temperature liquid-gas mixture. This mixture returns to the evaporator, where it absorbs heat from the wastewater and evaporates, moving on to the next cycle

In Figure 13(b), the impact of two-phase separation in the flash tank on the system's performance is emphasized. The liquid entering the evaporator possesses lower enthalpy compared to a single-stage cycle, resulting in a greater enthalpy difference across the evaporator. Additionally, the saturated vapor from the flash tank has a lower temperature than the vapor in the compressor, leading to a reduction in the compressor discharge temperature. This decrease in compressor power consumption contributes to a higher coefficient of performance (COP) for the overall system.

Figure 14 shows a schematic diagram of a three-stage compression heat pump system and explains its operating configuration with the following operating principle:

(1) First compression stage: The refrigerant from the evaporator is first compressed in the first stage. It is then mixed with vapor refrigerant at the first-stage pressure.

(2) Second compression stage: The mixed vapor enters the compressor in the second compression stage. In the third stage, the mixed refrigerant is further compressed.

(3) Condensation and expansion: The compressed refrigerant is cooled in the condenser and flows through the third-stage expansion valve. In the expansion tank II, the refrigerant undergoes phase separation into liquid and vapor.

(4) Second-stage mixing: The vapor refrigerant pressure is mixed with the exhaust gas from compression. The liquid refrigerant is further cooled in a subcooler and enters the second-stage expansion valve.

(5) First-stage mixing: In the expansion tank **I**, the refrigerant is again separated into liquid and vapor. The vapor refrigerant at the first-stage pressure is mixed with the exhaust gas from the first-stage compression. The liquid refrigerant then enters the first-stage expansion valve and is heated by the waste heat of the evaporator.

From Figures 13(b) and 14(b), it is clear that the pressure difference decreases at each compression stage and expansion process of the multistage compression heat pump. This reduction in pressure difference significantly contributes to the reduction of irreversible losses and ultimately improves the exergy efficiency of the system. Furthermore, considering the pressure ratio and outlet temperature, the temperature difference during the evaporation and condensation stages can be further increased by installing an additional compression stage. This feature makes the system suitable for the efficient utilization of low-grade industrial waste heat and represents a promising approach for the development of high-temperature heat pumps capable of delivering pressurized hot water at temperatures up to 120°C.

A software Energy Equation Solver (EES) was used to solve the equations above and to perform exergy analysis of all system components used in EES which is a powerful software for finding some important thermophysical properties of the refrigerants and solving thermodynamic and heat transfer problems. The second advantage of using EES is that it can solve a system of simultaneous equations which is required for heat pump air conditioning using

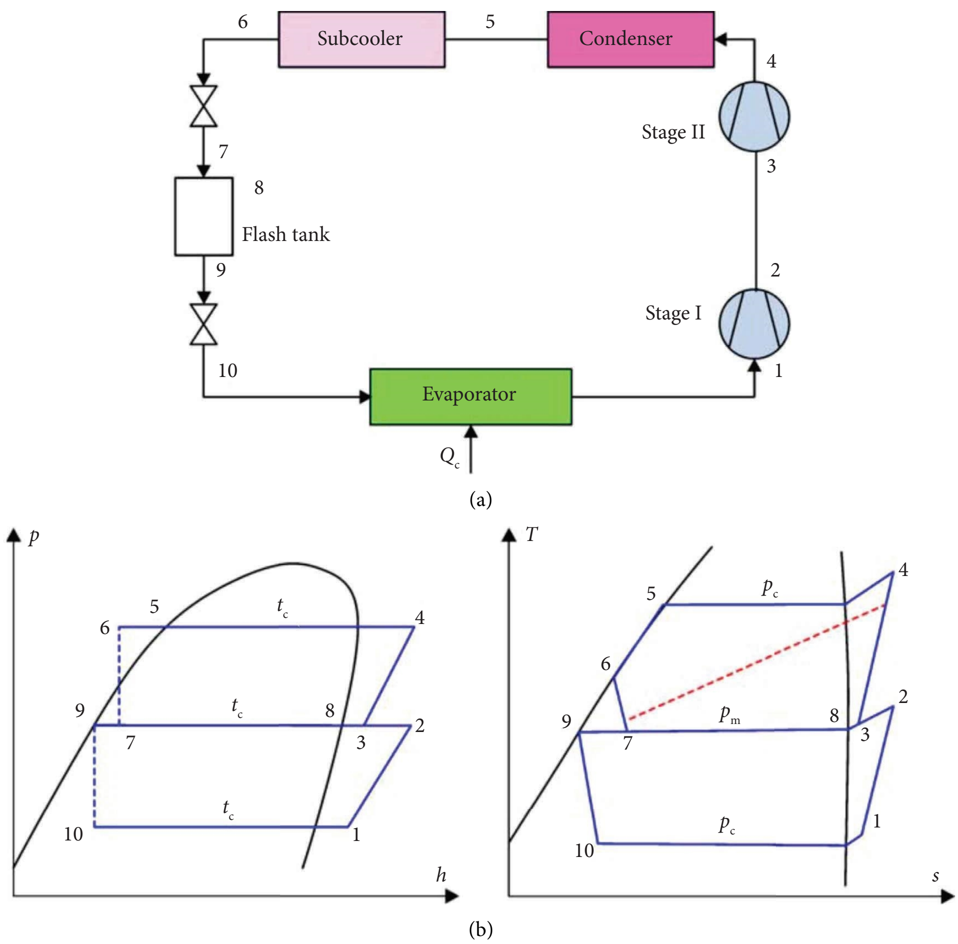

FIGURE 13: Description of two-stage compression heat pump system. (a) Schematic diagram; (b) diagrams of P-h and T-s [34].

R1234ze refrigerant. The analysis procedure follows the flowchart shown in Figure 15. EES database was used in the calculation step of thermodynamic properties of refrigerants.

9. Parameters for Selection of Cycle for the Heat Pump Air Conditioning System Using R1234ze Refrigerant

Unlike other types of heating systems that produce heat, such as a furnace, boilers, and electric heating systems, the basic HP cycle has many different parts and functions. HP absorbs heat in the refrigerant, also known as the working fluid, at small temperatures ("source"). The fluid is then compressed, causing the temperature to rise and the heat to be rejected at a higher temperature ("sink"). Before restarting the heat absorption process, the expansion process returns the fluid to its original state as initial temperature, pressure, entropy, and enthalpy to complete the cycle. In this attitude, heat from the environment or "wasted" heat from manufacturing process flows can be valued and used in other processes at the cost of labor [21, 26, 35]. The amount of heat transmitted to the heat sink divided by the amount of work delivered to the compressor (equation (1)) is how the coefficient of performance represents the thermodynamic efficiency of an HP system. The coefficient of performance of HP usually exceeds 1, and for direct compression in the open cycle, it can reach values >10 and 5 or 6 for the indirect closed cycle. On the other hand, industrial boilers typically achieve a thermal efficiency of 77–88% or coefficient of performance up to 0.95.

$$\mathrm{COPhp} = \frac{\mathbf{Qh}}{\mathbf{W}}. \tag{1}$$

As shown in Figure 16 of phase diagrams, the four stages of the Carnot cycle are temperature-entropy (T-s) and pressure-enthalpy (P-h), with the black curve representing the saturation region (i.e., the storm lines mixing liquid and vapor) and the blue curve lines representing the stages of the cycle. The source temperature and sink temperature can be directly related to the coefficient of performance of the Carnot HP cycle. The

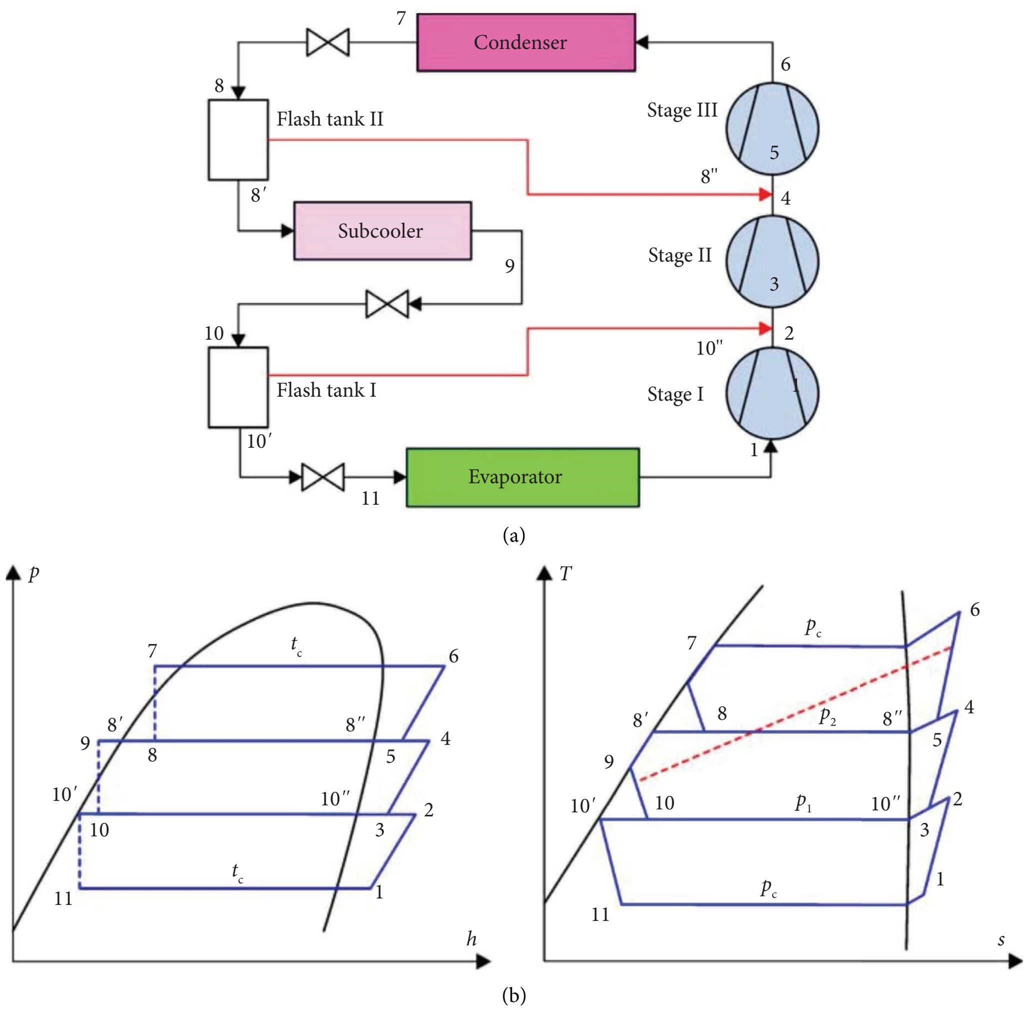

Figure 14: Description of three-stage compression heat pump system. (a) Schematic diagram; (b) diagrams of P-h and T-s [34].

coefficient of performance of the Carnot HP cycle can be directly related to the sink temperature and source temperature:

$$\begin{aligned} \text{COPHP} &= \frac{\mathbf{Qh}}{\mathbf{W}} \\ &= \frac{\mathbf{QTH\Delta sh}}{/TH - TL)\Delta s} \\ &= \frac{\text{TH}}{\text{TH} - \text{TL}}. \end{aligned} \tag{2}$$

10. Thermodynamic Properties Analysis of Employed Liquids

R114 has been mainly replaced in recent years by R236fa, R245fa, R134a, and R227ea, in MHTHP applications [21]. As mentioned in Table 2, the basic environmental and thermodynamic properties of the nominated working fluids R236fa, R245fa, R134a, and R227ea have 0 ODP, and their GWP values are still quite good. Due to its exceptionally low GWP and very similar thermodynamic properties to R245fa, R1234ze (Z) has been the subject of intense investigation over the past decade, and it is concluded that R1234ze (Z) is appropriate for MHTHP applications. The theoretic cycle performance of the nominated working fluid is tested and compared under the following conditions: temperature rise of 50 K, over 30 K heat (to prevent wet isothermal compression), and a degree of subcooling of 5 K. The condensation temperature range of R1234ze for the heat application extends from 60°C to below its critical temperature. The isentropic efficiency of the compressor is set to 1.2, and the throttling process of the system is isentropic. Condensation and evaporation are adiabatic and isobaric processes, respectively, which show the theoretical cycle performance of the selected working fluid. The estimated theoretical COPs for R1234ze (Z), R114, R227ea, R236fa, R134a, and R245fa are shown in Figure 1(a). Each working fluid has a specific condensation temperature that makes the best use of the

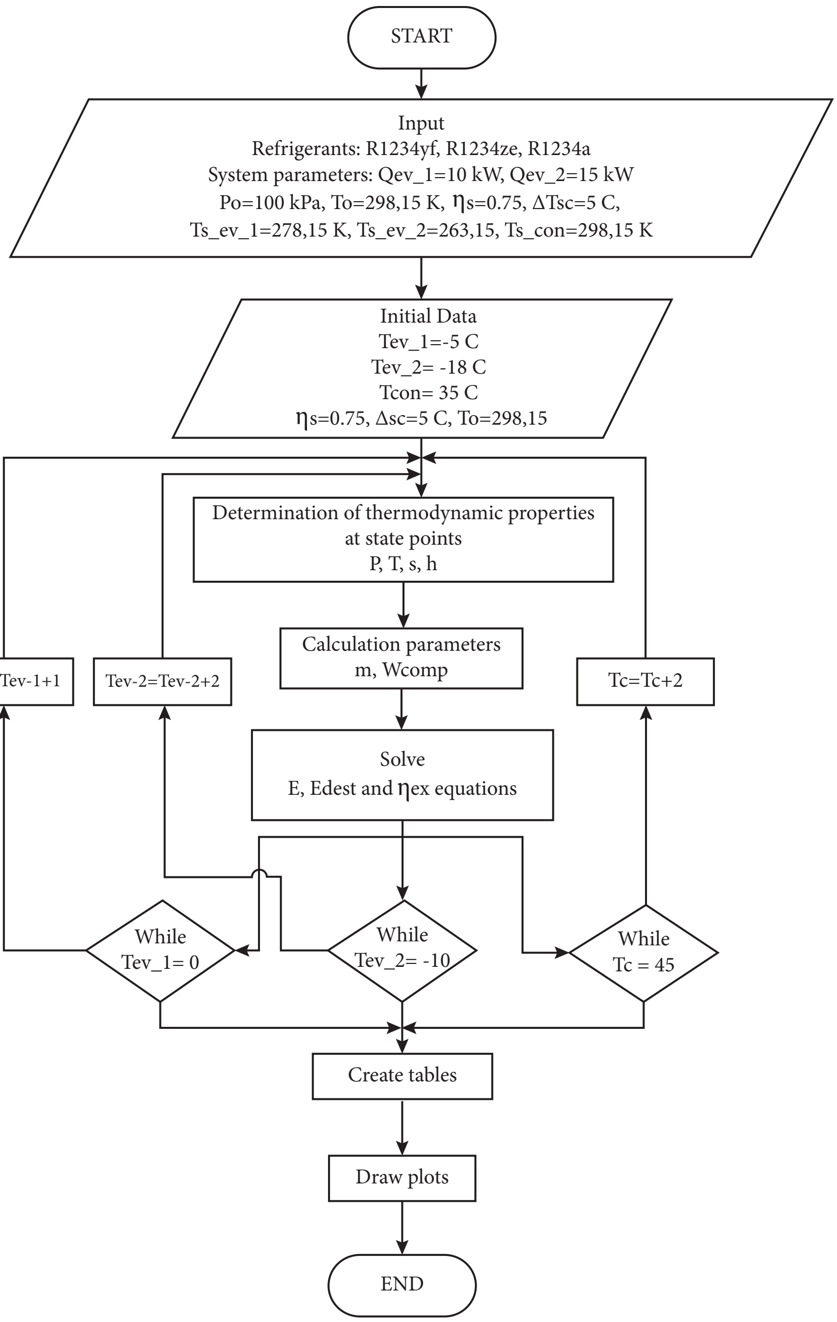

Figure 15: Flowchart of R1234Ze refrigerant used for heat pump air conditioning [35].

COP, which is approximately 50 K below the critical temperature. The coefficient of performance of R227ea was the lowermost and the COP of R1234ze (Z) was the highest among the designated employed fluids. The maximum coefficient of performance of R1234ze (Z) is about 6.98 at condensation temperatures up to 109°C [7].

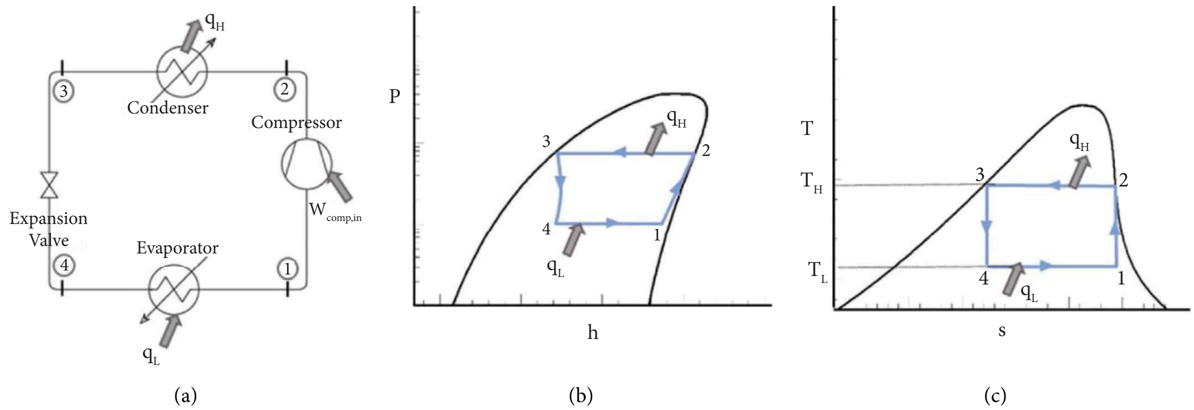

FIGURE 16: (a) Schematic Carnot cycle illustrated using (b) P-h and (c) T-s diagrams [36].

TABLE 2: Different types of refrigerants and their characteristics [7, 8, 37].

Operational fluids	Classification	Classification GWP	ASHRAE group	Cost ($/kg)	Restrictions
R1234ze	HFO	<0.9	A2L	89	Little flammability, stability issues
R32	HFC	687	A2L	3.1	Small flammability, medium GWP
R134a	HFC	1121	A1	4.9	Extraordinary GWP
R744 (CO_2)	Natural refrigerant	1	A1	0.8	Short COP
R290 (propane)	HC (natural refrigerant)	3	A3	1.4	Extraordinary flammability
R717 (NH3)	Natural refrigerant	<1	B1	1.6	Poisonousness
R1234yf	HFO	<0.9	A2L	90	Small flammability, stability issues
R600a (Iso- butane)	HC (natural refrigerant)	4	A3	2.1	Extraordinary flammability
R152a	HFC	140	A2	1.4	Medium flammability, low GWP
R717 (NH3)	Natural refrigerant	<1	B1	1.6	Poisonousness
R404a	HFC	3920	A1	3.6	Extraordinary GWP

TABLE 3: Basic thermodynamic and environmental properties of selected working fluids [21].

Substance	Molar mass (kg·kmol−L)	Tb (K)	Tc (K)	Pc (MPa)	ω	ODP	GWP/100 year
R1234ze (Z)	113.04	288.9	423.27	3.533	0.3274	0	<1
R245fa	135.05	289.29	427.16	3.651	0.3776	0	950
R236fa	151.04	272.66	398.07	3.2	0.377	0	9400
R227ea	172.03	255.81	374.9	2.925	0.357	0	3500
R114	171.92	286.74	418.83	3.257	0.2523	0.85	9800
R134a	104.03	267.08	374.21	4.0593	0.32684	0	1300

In Table 3, various refrigerant properties are discussed based on the molar mass, temperature, pressure, ozone depletion potential, and other related parameters. Based on the table, we can conclude that the R1234ze refrigerant is having low ODP and GWP.

11. Conclusion and Future Scope

Following an in-depth analysis of R1234ze (Z) extensively discussed and compared for its application in heat pump air conditioners utilizing a vapor compression cycle, it emerges as an environmentally friendly working fluid with exceptional cycle performance. The study investigates its cycle performance with temperature increases of 50 K and 60 K, respectively, comparing the results using a heat pump air conditioning system across condensing temperature ranges from 65°C to 90°C.

Key conclusions drawn from the above discussion are as follows:

(1) With a temperature increase of 50 K, R1234ze (Z) exhibits a maximum coefficient of performance (COP) value of approximately 3.87, surpassing that of refrigerant R245fa by 42% at an ambient condensing temperature of 88°C.

(2) At a condensation temperature of 88°C and a temperature rise of 58K, R1234ze (Z) achieves a maximum volumetric heat capacity of 3.0 MJ·m^3 and a maximum pressure ratio of approximately 5.8, with all discharge temperatures below 97°C.

(3) At a condensing temperature of 85°C, R1234ze (Z) shows maximum values of heat capacity and power input (1.098 KW and 4.001 KW, respectively) with a temperature increase of 47 K.

(4) The findings affirm that R1234ze (Z) is a highly suitable working fluid for heat pump air conditioning systems employing a vapor compression cycle due to its advantageous cycle performance and superior thermodynamic properties.

(5) The trend in heavy ventilation air conditioning refrigeration systems is shifting towards low-GWP refrigerants. In the upcoming years, the enforcement of natural refrigerants or HFOs is expected for various heat pump and air conditioning applications, driven by considerations such as performance, costs, and flammability.

(6) Based on parametric, experimental, and simulation studies, one of the most promising HFO refrigerants for heat pump air conditioning systems is identified as R1234ze (E) with a global warming potential (GWP) of 4 and minor flammability compared to other refrigerants, excluding R1234yf. The current research article explores the application of R1234ze (E), whether in its pure form or mixed with other refrigerants, for heat pump air conditioning.

(7) Future work may involve utilizing refrigerants such as R1234ze and HFO in heat pump air conditioning systems for diverse applications, including heating in winter and cooling in summer, emphasizing their versatility and potential for widespread use.

Nomenclature

ω: Acentric factor
W: Power of compressor (input)
Q: Heat ability (W)
Pr: Pressure ratio
γ: Latent heat ($\text{kJ}\cdot\text{kg}^{-1}$)
Pc: Critical pressure (MPa)
VHC: Volumetric heating capability ($\text{MJ}\cdot\text{m}^3$)
Tc: Critical temperature (K)
P: Pressure (MPa)
Tb: Normal boiling temperature (K)
oT: Temperature lift (K)
t: Temperature (°C)

Subscripts

Evap: Evaporation
Disch: Discharge
Cond: Condensation

Abbreviations

MHTHP: Moderately high-temperature heat pump
IHX: Internal heat exchanger
ORC: Organic Rankine cycle
HFCs: Hydrofluorocarbons
HFOs: Hydrofluoric olefins
ODP: Ozone depletion potential
HTHP: High-temperature heat pump
HCFCs: Hydrochlorofluorocarbons
HCs: Hydrocarbons
GWP: Global warming potential
R&D: Research and development.

Data Availability

All the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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