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ARTICLE

Development of Environmentally Friendly and Energy Efficient Refrigerants for Refrigeration Systems

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ABSTRACT

This paper presents the improvement of eco-friendly and power consumption saving refrigerants for refrigeration systems. The novel azeotropic refrigerant mixtures of HFCs and HCs can replace refrigeration systems, and using the R134, R32, R125, and R1270 refrigerants in several compositions found using the decision tree function of the RapidMiner software (which came first in the KDnuggets annual software poll). All refrigerant results are mixed of POE, which is A1 classification refrigerant, non-flammable, and innocuous refrigerant, and using REFPROP software and CYCLE_D-HX software are under the CAN/ANSI/AHRI540 standards. The boiling point of the new refrigerant mix R-No.595 is 4.58%, lower than that of R404A, with a higher refrigerant effect and 50.34% lower GWP value than R404A. The proposed mix R-No.595 can be operated in hot environmental country and has high critical temperature and heat-rejection effects, due to the presence of R32 and R1270. The COPc of R463A is 13.49%, higher than R404A in freeze condition. The novel refrigerant mixes provide alternate refrigerant options mixed of 1% R1270, and which are related with the development of current refrigerants, containing a compose of HFOs and eco refrigerants for producing low-GWP, zero ODP, high-refrigerant effect, low-operating pressure, and innocuous refrigerants.

KEYWORDS

Refrigerant; refrigeration system; energy efficiency; environmentally friendly; data mining

1 Introduction

Power consumption in Thailand's business sector has ranked second among overall power consumption in the country and should be decreased [1]. The number of retail stores in Thailand was more than 25,000 in 2020, and this number continuously increases on every year [2]. Some retail stores are open 24 hours per day and, therefore, the retail sector is the fourth largest power consumption in the business sector, consuming more energy than residences [3]. The components that contribute to the power consumption of retail stores in Thailand, rated from highest to lowest, are refrigeration systems, air-conditioning systems, electrical equipment, and lighting [4,5]. The ratio of power consumption in retail stores in Thailand have been previously rated, as shown in Fig. 1 below [6]. The excellent options for decreasing power consumption in retail stores in Thailand are novel equipment and performance power consumption control system. An excellent model of power consumption savings in refrigeration systems is shown in Fig. 2 below [7]. Power consumption savings in refrigeration systems can be achieved through decreased power consumption of the compressor, as this it is the component that benefits the most power consumption.

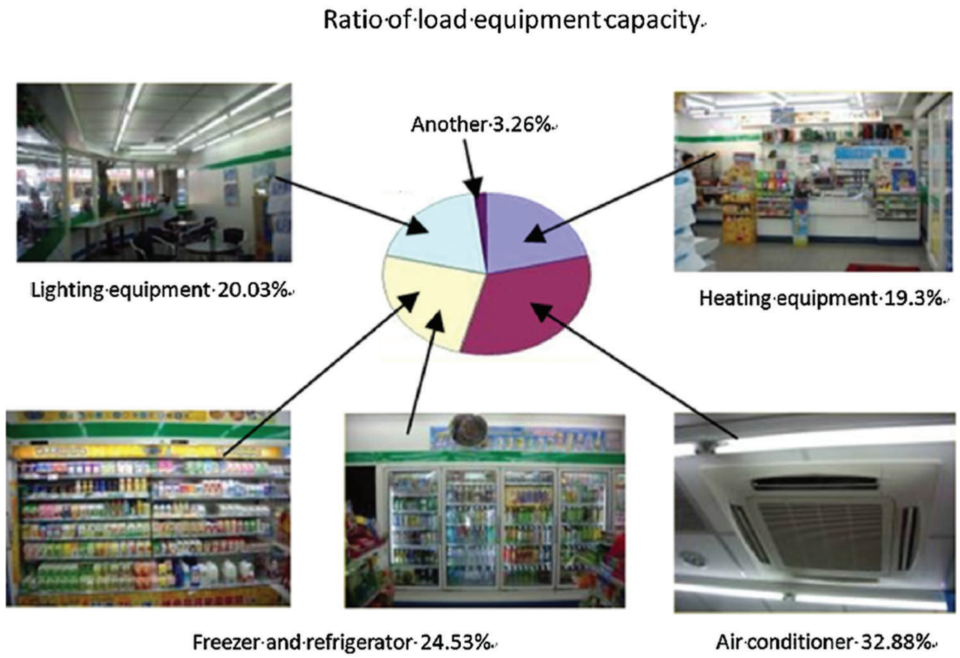

Figure 1: Proportions of energy use in Taiwanese convenience stores [6]

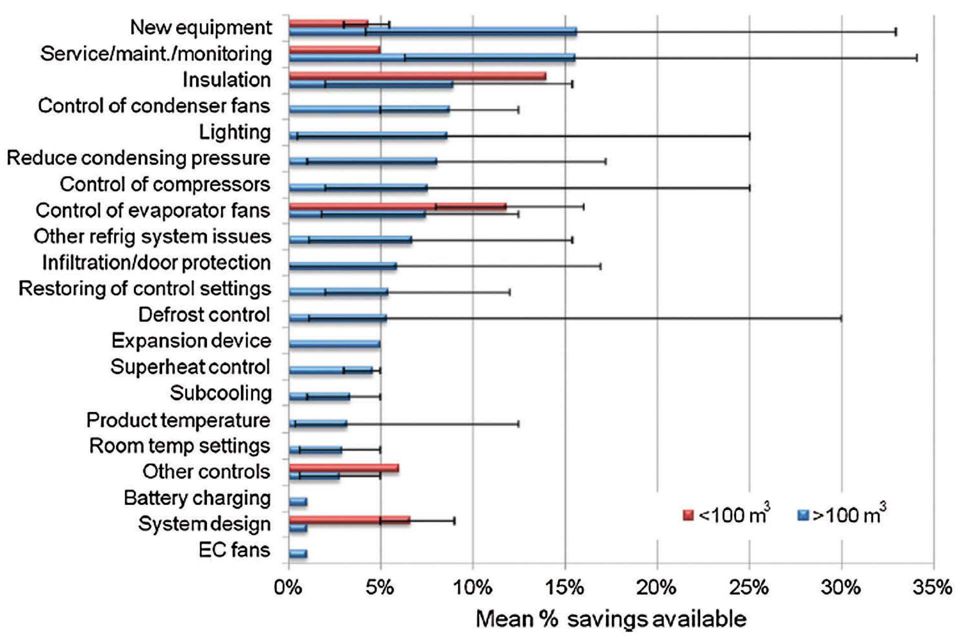

Figure 2: Examples of energy savings in refrigeration systems [7]

Thailand refrigerant trends have shown improvement of reduced GWP and increased energy efficiency, as shown in Fig. 3 [8,9], that concerned to the HFCs Discontinue timetable, as shown in Fig. 4 [10]. Starting generation refrigerants are mixed of eco refrigerants and HCs, both refrigerants do not affect the eco, have GWP close to zero, and have zero ODP [11–13]. R744 high operates pressure and is combustible and highly toxic [14–16]. Following the next generation refrigerants are mixed of CFCs [17–19] and HCFCs [20–22], can operate under low pressure that easy to use, and are innocuous. But, the GWP and ODP increased. Therefore, progressing of refrigerant developed to reduced ODP and GWP. Moreover, in present generation refrigerants (i.e., CFCs and HCFCs) were further developed as HFCs refrigerants that low GWP and zero ODP [23–25]. Future generation refrigerants are generally HFOs with low capacity and low GWP [26–28]. These refrigerants are generally a mixture of HFCs [29–31], HFOs [32–34], HCs [35–37] and eco refrigerants [38–40].

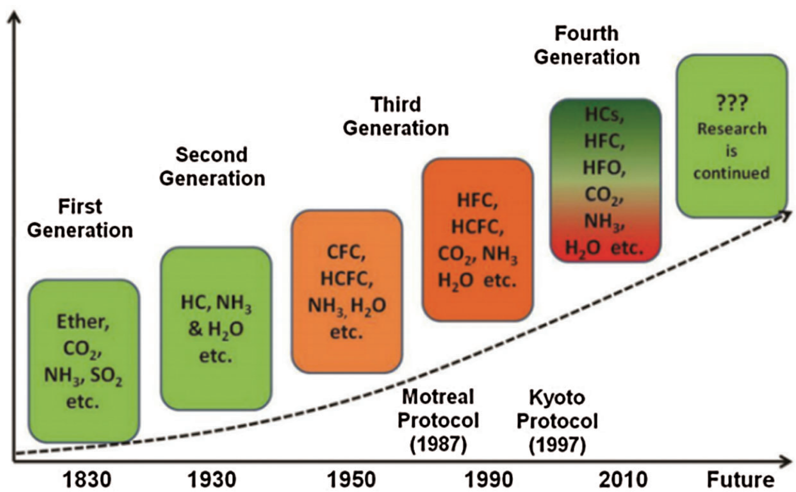

Figure 3: Evolution of refrigerants [8,9]

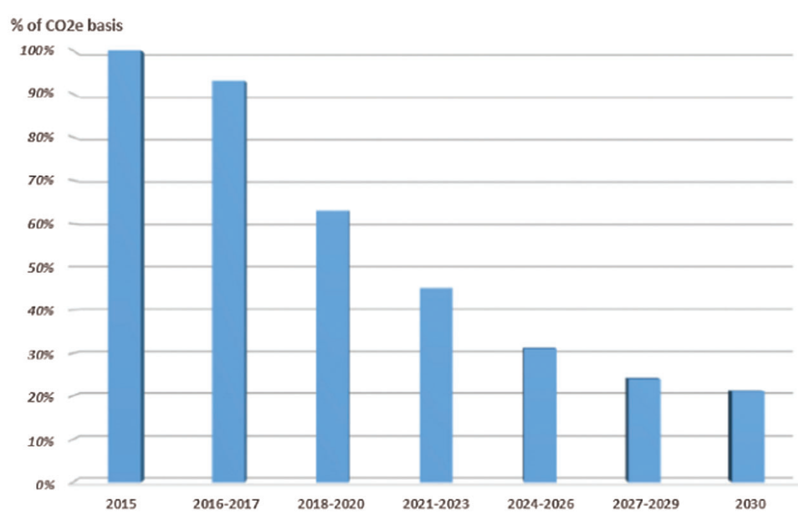

Figure 4: Hydrofluorocarbon (HFCs) phase-down schedule (Co2e %) [10]

Refrigerants need to be low-GWP, zero-ODP, high-capacity, low-pressure, and non-toxic, and should, thus, be mixed with HCs and HFOs; however, current refrigerants are still highly flammable and have low capacity. An alternative is to incorporate other HFCs. R32 is low-GWP, zero ODP, high-capacity, and non-toxic, but operates under high pressure and is flammable; in contrast to R134A, which possesses highly similar properties but can operate under low pressure and has low capacity. Current refrigeration systems use R22 [41], as well as R417A [42], R417B [43], R422A [44], R422B [45], R422C [46], R422D [47], R424A [48], R433A [49], R437A [50], R438A [51], and R453A [52], all of which were developed as alternatives to R22 and which are mixed with HCs and HFCs, as shown in Tabs. 1–4. The lowest normal boiling points (of R422A and R422C) are −46.80°C and −46.20°C, respectively, lower than that of R22 by 12.82% and 11.69%. This is due to the presence of hydrofluorocarbon (HFCs) R125 in their composition (85.1% and 82.0%, respectively), consistent with those of R410A and R507, which have boiling points of −51.6°C and −46.74°C, respectively, and are considered attractive as alternative refrigerants to R134A and R404A, due to their HFCs R125 content of 50%. The boiling point of R125 is −48.1°C, with a high GWP value (3,450); leading to R422A and R422C having the high GWP values of 3,143 and 3,185, respectively. R422A and R422C also have hydrocarbon (HCs) R601a in their composition (3%). The boiling point and GWP of R601a are 0 and −11.73°C, respectively, the effect of which is reducing the GWP and increasing the boiling point of refrigerant mixtures it is contained in. The lower GWP, compared with R22 f R453A and R437A (1,765 and 1,805, respectively) is due to hydrofluorocarbon (HFCs) R134a (53.8% and 78.5%) in their composition and hydrofluorocarbon (HFCs) R32 (20%) in the composition of R453A; this is consistent with R407A, R407H, and R407F, which combine R134a and R32 with R744 in contents of 6% and 3%, respectively, in their compositions. The boiling point and GWP naturally change when adjusting the composition of the refrigerant. The refrigerant effect and heat rejection of R453A were found to be higher than those of R22, due to the presence of hydrofluorocarbon (HFCs) R32 (20%). R453A also has the hydrocarbon (HCs) R600 (0.6%) in its composition. The lowest refrigerant work was found for R422A, which possesses HCs R600a (3%) in its composition. The mixed-refrigerant design should be comparable to natural refrigerants, in terms of having a strong refrigerant effect and high heat rejection, but certain hydrocarbon refrigerant types (e.g., R290 and R1270) are commonly selected for their refrigerant effect and high heat rejection. However, the high refrigerant work and high operating pressure of such refrigerants affect the power consumption of the compressor. Considering systems that operate with R134A [53], R450A [54], R456A [40], R513A [55], and R515A [40] are all refrigerants that have been developed as an alternative to R134A, which are mixed with HCs, HFCs, and HFOs and operated under low pressure, achieving similar results to R453A operating under high pressure with 20% hydrofluorocarbon (HFCs) R32 content in its composition, as shown in Tab. 5. The fourth-generation refrigerant R404A was the basis for this research, which is currently the most-used refrigerant, as shown in Fig. 5. R404A is an azeotropic blend of 143a/125/134a with zero ODP, which is non-flammable, non-toxic, and operates under low pressure, with a GWP of 3922 [56]. R407A [57], R407F [58], R407H [59], R410A [60], R442A [52], R448A [61], R449A [62], R452A [63], R453A [64], and R463A [65] are all refrigerants developed to be retrofitted to replace R404A, as shown in Tabs. 6–9. The lowest normal boiling point of R463A is –60.13°C, which is lower than that of R404A by 23%. This is due to hydrofluorocarbon (HFCs) R32 (36%) and carbon dioxide (CO_2) R744 (7%) being in its composition, consistent with R445A [64] and R455A [65]. R445A and R455A both have low boiling points (–49.15°C and –52.0°C, respectively) and are attractive as alternative refrigerants with lower GWP than R134A and R404A, due to the CO_2 R744 content of 6% and 3%, respectively, in their compositions. R448A and R449A displayed the lowest GWP values of 1273 and 1282, respectively, due to the HFOs R1234yf and R1234ze in their compositions. The GWP of R463A has been found to be 1377, with a lower boiling point than that of R404A by 23%; even though the ratio of R1234yf in R463A is less than that in both R448A and R449A. However, the GWP of R463A has been found to be slightly higher than those of R448A and R449A. The cost of R463A is also lower than R448A and R449A. Hydrofluorocarbons can also be combined with carbon dioxide (CO_2), which has a lower GWP and boiling point. The lower boiling point and GWP are consistent with the evolution of the fourth-generation refrigerants that contain a mixture of HFCs, HFOs, HCs, and natural refrigerants, which are required to produce a low-GWP, zero ODP, high-capacity, low-operating pressure, and non-toxic refrigerant. The refrigerant effect and heat rejection of R463A have been found to be higher than those of R404A, due to the presence of hydrofluorocarbon (HFCs) R32 (36%) and carbon dioxide (CO_2) R744 (7%) in its composition, consistent with R424A and R453A, which are composed of hydrocarbons (HCs) at contents of 1.8% and 1.2%, respectively. The mixed-refrigerant design should be comparable to natural refrigerants, in terms of having a strong refrigerant effect and high heat rejection. Refrigerants operated under low pressure display low refrigerant work value; in this case, the lowest refrigerant work is observed in R452A. This refrigerant possesses HFOs R1234yf and R1234ze (E) in its composition. The highest refrigerant work value is observed for R463A, which contains hydrofluorocarbon (HFCs) R32 (36%) and carbon dioxide (CO_2) R744 (7%), and operates at the highest evaporator pressure. This means that a refrigerant system which is operated at low pressure should use a mix of refrigerants that can operate under low pressure, such as R1234yf, R1234ze, and R134A. R450A [49], R456A [50], R513A [51], and R515A [50], which are mixed with hydrofluoroolefins (HFOs) and can operate under low pressure, have achieved similar results. R453A had the highest COPc, as R453A does not have the highest refrigerant effect and heat rejection, nor the lowest boiling point, but can be operated under low pressure, which has an impact on low refrigerant work. The COPc level of R463A was recorded at 1.34, which is 10% higher than that of R404A under low-temperature conditions only. The promising results for COPc obtained by R407F, R448A, and R449A are due to the refrigerants being operated under low pressure, which has an impact on low refrigerant work. The same effect has been observed for R453A; however, these four refrigerants do not have a low normal boiling point or high Cp liquid/vapor or liquid/vapor conductivity. This shows that a mixed-refrigerant design should consider all parameters, such as the GWP, boiling point, Cp liquid/vapor and liquid/vapor conductivity, refrigerant effect, heat rejection, refrigerant work, evaporator pressure, high pressure, and COPc.

Table 1: Properties of R22, R417A, and R417B

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R22 [41]			R417A [42]			R417B [43]		
Composition	R22			R125/R134a/R600			R125/134a/600		
Mass percentage	100			46.6/60/3.4			79/18.3/2.7		
Boiling point (°C)	−40.80			−39.10			−45.20		
Critical pressure (kPa)	4,990			4,036			3,737		
Critical temperature (°C)	96			87			74		
ODP	0.055			0			0		
GWP	1,600			1,950			3,027		
Class	A1			A1			A1		
Lubricant type	MO			MO/AB/POE			MO/POE		

Due to the costs shown in Fig. 6 [43], refrigerants should be mixed with HFOs. The figure shows that the HFOs had the highest refrigerant cost, but does not include HCs refrigerant costs compared with HFO refrigerant costs, and is presented for comparative purposes in this research (as it is generally composed of HCs). The class properties of hydrocarbon refrigerants are shown in Fig. 7 below. Some zero ODP and near-zero GWP Class A3 refrigerants, as shown in Tab. 10, are R170 [66], R290 [67], R600 [68], R600a [69] and Tab. 11 for R601 [70], R601a [71], R1150 [72], and R1270 [73]. The lowest boiling points were found to be −88.70°C and −103.8°C, respectively, for R170 and R1270; however, their critical temperatures were found to be 32.17°C and 9.5°C. This means that these cannot be operated as refrigerants in accordance with the CAN/ANSI/AHRI540 Air-Conditioning, Heating, and Refrigeration Institute (AHRI) standards considered in this research [74–76]. R290 and R1270 were found to have boiling points near that of with R22 (−42.1°C and −47.7°C, respectively), but operate at high condenser pressures, which affect the evaporator pressure, condenser pressure, and cooling coefficient of performance. Therefore, in this research, we used R1270 for the base line for new refrigerant mixes, as R1270 has a low boiling point and high refrigerant effect.

Table 2: Properties of R422A, R422B, and R422C

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R422A [44]			R422B [45]			R422C [46]		
Composition	R125/R134a/R600a			R125/R134a/R600a			R125/R134a/R600a		
Mass percentage	85.1/11.5/3.4			55/42/3			82/15/3		
Boiling point (°C)	−46.80			−41.59			−46.20		
Critical pressure (kPa)	3,665			3,857			3,696		
Critical temperature (°C)	72			82			72		
ODP	0			0			0		
GWP	2,530			2,526			3,085		
Class	A1			A1			A0		
Lubricant type	MO/AB/POE			MO/POE			MO/POE		

Table 3: Properties of R422D, R424A, and R437A

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R422D [47]			R424A [48]			R437A [50]		
Composition	R125/R134a/ R600a			R125/R134a/R600/R600a/ R601a			R125/134A/R600/ R601		
Mass percentage	62.1/31.5/3.4			50.5/47/1/0.9/0.9			19.5/78.5/1.4/0.6		
Boiling point (°C)	−43.50			−38.70			−32.65		
Critical pressure (kPa)	3,795			4,040			4,003		
Critical temperature (°C)	80			89			95		
ODP	0			0			0		
GWP	2,330			2,440			1,805		
Class	A1			A1			A1		
Lubricant type	MO/AB/POE			MO/AB/POE			MO/POE		

Table 4: Properties of R438A and R453A

Condition	LT	MT	HT	LT	MT	HT
Refrigerant	R438A [51]			R R453A [52]		
Composition	R125/134A/R32/R600/R601a			R125/R32/R134A/R227ea/R600/R601A		
Mass percentage	45/44.2/8.5/1.7/0.6			20/20/53.8/5/0.6/0.6		
Boiling point (°C)	−42.61			−42.20		

Table 4 (continued).

Condition	LT	MT	HT	LT	MT	HT
Critical pressure (kPa)	4,179			4,530		
Critical temperature (°C)	84			88		
ODP	0			0		
GWP	2,265			1,765		
Class	A0			A1		
Lubricant type	MO/POE			MO/POE		

Table 5: Properties of R134A, R450A, R456A, R513A, and R515A

Refrigerant	R134A [53]	R450A [54]	R456A [40]	R513A [55]	R515A [40]
Composition	R134A	R134A/ R12354ze(E)	R134a/R32/ R1234ze (E)	R134A/ R1234yf	R227ea/ R1234ze
Mass percentage	100	42/58	45/6/49	44/56	12/88
Boiling point (°C)	–26.07	–23.5	–30.75	–28.3	–18.75
Critical pressure (kPa)	4060	3814	4175	3700	3555
Critical temperature (°C)	101.06	105.87	102.65	97.7	108.65
ODP	0	0	0	0	0
GWP	1430	547	687	570	387
Class	A1	A1	A1	A1	A1
Lubricant type	POE	POE	POE	POE	POE

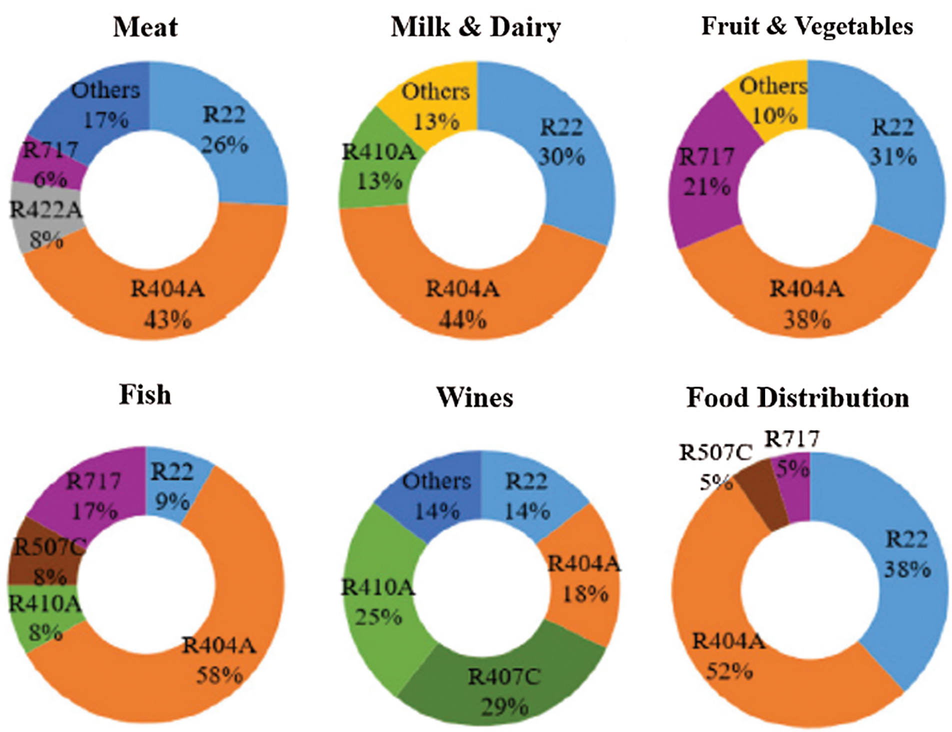

Figure 5: Top refrigerants in the food industry [9]

Table 6: Properties of R404A, R407A, and R407F

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R404A [56]			R407A [57]			R407F [58]		
Composition	R125/R143/R134A			R125/R32/R134A			R125/R32/R134A		
Mass percentage	44/52/4			40/20/40			30/30/40		
Boiling point (°C) at 1 kPa	–46.6			–45.28			–46.33		
Critical pressure (kPa)	3728			4494			4754		
Critical temperature (°C)	72.1			82			82.6		
ODP	0			0			0		
GWP	3943			2107			1825		
Class	A1			A1			A1		
Lubricant type	POE			POE			POE		
Q_{evap} (kJ/kg)	83.66			139.02			N/A		
Q_{cond} (kJ/kg)	159.8			198.57			N/A		
Work (kJ/kg)	76.14			59.55			N/A		
COPc	1.099			2.335			N/A		
Evaporator pressure (kPa)	183.30			477.3			N/A		
Condenser pressure (kPa)	2197.50			2284.10			N/A		
Evaporator temp glide (°C)	–0.4	–0.5	N/A	119.21	126.89	114.83	192.46	184.93	170.29
Condenser temp glide (°C)	0.3	0.3	N/A	216.04	189.24	166.05	328.41	266.99	237.2

Table 7: Properties of R407H, R410A, and R422A

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R407H [59]			R410A [60]			R442A [52]		
Composition	R125/R32/R134A			R125/R32			R125/R32/R1234A /R227ea/R152A		
Mass percentage	15/32.5/52.5			50/50			31/31/30/5/3		
Boiling point (°C)	–44.6			–51.6			–46.5		
Critical pressure (kPa)	4856			4811			4760		
Critical temperature (°C)	86.53			70.81			82.4		
ODP	0			0			0		
GWP	1400			1900			1888		
Class	A1			A1			A1		
Lubricant type	POE			POE			POE		
Q_{evap} (kJ/kg)	148.59			155.8			142.95		
Q_{cond} (kJ/kg)	263.52			229.56			203.59		
Work (kJ/kg)	114.94			73.76			60.64		

Table 7 (continued).

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT
COPc	1.293			2.112			2.357		
Evaporator pressure (kPa)	135.00			379.10			656.8		
Condenser pressure (kPa)	2060.40			2265.80			2915.4		
Evaporator temp glide (°C)	–3.9	–4.1	–3.7	139.33	188.53	N/A	191.98	184.39	169.63
Condenser temp glide (°C)	4.7	4.5	3.9	248.17	271.65	N/A	328.25	266.68	236.71

Table 8: Properties of R448A, R449A, and R452A

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R448A [61]			R449A [62]			R452A [63]		
Composition	R125/R32/R134A/ R1234yf/R12354ze(E)			R125/R32/R134A/ R1234yf			R125/R32/R1234yf		
Mass percentage	26/26/20/21/7			24.7/24.3/25.7/25.3			59/11/30		
Boiling point (°C)	–40.1			–45.95			–47.2		
Critical pressure (kPa)	4675			4662			4014		
Critical temperature (°C)	83.66			83.85			75.05		
ODP	0			0			0		
GWP	1273			1282			1945		
Class	A1			A1			A1		
Lubricant type	POE			POE			POE		
Q_{evap} (kJ/kg)	179.93			172.76			158.78		
Q_{cond} (kJ/kg)	305.77			249.11			221.17		
Work (kJ/kg)	125.84			76.35			62.39		
COPc	1.43			2.263			2.545		
Evaporator pressure (kPa)	150.60			410.60			701.90		
Condenser pressure (kPa)	2051.80			2265.90			2903.70		
Evaporator temp glide (°C)	–4.9	–4.7	–4.4	178.08	170.94	157.04	83.97	92.46	82.56
Condenser temp glide (°C)	4.5	4.3	3.7	301.63	245.91	218.33	159.88	141.82	122.68

Table 9: Properties of R453A and R463A

Condition	LT	MT	HT	LT	MT	HT
Refrigerant	R453A [64],			R463A [65]		
Composition	R125/R32/R134A/R227ea/R600/R601A			R125/R32/R134A/R1234yf/R744		
Mass percentage	20/20/53.8/5/0.6/0.6			30/36/14/14/6		
Boiling point (°C)	–42.2			–60.13		
Critical pressure (kPa)	4530			5283		

(Continued)

Table 9 (continued).

Condition	LT	MT	HT	LT	MT	HT
Critical temperature (°C)	87.9			73.15		
ODP	0			0		
GWP	1765			1377		
Class	A1			A1		
Lubricant type	POE			POE		
Q_{evap} (kJ/kg)	184.91			178.36		
Q_{cond} (kJ/kg)	312			255.92		
Work (kJ/kg)	127.56			77.56		
COPc	1.45			2.3		
Evaporator pressure (kPa)	121.00			342.10		
Condenser pressure (kPa)	1808.70			2002.50		
Evaporator temp glide (°C)	–5.2	–5.1	165.49	194.65	186.07	168.25
Condenser temp glide (°C)	5.0	4.8	228.96	340.43	273.5	239.3

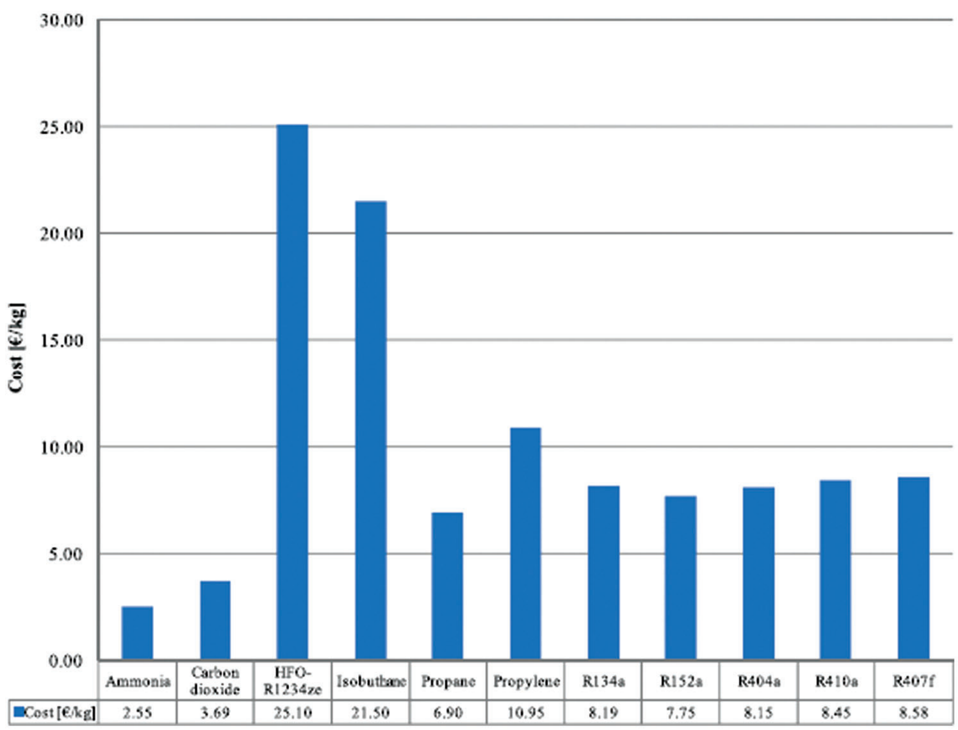

Figure 6: Cost of refrigerants [43]

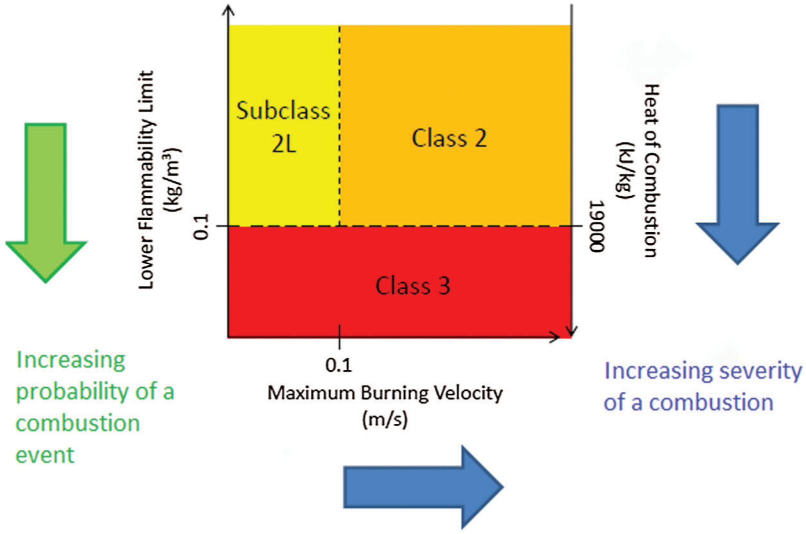

Figure 7: Refrigerant classification [2]

Table 10: Properties of R170, R290, R600, and R600a

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R170 [66]			R290 [67]			R600 [68]			R600a [69]		
Formula	C_2H_6			C_3H_8			C_4H_{10}			C_4H_{10}		
Chemical name	Ethane			Propane			Butane			Isobutane		
Boiling point (°C)	−88.7			−42.1			−0.5			−11.73		
Critical pressure (kPa)	4872			4251			3796			3629		
Critical temperature (°C)	32.17			96.74			151.98			134.66		
ODP	0			0			0			0		
GWP	3			3			3			3		
Class	A3			A3			A3			A3		
Lubricant type	MO/POE			MO/POE			MO/POE			MO/POE		
Q_{evap} (kJ/kg)	N/A	N/A	N/A	388.96	240.37	223.89	235.72	261.99	255.88	207.03	231.52	223.97
Q_{cond} (kJ/kg)	N/A	N/A	N/A	221.85	349.48	314.59	400.21	371.49	348.29	358.39	332.01	308.46
Work (kJ/kg)	N/A	N/A	N/A	221.85	109.11	90.70	164.50	109.51	92.41	151.35	100.49	84.49
COPc	N/A	N/A	N/A	1.33	2.20	2.47	1.43	2.39	2.77	1.37	2.30	2.65
Evaporator pressure (kPa)	N/A	N/A	N/A	157.70	385.90	623.90	26.20	80.20	145.60	43.30	123.50	216.00
Condenser pressure (kPa)	N/A	N/A	N/A	1653.10	1803.10	2269.40	484.30	535.40	705.00	670.60	736.80	955.00

Table 11: Properties of R601, R601a, R1150, and R1270

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R601 [70]			R601a [71]			R1150 [72]			R1270 [73]		
Formula	C_5H_{12}			C_5H_{12}			C_2H_4			C_3H_6		
Chemical name	Pentane			Isopentane			Ethylene			Propylene		
Boiling point (°C)	36.1			27.7			−103.8			−47.7		
Critical pressure (kPa)	3370			3378			5042			4660		
Critical Temperature (°C)	196.55			187.2			9.5			92.4		

(Continued)

Table 11 (continued).

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT	LT	MT	HT
ODP	0			0			0			0		
GWP	4			4			3			2		
Class	A3			A3			A3			A3		
Lubricant type	MO/POE			MO/POE			MO/POE			MO/POE		
Q_{evap} (kJ/kg)	239.30	267.22	264.13	221.18	248.05	244.65	N/A	N/A	N/A	232.45	247.13	228.13
Q_{cond} (kJ/kg)	402.16	376.31	356.72	374.81	350.99	331.95	N/A	N/A	N/A	404.89	358.77	320.62
Work (kJ/kg)	162.86	109.09	92.59	153.63	102.94	87.30	N/A	N/A	N/A	172.44	111.64	92.48
COPc	1.47	2.45	2.85	1.44	2.41	2.80	N/A	N/A	N/A	1.35	2.21	2.47
Evaporator pressure (kPa)	4.70	18.10	37.00	7.20	25.90	51.20	N/A	N/A	N/A	199.70	478.10	764.40
Condenser pressure (kPa)	155.80	175.10	242.20	201.70	225.40	307.00	N/A	N/A	N/A	1964.90	2143.80	2686.70

2 Methodology

For the properties of refrigerants and the refrigeration simulation system, we used the REFPROP database and CYCLE_D-HX software from the National Institute of Standards and Technology [78–80], respectively, as shown in Fig. 9 below. The properties of all refrigerants, summarized in Tab. 14b, conformed to the use of REFPROP and the CYCLE_D-HX software, as stipulated by the National Institute of Standards and Technology (NIST) [78–80], in accordance with the CAN/ANSI/AHRI540 Air-Conditioning, Heating, and Refrigeration Institute (AHRI) standards, as shown in Tab. 12 [74–76]. Both software programs can pre-define mixtures and create new refrigerant mixtures. REFPROP can display results related to refrigerant properties under various conditions, and the CYCLE_D-HX software can also display results related to refrigerant cycles under various conditions. The results illustrated the relationships of all parameters, such as GWP, boiling point, refrigerant effect, heat rejection, refrigerant work, evaporator pressure, high pressure, and cooling coefficient of performance (COPc), as well as the result of the decision tree function through datamining using the RapidMiner software (which came first in the 2013 KDnuggets annual software poll [77]), as shown in Fig. 8 below. The baseline refrigerant, using R134, R32, R125, and R1270, was determined from the literature review.

3 Results and Discussion

The mixture of refrigerants R134, R32, R125, and R1270 can be carried out in 4,539 different types, as reported in Tab. 13 below, which shows the refrigerant mixtures with R1270 fixed at 1% and various mass percentages of R134, R32, and R125. The refrigerant proportion mixed with R125 was, more or less, similar to that of the R32 mixture, and also possessed the Class A1 non-flammability property, similar to R410A (which is comprised of 50% R125 and 50% R32) [81–83]. The class A2 mixed refrigerants had a mass percentage of R32 higher than that of R125, similar to R452B (R32/125/1234yf [67/7/26]). The GWP, calculated by mass percentage of refrigerants, and boiling point, simulated using the National Institute of Standards and Technology (NIST) reference fluid thermodynamic and transport properties (REFPROP) database software and the NIST vapor compression cycle model accounting for refrigerant thermodynamic and transport properties (CYCLE_D-HX) software, were in accordance with the CAN/ANSI/AHRI540 standards of the Air-Conditioning, Heating, and Refrigeration Institute (AHRI).

The refrigerant mixes were developed to have low GWP, zero ODP, high capacity, low pressure, and no toxicity [6], such that we could select the refrigerant requirements from refrigerant data 4,539 type using the RapidMiner software. The refrigerant requirements were: class A1, boiling point lower than that of R404 (−46.5°C), and GWP lower than 2000. The datamining function by decision tree in the RapidMiner software obtained four refrigerant results that followed the refrigerant requirement, as shown in Figs. 10 and 11, and listed in Tab. 14a below.

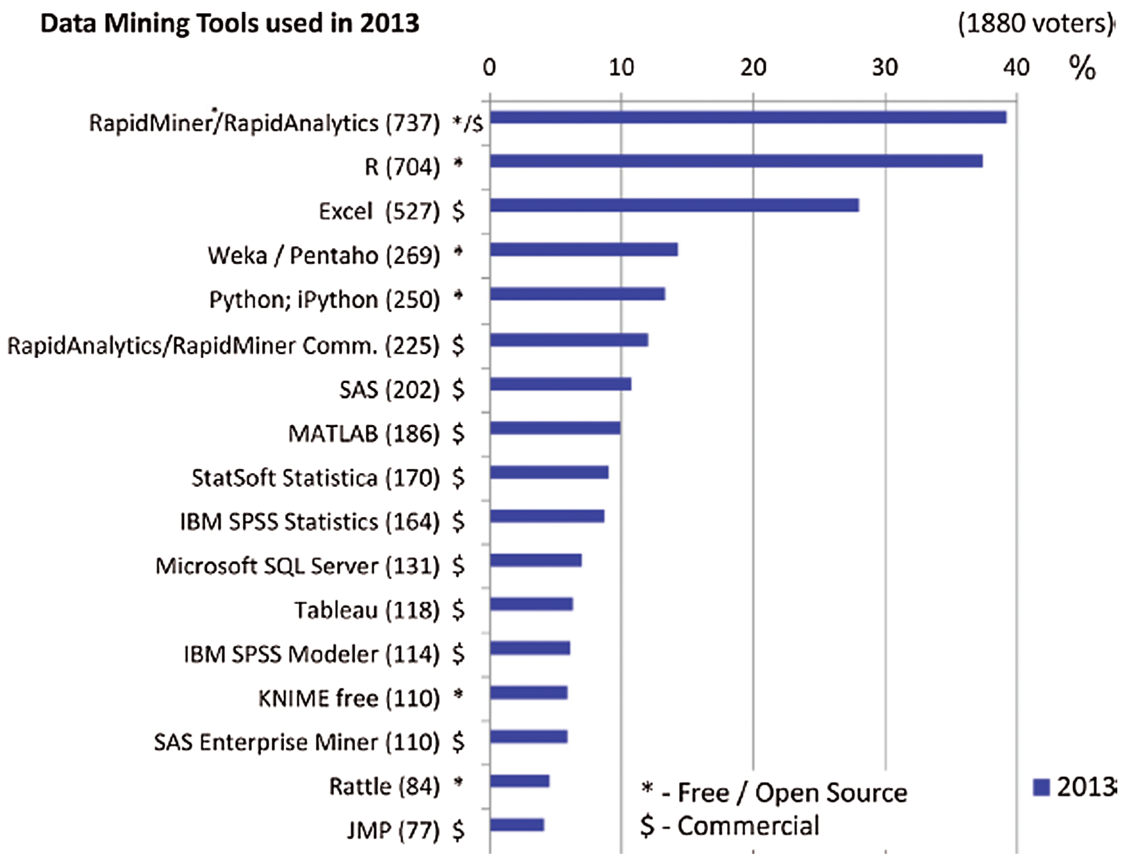

Figure 8: Report of the KDnuggets annual software poll on the most-used data mining tools [77]

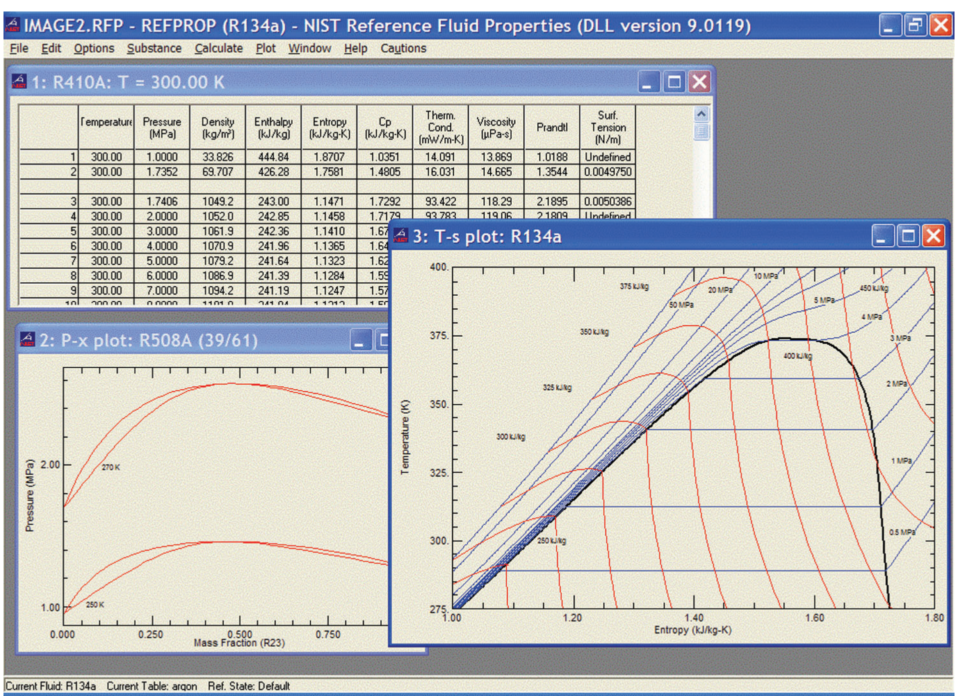

Figure 9: The REFPROP software used for refrigerant properties [78–80]

Table 12: Standard testing for refrigeration systems [74–76]

Temperature point	Air conditioning and heat pump		Refrigeration		
	Heating	Cooling	Low	Medium	High
Suction dew point (°C)	–15.0	10.0	–31.5	–6.5	7.0
Discharge dew point (°C)	35.0	46.0	40.5	43.5	54.5
Suction return gas temperature (°C)	–4.0	21.0	4.5	18.5	18.5
Superheat (K)	11.0	11.0	11.0	11.0	11.0
Subcooling (K)	0.0	0.0	0.0	0.0	0.0

Table 13: Refrigerant mixtures of R134, R32, R125, and R1270

Refrigerant	R134A (%)	R32 (%)	R125 (%)	R1270 (%)	Summary (%)	GWP	Boiling point (°C)	Class A
R-No.1	1	1	97	1	100	3,366	−47.91	1
R-No.2	1	2	96	1	100	3,339	−47.95	1
R-No.3	1	3	95	1	100	3,311	−47.98	1
R-No.4	1	4	94	1	100	3,283	−48.02	1
●	●	●	●	●	●	●	●	●
R-No.94	1	94	4	1	100	786	−51.26	2
R-No.95	1	95	3	1	100	758	−51.30	2
R-No.96	1	96	2	1	100	730	−51.33	2
R-No.97	2	3	94	1	100	3,289	−47.76	1
R-No.98	2	4	93	1	100	3,262	−47.80	1
R-No.99	2	5	92	1	100	3,234	−47.84	1
R-No.100	2	6	91	1	100	3,206	−47.87	1
●	●	●	●	●	●	●	●	●
R-No.187	2	93	4	1	100	792	−51.00	2
R-No.188	2	94	3	1	100	764	−51.04	2
R-No.189	2	95	2	1	100	736	−51.08	2
R-No.190	3	3	93	1	100	3,268	−47.54	1
R-No.191	3	4	92	1	100	3,240	−47.58	1
R-No.192	3	5	91	1	100	3,212	−47.62	1
●	●	●	●	●	●	●	●	●
R-No.4534	92	3	4	1	100	1,354	−27.96	1
R-No.4535	92	4	3	1	100	1,327	−28.00	2
R-No.4536	92	5	2	1	100	1,299	−28.04	2
R-No.4537	93	3	3	1	100	1,333	−27.74	1
R-No.4538	94	3	2	1	100	1,311	−27.52	2
R-No.4539	95	3	1	1	100	1,290	−27.30	2

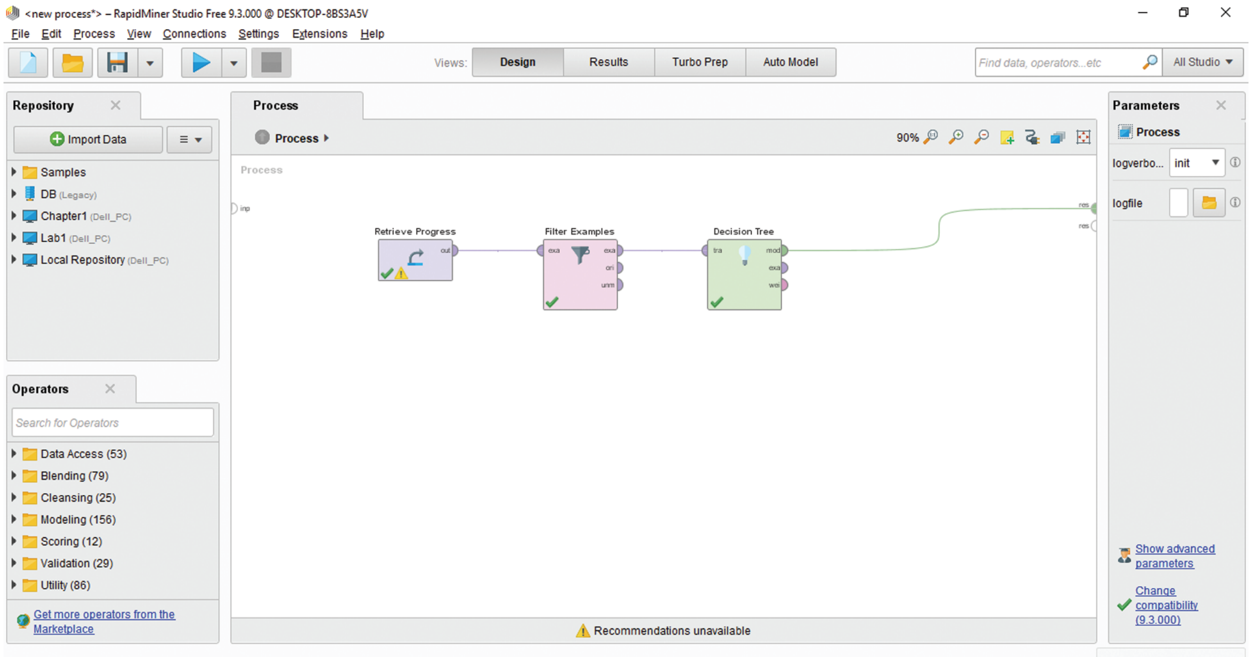

Figure 10: The datamining function by decision tree in RapidMiner

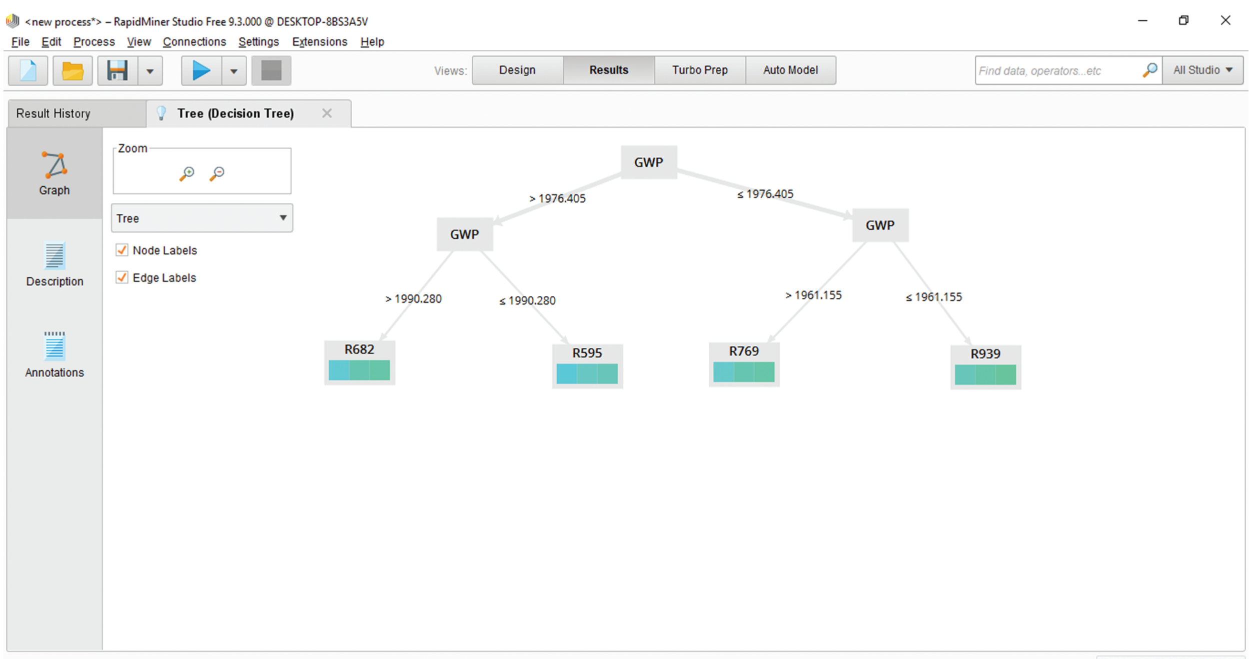

Figure 11: The four refrigerants following our refrigerant requirements

The simulation system then used the REFPROP and CYCLE_D-HX software of the National Institute of Standards and Technology [19] to define new mixtures from the results of the RapidMiner software, in order to verify that the properties and simulation system follow the CAN/ANSI/AHRI540 standard of the Air-conditioning, Heating, and Refrigeration Institute (AHRI), as shown in Tabs. 14b and 15. All refrigerant results were composed of polyol ester oil (POE), which is classified as a Class A1 incombustible and non-toxic refrigerant. R-No.595 had the lowest boiling point at −48.21°C; lower than that of R404A by 4.58%. This was due to the presence of hydrofluorocarbon (HFCs) R32 (36%) and hydrocarbon (HCs) R1270 (1%). The lowest GWP was 1,958, 50.34% lower than that of R404A, which was due to the presence of hydrofluorocarbon (HFCs) R134A (11%) and hydrocarbon (HCs) R1270 (1%). The critical pressures and temperatures of all refrigerants were found to be higher than those of R404A and, so, they can all be used in high ambient temperature environments. The highest refrigerant effect was attained by R-No.595, with 138.72 and 142.93 kJ/kg for low and medium conditions, respectively. The highest heat rejection was 248.83 and 212.52 kJ/kg for low and medium conditions, respectively, consistent with the normal boiling point. For all refrigerants, the cooling coefficient of performance (COPc) was lower than that of R404A (13.49%), only for low temperature conditions. This was due to the presence of hydrofluorocarbon (HFCs) R32 and hydrocarbon (HCs) R1270; however, R32 operates at high pressures, thus affecting the evaporator pressure, condenser pressure, and COPc under medium temperature conditions (as the work of compressor will be high). This shows that a mixed-refrigerant design should consider all parameters, such as the GWP, boiling point, Cp liquid/vapor and liquid/vapor conductivity, refrigerant effect, heat rejection, refrigerant work, evaporator pressure, high pressure, and COPc.

Table 14a: The four refrigerants found using the RapidMiner software

Refrigerant	R134A	R32	R125	R1270	Summary	GWP	Boiling point	Class A
R-No.682	8	45	46	1	100	1,995	−47.96	1
R-No.595	7	46	46	1	100	1,989	−48.21	1
R-No.769	9	45	45	1	100	1,973	−47.74	1
R-No.939	11	44	44	1	100	1,958	−47.26	1

Table 14b: Results of the simulation system using REFPROP and CYCLE_D-HX

Condition	LT	MT	HT	LT	MT	HT	LT	MT	HT
Refrigerant	R404A			R-No.682			R-No.595		
Composition	R125/R143/R134A			R134A/R32/R125/ R1270			R134A/R32/R125/R1270		
Mass percentage	44/52/4			8/45/46/1			7/46/46/1		
Boiling point (°C)	−46.6			−47.96			−48.21		
Critical Pressure (kPa)	3728			4856			4867		
Critical temperature (°C)	72.1			72.83			72.6		
ODP	0			0			0		
GWP	3943			1,995			1,989		
Class	A1			A1			A1		
Lubricant type	POE			POE			POE		
Q_{evap} (kJ/kg)	83.66	139.02	N/A	137.87	142.2	N/A	138.72	142.93	N/A
Q_{cond} (kJ/kg)	159.8	198.57	N/A	247.52	211.55	N/A	248.83	212.52	N/A
Work (kJ/kg)	76.14	59.55	N/A	109.66	69.34	N/A	110.11	69.59	N/A
COPc	1.099	2.335	N/A	1.257	2.051	N/A	1.260	2.054	N/A
Evaporator pressure (kPa)	183.30	477.3	N/A	226.00	588.4	N/A	229.30	595.40	N/A
Condenser pressure (kPa)	2197.50	2284.10	N/A	2750.50	3017.60	N/A	2769.30	3038.20	N/A
Evaporator temp glide (°C)	−0.4	−0.5	N/A	−1.5	−1.5	N/A	−1.4	−1.3	N/A
Condenser temp glide (°C)	0.3	0.3	N/A	1.5	1.4	N/A	1.3	1.2	N/A

Table 15: Results of the simulation system using REFPROP and CYCLE_D-HX

Condition	LT	MT	HT	LT	MT	HT
Refrigerant	R-No.769			R-No.939		
Composition	R134A/R32/R125/R1270			R134A/R32/R125/R1270		
Mass percentage	9/45/45/1			11/44/44/1		
Boiling point (°C)	−47.74			−47.26		
Critical pressure (kPa)	4863			4859		
Critical temperature (°C)	73.16			73.71		
ODP	0			0		
GWP	1,973			1,958		
Class	A1			A1		
Lubricant type	POE			POE		
Q_{evap} (kJ/kg)	138.68	143.07	N/A	138.61	143.19	N/A
Q_{cond} (kJ/kg)	248.92	212.8	N/A	248.97	213.04	N/A
Work (kJ/kg)	110.25	69.72	N/A	110.36	69.84	N/A
COPc	1.258	2.052	N/A	1.256	2.05	N/A
Evaporator pressure (kPa)	223.30	582.7	N/A	217.40	570.20	N/A
Condenser pressure (kPa)	2735.70	3001.50	N/A	2702.20	2965.00	N/A
Evaporator temp glide (°C)	−1.7	−1.6	N/A	−1.9	−1.9	N/A
Condenser temp glide (°C)	1.6	1.5	N/A	1.8	1.7	N/A

4 Conclusions

In this paper, we determined new refrigerant mixtures comprised of R134, R32, R125, and R1270 by using refrigerant composition results of the decision tree function in the RapidMiner software, which came first in KDnuggets annual software poll. All resulting refrigerants were composed of polyol ester oil (POE), which has been classified as a Class A1, incombustible, and non-toxic refrigerant. The properties of the refrigerants were verified using the National Institute of Standards and Technology (NIST) reference fluid thermodynamic and transport properties database (REFPROP) software and the NIST vapor compression cycle model accounting for refrigerant thermodynamic and transport properties (CYCLE_D-HX) software, and were in accordance with the CAN/ANSI/AHRI540 standards of the Air-Conditioning, Heating, and Refrigeration Institute (AHRI). It was indicated that the normal boiling point of R-No. 595 was higher than that of R404A by 4.58%, with a higher cooling capacity and a lower GWP than those of R404A by a margin of 50.34% due to the presence of hydrofluorocarbon (HFCs) R32 and hydrocarbon (HCs) R1270. The COP of R-No. 595 was found to be higher than that of R404A by 13.49% under low temperatures. It should be emphasized that a mixed-refrigerant design must consider all relevant parameters, such as the GWP, boiling point, Cp liquid/vapor and liquid/vapor conductivity, refrigerant effect, heat rejection, refrigerant work, evaporator pressure, high pressure, and COPc. The proposed refrigerant mixes provide alternate refrigerant options which are composed of 1% hydrocarbon (HCs) R1270, consistent with the evolution of the fourth-generation refrigerants; which contain a mixture of HFCs, HFOs, HCs, and natural refrigerants, in order to produce a low-GWP, zero ODP, high-capacity, low-operating pressure, and non-toxic refrigerants. In the future, researchers should incorporate the use of natural refrigerants that have low cost. The problems of high evaporator pressure and high condenser pressure, which lead to high refrigerant work, can be solved by adjusting the composition of the refrigerant or mix (i.e., by using a refrigerant that operates at low pressure), thereby improving the COP of the refrigerant.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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