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저온용 대체냉매의 성능 특성 연구

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Performance Characteristics Study on an Alternative Refrigerant in Low Temperature Applications

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Abstract >> This paper presents the results of thermodynamic cycle analysis and performance tests of alternative mixtures in low temperature applications. Two near-azeotropic binary mixtures R-152a/R-1270 (35:65 by wt.%) and R-290/E170 (35:65 by wt.%) are considered in this study. They have zero ODP (Ozone Depletion Potential) and much lower GWP (Global Warming Potential) than R-404A which is an alternative of R-502. Refrigeration cycle characteristics such as cooling capacity, coefficient of performance, suction and discharge pressures and temperatures are compared to those for the baseline refrigerants (R-502 and R-404A) cycles. The performance tests are conducted at the evaporation and condensation temperatures of 5°C and 45°C, subcooling and superheating temperatures of 5°C, respectively. Performance comparisons between baseline and alternative refrigerants are conducted on the same cooling capacity. The system performance of newly proposed refrigerant mixtures show promising results.

Key words : Alternative refrigerant(대체냉매), Refrigerant mixtures(혼합냉매), Refrigeration capacity(냉동능력), COP(성적계수), GWP(지구온난화지수)

Nomenclature

COP : Coefficient of performance
C_v, C_p : Specific heat (J/kgK)
L : Liquid
P : Pressure (kPa)
ΔP : Pressure difference (kPa)
RPM : Revolution per minute (rev/min)
T : Temperature (°C)
V : Vapor

Subscript

Cond : Condensation
dis : Discharge
evap : Evaporation
glide : temperature glide

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1. Introduction

Due to increasing concerns about ozone depletion, HFC refrigerants have played an important role in replacing CFC/HCFC substances[1)]. As a replacement of R-502 (HCFC-22/CFC-115=48.8/52.2 by wt.%), near-azeotropic HFC mixture R-404A (HFC-125/143a/134a= 44/52/4 by wt.%) are widely used in refrigeration and air conditioning applications. However, HFC refrigerant (R-404A) is included in the basket of greenhouse gases for control by the Kyoto Protocol which is effective on February 16, 2005. Therefore, there have been efforts on the research for long term substitution of the R-502.

Stegou-Sagia and Paignigiannis[2)] conducted performance evaluation with the mixtures (R-401B, R-401C, R-402A, R-404A, R-406A, R-408A, R-409A, R-410A, R-410B and R-507) as replacements of R-12, R-22 and R-502 in vapor compression refrigerating cycles on the basis of exergy aspects.

Camporese et al.[3)] conducted experimental investigation using sixteen refrigerant mixtures as potential short- and mid-term substitutes for R-12 and R-502. The performance of the R-12, R-502, and their proposed alternatives were compared by testing two different refrigerating units. In addition, the solubility with various lubricant oils was investigated by measuring critical solubility temperatures.

Domanski and Didion[4)] reported theoretical evaluation result of nine R-22 alternatives and three R-502 alternatives. Their study conducted with a semi-theoretical mode, CYCLE-11, with a pure cross-flow heat exchanger. Performance simulations were also conducted in a modified system equipped with a liquid-line/suction-line heat exchanger((LLSL-HX) cycle. Their simulations showed that the LLSL-HX cycle might be warranted for some of the candidate alternatives. Xuan and Chen[5)] presented experimental results using ternary near-azeotropic mixture, composed of R-161/125/143a (10/45/45 by wt.%) as an alternative refrigerant to R-502. They conducted drop-in tests on a vapour compression refrigeration plant with a reciprocating compressor, which was originally designed to use R-404A, a major substitute for R-502.

According to the revised F-Gas Regulation, from 1 January 2020 stationary refrigeration equipment using high GWP refrigerant (GWP> 2500) is prohibited from placing on the European market[6)]. Moreover, the use of such greenhouse gases to service or maintain refrigeration equipment with a charge amount of 40 ton of CO_2 equivalent or more, shall be prohibited from the same date[6)]. This will significantly affect the refrigeration industry using R-404A due to its high GWP value of 3750.

This paper presents the characteristics and performance of long-term R-502 alternative refrigerants. Theoretical cycle analysis has been performed using NIST REFPROP[7)] and reported thermodynamic analysis results with two potential low GWP alternative refrigerants, R-502 and R-404A[8)]. Experiment investigation is also conducted using one alternative refrigerant and compared its results to R-404A.

2. Thermodynamic cycle analysis

The objective of the analysis is to find new environmentally friendly near- azeotropic mixtures that are likely to show higher performance than the R-502 and the R-404A system at the same operating conditions. This analysis was performed under ASHRAE LBP (low back pressure) test condition and subroutines of the

Table 1 Thermodynamic cycle analysis results for RE170 (DME) and R290 mixtures

	A	B	C	D	E	F	G	H	I	L	M	N	O	Q	R	S	T
1	Te=-23.3°C, Tc=54.4°C, Tamb=32.2°C																
2	RE170	R290	Pe	Pc	Pe/Pc	dTc	dTe'	Xe-in	dhe'	Tdis	RHOLc	VISCVe	Cap-Vol	COP	THLe	THVe	Cp/Cv
3	(wt, %)	(wt, %)	[kPa]	[kPa]		[K]	[K]		[kJ/kg]	[°C]	[kg/m^3]	[uP]	[kJ/m^3]		[W/mK]	[W/mK]	
18	0.15	0.85	220.0	1931.0	8.77	0.02	0.00	0.34	264.9	118.5	460.2	70.15	1428.0	**2.76**	0.1273	0.01387	1.147
19	0.16	0.84	220.0	1932.0	8.78	0.01	0.00	0.34	265.5	118.6	461.7	70.19	1431.0	**2.77**	0.1277	0.01386	1.147
20	0.17	0.83	219.9	1933.0	8.79	0.01	0.00	0.34	266.1	118.7	463.3	70.23	1433.0	**2.77**	0.1282	0.01385	1.147
21	0.18	0.82	219.8	1933.0	8.80	0.01	0.01	0.34	266.7	118.8	464.9	70.27	1435.0	**2.77**	0.1287	0.01385	1.148
22	0.19	0.81	219.7	1934.0	8.80	0.00	0.01	0.34	267.3	119.0	466.4	70.31	1437.0	**2.78**	0.1292	0.01384	1.148
23	0.20	0.80	219.5	1934.0	8.81	0.00	0.02	0.34	268.0	119.1	468.0	70.35	1438.0	**2.78**	0.1297	0.01383	1.148
24	0.21	0.79	219.3	1934.0	8.82	0.00	0.03	0.33	268.6	119.2	469.6	70.39	1439.0	**2.78**	0.1301	0.01382	1.148
25	0.22	0.78	219.0	1934.0	8.83	0.00	0.05	0.33	269.2	119.4	471.3	70.43	1440.0	**2.79**	0.1306	0.01382	1.148
26	0.23	0.77	218.7	1934.0	8.85	0.00	0.06	0.33	269.9	119.5	472.9	70.47	1441.0	**2.79**	0.1311	0.01381	1.148
27	0.24	0.76	218.3	1934.0	8.86	0.01	0.08	0.33	270.6	119.7	474.5	70.51	1441.0	**2.79**	0.1316	0.01380	1.148
28	0.25	0.75	217.9	1933.0	8.87	0.01	0.11	0.33	271.2	119.8	476.2	70.55	1441.0	**2.79**	0.1321	0.01380	1.149
29	0.26	0.74	217.4	1932.0	8.89	0.02	0.14	0.33	271.9	120.0	477.9	70.59	1440.0	**2.79**	0.1326	0.01379	1.149
30	0.27	0.73	216.9	1931.0	8.90	0.03	0.17	0.33	272.6	120.1	479.5	70.63	1439.0	**2.80**	0.1331	0.01378	1.149
31	0.28	0.72	216.3	1929.0	8.92	0.04	0.21	0.33	273.3	120.3	481.2	70.67	1438.0	**2.80**	0.1337	0.01378	1.149
32	0.29	0.71	215.6	1928.0	8.94	0.06	0.25	0.33	274.0	120.5	482.9	70.71	1436.0	**2.80**	0.1342	0.01377	1.149
33	0.3	0.7	214.9	1926.0	8.96	0.07	0.30	0.33	274.7	120.6	484.6	70.76	1434.0	**2.80**	0.1347	0.01377	1.149
34	0.31	0.69	214.1	1924.0	8.98	0.09	0.35	0.33	275.4	120.8	486.4	70.80	1432.0	**2.80**	0.1352	0.01376	1.149
35	0.32	0.68	213.3	1921.0	9.01	0.12	0.41	0.33	276.1	121.0	488.1	70.84	1429.0	**2.80**	0.1357	0.01376	1.149
36	0.33	0.67	212.4	1919.0	9.03	0.14	0.48	0.33	276.9	121.2	489.8	70.89	1426.0	**2.80**	0.1363	0.01375	1.149
37	0.34	0.66	211.5	1916.0	9.06	0.17	0.55	0.33	277.6	121.4	491.6	70.93	1422.0	**2.80**	0.1368	0.01375	1.150
38	0.35	0.65	210.5	1913.0	9.09	0.20	0.63	0.33	278.4	121.6	493.4	70.98	1418.0	**2.80**	0.1374	0.01374	1.150
39	0.36	0.64	209.5	1909.0	9.12	0.24	0.71	0.33	279.1	121.8	495.2	71.03	1413.0	**2.80**	0.1379	0.01374	1.150
40	0.37	0.63	208.3	1906.0	9.15	0.28	0.80	0.32	279.9	122.0	496.9	71.07	1408.0	**2.80**	0.1385	0.01373	1.150
41	0.38	0.62	207.2	1902.0	9.18	0.32	0.89	0.32	280.7	122.2	498.7	71.12	1403.0	**2.80**	0.1390	0.01373	1.150
42	0.39	0.61	206.0	1898.0	9.22	0.37	0.99	0.32	281.5	122.4	500.6	71.17	1397.0	**2.80**	0.1396	0.01373	1.150
43	0.4	0.6	204.7	1894.0	9.25	0.42	1.10	0.32	282.3	122.7	502.4	71.22	1391.0	**2.80**	0.1402	0.01372	1.150
44	0.41	0.59	203.4	1889.0	9.29	0.47	1.21	0.32	283.1	122.9	504.2	71.27	1385.0	**2.80**	0.1407	0.01372	1.150
45	0.42	0.58	202.1	1885.0	9.33	0.53	1.32	0.32	283.9	123.1	506.0	71.32	1378.0	**2.80**	0.1413	0.01372	1.150
46	0.43	0.57	200.7	1880.0	9.37	0.59	1.44	0.32	284.8	123.3	507.9	71.37	1371.0	**2.79**	0.1419	0.01372	1.150

NIST database REFPROP 9.1[7)] were used to obtain thermodynamic properties of the refrigerant mixtures.

The analysis program automatically calculates the thermodynamic cycle up to five refrigerant mixtures by 1 weight % composition change steps. For example, ternary refrigerant mixture requires about 5000 compositions in analysis. Then, the final analysis data are summarized and can be opened at the MS-EXCEL as shown in Table 1.

From this analysis with dozens of refrigerant mixtures, final two candidates were selected and then performance test was performed with the best candidate refrigerant mixture.

2.1 Thermodynamic Properties

Two near-azeotropic binary mixtures, R-1270/152a (65/35 by wt.%) and R-290/E170 (65/35 by wt.%) are newly proposed. Where, R-E170 is known as DME (dimethyl ether) and which has been considered as an environmentally benign fuel for transportation, power generation and household. It is an LPG-like synthetic fuel that is produced through gasification of various renewable substances or fossil fuels. Table 2 shows comparisons of the thermodynamic properties between R-502, R-404A, and candidate refrigerant blends. As shown in Table 2, it is worth noting that newly proposed refrigerants have very low value of GWP. Moreover, due to their low density, the required refrigerant charge would be significantly less than that of R-502 and R-404A. They have excellent thermodynamic and transport properties such as thermal conductivity and viscosity. However high flammability

Table 2 Properties of R-502, R-404A, and alternative refrigerants[7,9)]

Refrigerant		R-502	R-404A	Near-azeotropic	Near-azeotropic
Composition (by wt.%)		R-22/115 (48.8:51.2)	R-125/143a/134a (44:52:4)	R-1270/152a (65:35)	R-290/DME (65:35)
Molecular Weight		111.63	97.6	50.5	44.8
Normal Boiling Point (°C)		-45.17	-46.2	-46.1	-41.3
Critical Temperature (°C)		80.15	72.0		
Critical Pressure (kPa)		3917.6	3728.9		
Density at 0°C (kg/m^3)	L V	1320 32.75	1149 30.97	643.1 13.90	580.9 10.52
Pressure at 0°C (kPa)		571	611	569.2	469.5
Latent Heat at 0°C (kJ/kg)		143	164.8	343.5	382
Thermal Conductivity at 0°C (W/m-K)	L V	0.0706 0.00974	0.0795 0.01231	0.112 0.01415	0.123 0.0158
Viscosity at 0°C (mPa-s)	L V	217 11.8	179 11.4	130 8.42	141 7.81
Cp/Cv at 0°C	V	1.25	1.24	1.29	1.25
ODP		0.221	0	0	0
GWP 100 year (CO_2=1)		4300	3750	55	13
Safety Group		A1	A1	A3	A3

is the most critical problem. Hence, use of these refrigerants requires much severe safety standards and safety measures along with the corresponding risk analysis.

2.2 Theoretical Comparison

By using the conditions listed in Table 3, thermodynamic refrigerating cycle analysis was performed. The calculation results of the cycle analysis are shown in Table 4. All the refrigerants considered in the study show that temperature glide during evaporation and condensation is below 1.0°C. From the simulation data, R-1270/152a (65/35 by wt.%) and R-290/E170 (65/35 by wt.%) it is observed that they show better COP (coefficient of performance) than R-502 and R-404A. However the drawback of R-1270/152a (65/35 by wt.%) is the high discharge temperature that provides negative effects on lubricant and refrigerant stability. At lower temperatures, any reactions initiated due to the compatibility problems between refrigerant, lubricant and materials of the system and compressor is likely to be slower. This indicates that the reliable life of the compressor is likely to be longer (Devotta et al.[10)]). Therefore, R-290/E170 (65/35 by wt.%) is seem to be more suitable to replace R-502.

Table 3 Conditions for thermodynamic cycle analysis

Location	Condition
Average Saturation Temperature of Evaporation	-23.3°C
Average Saturation Temperature of Condensation	54.4°C
Compressor Inlet/outlet Temperature	32.2°C

Table 4 Calculation results for thermodynamic cycle analysis

Refrigerant	R502	R404A	Near-azeotropic	Near-azeotropic
Composition (by wt.%)	R22/115 (48.8:51.2)	R125/143a/134a (44:52:4)	R1270/152a (65:35)	R290/DME (65:35)
P_{evap} (kPa)	257	272	258	211
P_{cond} (kPa)	2.34	2.59	2.27	1.91
$T_{glide,\ evap}$ (°C)	0.01	0.31	0.96	0.63
$T_{glide,\ cond}$ (°C)	0.02	0.22	0.25	0.20
$T_{discharge}$ (°C)	120.5	113.7	129.4	121.6
Compression Ratio	9.11	9.52	8.78	9.09
COP	2.59	2.60	2.74	2.80
Volumetric Capcity (kJ/m^3)	1587	1687	1688	1418

3. Experiment

The performance tests were carried out in a refrigeration cycle test apparatus. Test apparatus consists of circulation loop for the refrigerant and data acquisition system. Fig. 1 presents schematic diagram of the refrigerant cycle test rig. It consists of a compressor, an inverter motor, an oil separator, a condenser, a subcooler, a flow meter, a dryer, expansion devices, and an evaporator. The refrigerant is circulated by a swash plate compressor of the mobile air-conditioning system. Compressor speed was controlled by the inverter motor and its torque and RPM were measured. The refrigerant flow rate was measured using a Coriolis-type mass

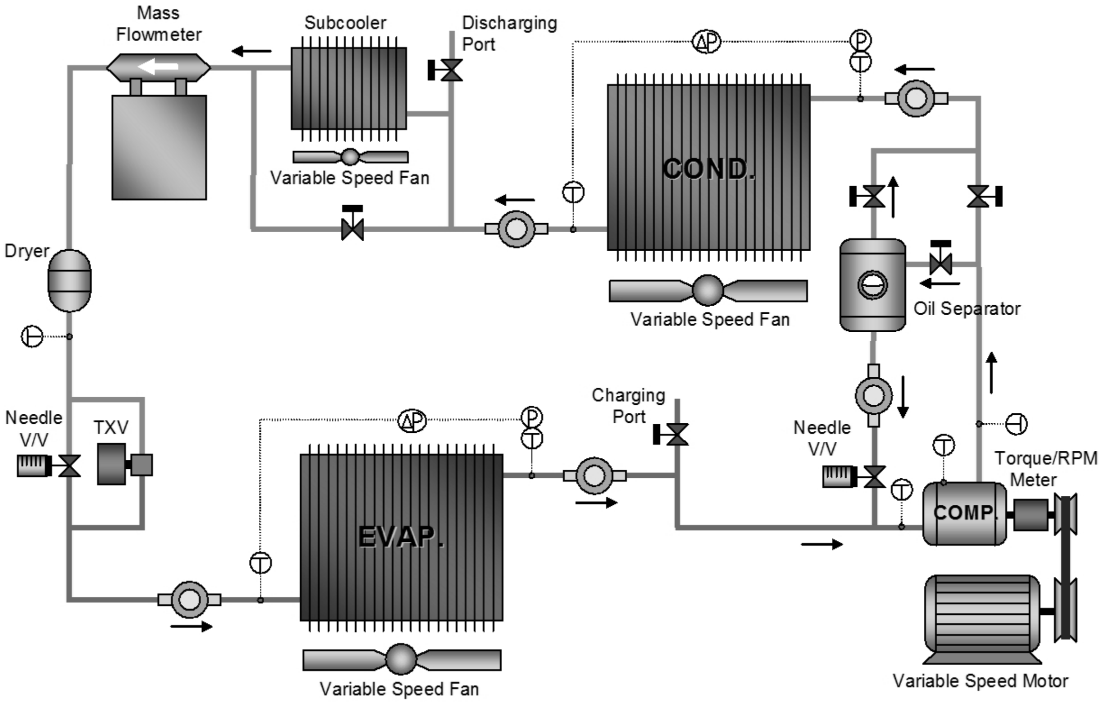

Fig. 1 Schematic diagram of the test apparatus

Table 5 Test conditions

Location	Condition
Average Saturation Temperature of Evaporation	5°C
Average Saturation Temperature of Condensation	45°C
Subcooling Temperature (at expansion device inlet)	5°C
Superheating Temperature (at evaporator outlet)	5°C
Cooling Capacity (kW)	2840

flow meter with a nominal flow range of 0~200 kg/h and an accuracy of ±0.1%.

The test conditions are summarized in Table 5 and specifications of the test apparatus are listed in Table 6.

R-404A and R-290/E170 (65/35 by wt.%) were used as the refrigerant. Table 6 shows that R-290/E170 (65/35 by wt.%) requires much less charge than R-404A. The test data were collected using a data acquisition system consisting of a data logger, a serial communication (RS-232C), and a PC. The data were analyzed in real time using a PC and a data reduction program (MS-Excel with a Visual Basic).

All of the information about the test conditions and test data were displayed on the monitor during the test, the test conditions were changed, based on this information. At steady state condition, 20 data points were collected during 120 seconds and averaged. The thermodynamic and transport properties of tested refrigerants were obtained from the NIST database REFPROP 9.1$^{7)}$.

The operating conditions (i.e. refrigerant pressures, superheating and subcooling temperature, etc) were controlled by the expansion devices and fan motor speed of the heat exchangers. During the performance evaluation test, discharged lubricant at the compressor outlet was returned to the inlet of the compressor by using an oil separator and a needle valve. In this test, superheating temperature was estimated at the outlet of the evaporator.

Owing to the discharged hot lubricant from the oil separator, refrigerant temperature increased largely. Hence, it was not suitable to estimate superheating temperature at the compressor inlet. The baseline tests were first performed using R-404A. Then, the performance test for R-290/E170 (65/35 by wt.%) was conducted. Comparisons among different refrigerants were carried out on the same cooling capacity. For each measurement, the expansion device was adjusted

Table 6 Basic specifications of the test apparatus

Item	Specification	
Refrigerant	R-404A	R-290/E170 (65:35 by wt.%)
Refrigerant Charge	800 g	470 g
Compressor	Swash Plate Type, 10 Cylinders, Displacement 110 cc	
Evaporator	Fin and Tube Type, O.D.=9.54 mm, W400xH340xD100 mm	
Condenser	Fin and Tube Type, O.D.=9.54 mm, W400xH340xD100 mm	
Subcooler	Brazed Parallel Flow Type, W110xH130xD19 mm	
Expansion Device	TXV (Thermo Expansion Valve) and Needle Valve	
Lubricant	PAG (UCON-244), 150 cc (Initial charge)	

Table 7 Experimental results

Item	Test Result		
Refrigerant	R-404A	R-290/E170 (65/35 by wt.%)	Ratio $\frac{\text{R-290/E170}}{\text{R-404A}}$
Mass Flowrate [kg/h]	70.9	28.8	40.6%
Compressor RPM	500.9	633.5	126.5%
Evaporation Pressure Drop [kPa]	95.7	83.2	86.9%
Discharge Temperature [°C]	66.3	65.7	-
Compressor Power [W]	780.7	781.4	100.1%
Cooling Capacity [W]	2836	2838	100.1%
COP	3.63	3.63	100.0%

for the system to have the test condition.

The cooling capacity was calculated with the refrigerant mass flow rate and estimated enthalpy difference of the evaporator. The coefficient of performance was estimated with the cooling capacity and the shaft power of the compressor. The refrigerant temperatures were measured using inserted RTDs and an attached T-type thermocouple. The pressures and the pressure differences were measured by the transducers connected to the static pressure taps.

4. Results and discussion

Table 6 shows performance evaluation test result for R-404A and R-290/E170 (65/35 by wt.%). It shows that for the same cooling capacity, system performance of R-290/E170 (65/35 by wt.%) is very similar to that of R-404A. Because of its lower volumetric capacity, R-290/E170 (65/35 by wt.%) requires 26.5% higher compressor speed. But mass flowrate of R-290/E170 (65/35 by wt.%) is about 40% of R404A because of its larger latent heat. By the way, R-290/E170 (65/35 by wt.%) shows 13.1% lower pressure drop during evaporation. From these results, it seems that R-290/E170 (65/35 by wt.%) shows better performance than R-404A.

Figure 2 shows the cooling capacity and coefficient of performance results of R-290/E170 (65/35 by wt.%) as functions of the compressor speed. As shown in the

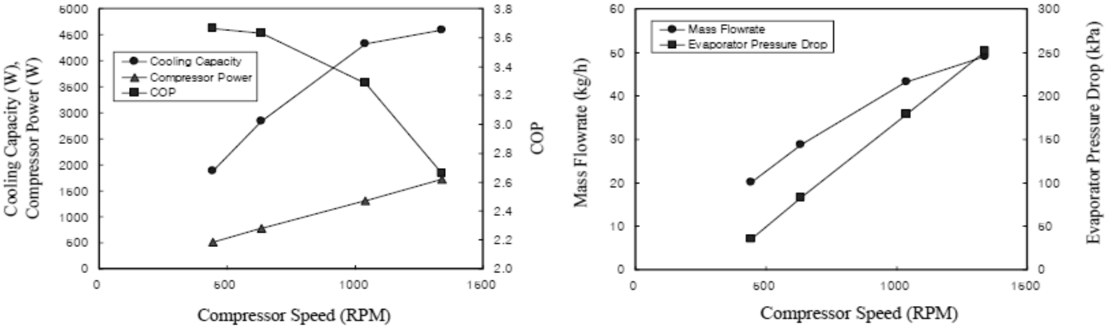

Fig. 2 Test results versus compressor speed for R-290/E170 (65/35 by wt.%)

figure, COP decreases with the compressor speed and compressor power increases linearly with the compressor speed.

Mass flow rate and pressure drop during evaporation of R-290/E170 (65/35 by wt.%) are depicted in Figure 2 as functions of the compressor speed. Pressure drop in the evaporator increases almost linearly with compressor speed. It is speculated that pressure drop is main reason for COP degradation in higher compressor speed. Hence, lower pressure drop refrigerant would be favourable especially at higher mass flow rate region.

5. Conclusions

In this study, new environmentally friendly near-azeotropic alternatives to R-502 were proposed: R-152a/1270 (35:65 by wt.%) and R-290/E170 (35:65 by wt.%). The theoretical thermodynamic cycle analysis showed that R-290/E170 (35:65 by wt.%) had the best characteristics and performance among the blends under investigation: R-502, R-404A, R-152a/1270 (35:65 by wt.%), and R-290/E170 (35:65 by wt.%). Performance tests were conducted with evaporation and condensation temperature of 5°C and 45°C, respectively and subcooling and superheating temperatures of 5°C. At the same cooling capacity, R-290/E170(65:35 by wt.%) system showed that refrigerant charge amount and evaporator pressure drop are 41% and 13.1% lower than R-404A system, respectively. COP and discharge temperature were almost the same for the both systems.

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