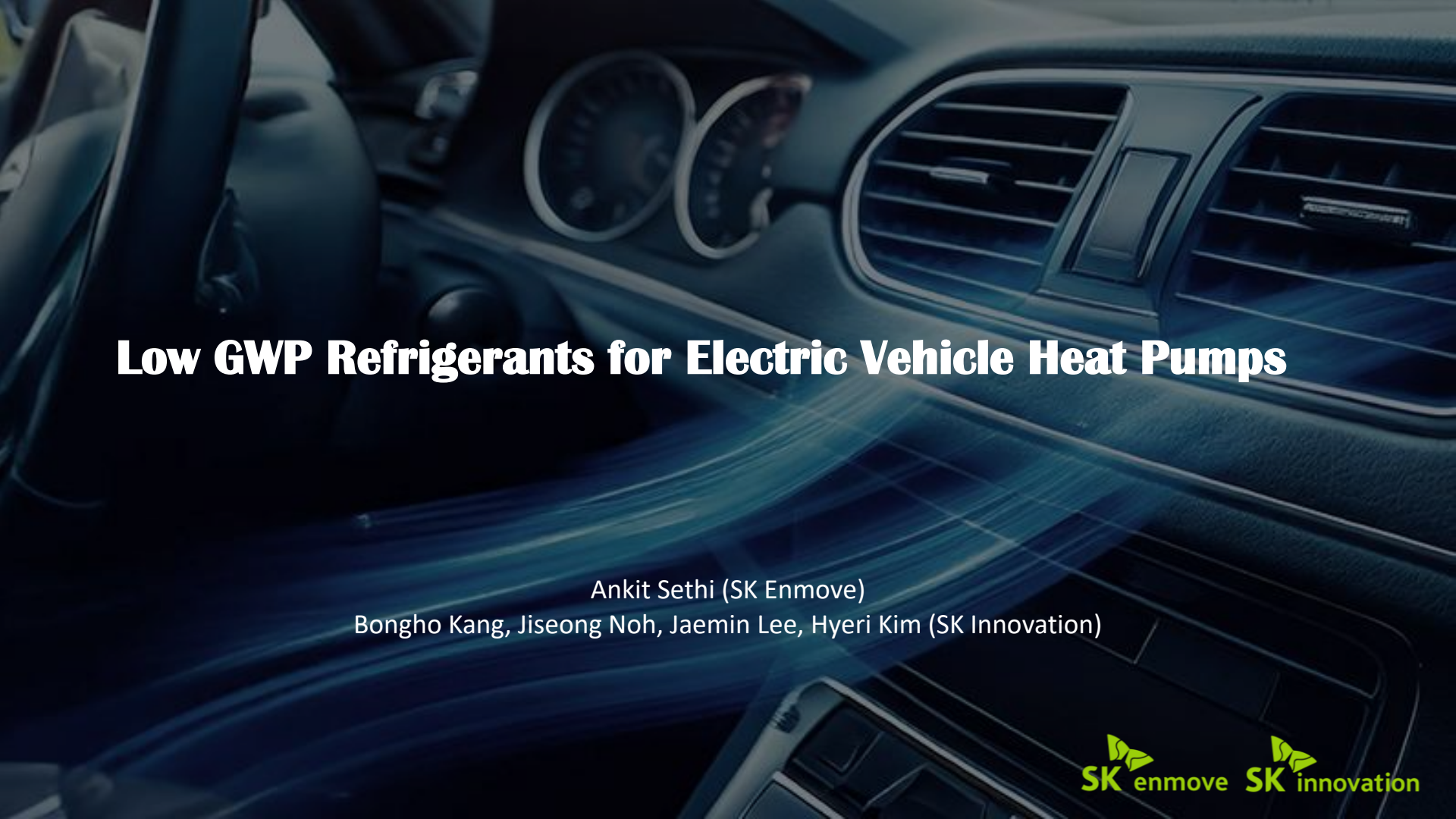


Low GWP Refrigerants for Electric Vehicle Heat Pumps

Ankit Sethi (SK Enmove)
Bongho Kang, Jiseong Noh, Jaemin Lee, Hyeri Kim (SK Innovation)

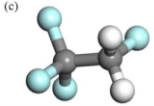
SK enmove SK innovation

Contents

Background

Environmental Regulations

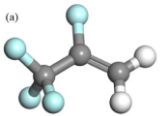
Gen. 3 Refrigerant
R-134a



High GWP

F-gas Regulation

Gen.4 Refrigerant
R-1234yf



PFAS Concerns

PFAS Regulation

Next Gen.
New Refrigerant

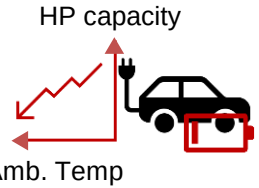
Meet all regulation

Heat pump capacity for EV

Low temp. Thermal management

Applying heat pumps for efficiency

Insufficient refrigerant



Reduced heat pump performance at low temp. Need for improvement

Need for new refrigerants

SK Refrigerants

New Refrigerants Meeting Market Needs

① Regulations ② Toxicity/Flammability ③ System Compatability ④ System performance

Comparison of Alternative Refrigerants for Automobile HVAC

● Good ● Acceptable ● Concerns

Category	R-1234yf	R-744 (CO_2)	R-290 (Propane)	R-494B	R-4101A
Composition	Single	Single	Single	Ternary	Ternary
⊖ Regulations	● (PFAS concerns)	●	●	●	●
⊜ Toxicity/Flammability	●	●	● (flammability)	●	●
⊛ System compatibility	●	● (High pressure system)	● (in-direct system)	●	●
④ System performance	●	●	●	●	●

Overview of Refrigerants

Property	R-494B	R-4101A	R-1234yf
Composition (wt%)	CF3I / R-152a / R-744 (58 / 38 / 4)	CF3I / R-152a / R-32 (58.5 / 30.5 / 11)	-
GWP	48	113	~1
Environmental	Non-PFAS	Non-PFAS	PFAS, TFA concerns
ASHRAE Classification	A2L (A1 under most conditions)	A2L (A1 under most conditions)	A2L
Expected ISO Classification	A1/A2L	A1/A2L	A2L
Boiling point (℃) (@1barA)	-48.5	-39.2	-29.5
Dew Point (℃) (@1barA)	-29.5	-31.7	-29.5
Critical Temperature (℃)	107.6	102.9	94.7
Full Temp. Glide @ 50℃ (K)	13.3	6.2	0.0
Full Temp. Glide @ 0℃ (K)	17.2	7.2	0.0

- Both refrigerants are A2L replacements for R-1234yf MVAC system allowing existing system architectures
- No refrigerant ignition observed when exposed to various automotive electrical ignition sources
- Risk assessment expected to show lower risk of fire due to refrigerant ignition compared to R1234yf

SK refrigerants have suitable properties to offer potential improvement in system performance

SK Refrigerants-PFAS

R494B and R4101A are PFAS-Free

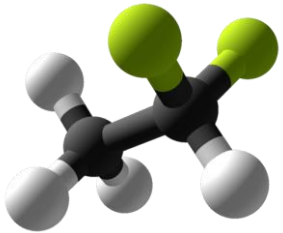
Definition of PFAS

EU&OECD : “Any substance that contains at least one fully fluorinated methyl (CF3-) or methylene (-CF2-) carbon atom without any H/Cl/Br/I attached to it.”

US State (Maine and Minnesota) : one fully fluorinated carbon molecule (includes HFOs and most other F-gases)

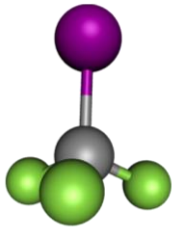
R-152a (Not PFAS)

Name : 1,1-Difluoroethane
Chemical Formula : $C_2H_4F_2$
CAS No. : 75-37-6



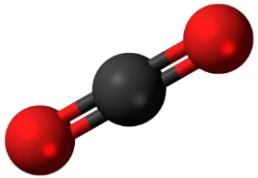
CF3I (Not PFAS)

Name : Trifluoroiodomethane
Chemical Formula : CF_3I
CAS No. : 2314-97-8



R-744 (Not PFAS)

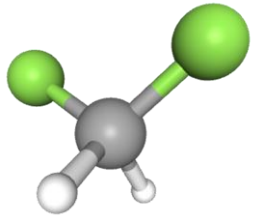
Name : Carbon Dioxide
Chemical Formula : CO_2
CAS No. : 124-38-9



Non-Fluorine

R-32 (Not PFAS)

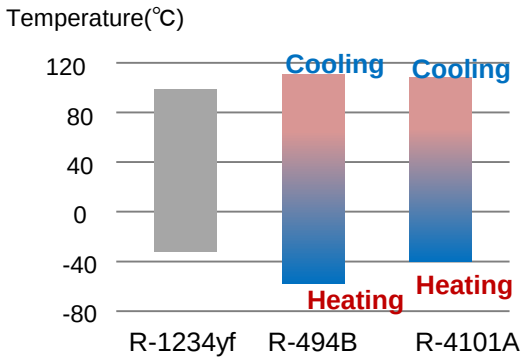
Name : Difluoromethane
Chemical Formula : CH_2F_2
CAS No. : 75-10-5



SK Refrigerants - Properties

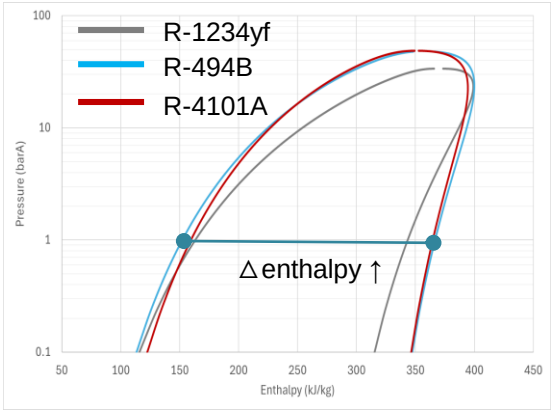
Designed properties for System Performance Improvement

Operating range



Extension of
heating operating range

Enthalpy properties



Extension of enthalpy range
(Lower mass flow rates for same capacity)

SK Refrigerants – thermodynamic performance simulation

Name	Class	GWP (AR4)	Cap Cooling	COP Cooling	Cap Heating	COP Heating	P_{disch}	Full Glide (K)	Evap. Glide (K)	Cond. Glide (K)
R-1234yf	A2L	<1	100%	100%	100%	100%	100%	0.0	0.0	0.0
R-494B	A2L	48	133%	107%	139%	113%	119%	17.6	4.9	12.8
R-4101A	A2L	113	139%	108%	150%	113%	120%	7.2	4.2	6.1

- Cooling: Tcd=55 ℃, Tev=-2 ℃, Subcooling:5 ℃, Superheat:10 ℃, Isentropic Eff: 70%
- Heating: Tcd=65 ℃, Tev=-30 ℃, Subcooling:5 ℃, Superheat:10 ℃, Isentropic Eff: 70%

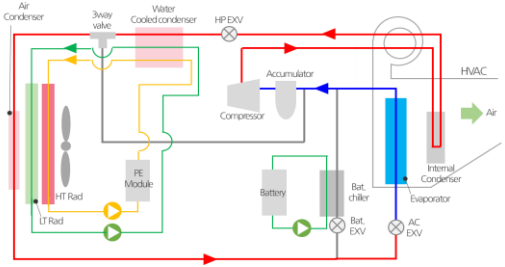
- R-494B and R-4101A show superior performance compared to R-1234yf
- Discharge pressure within 20% of R1234yf suggesting no change required in design of components

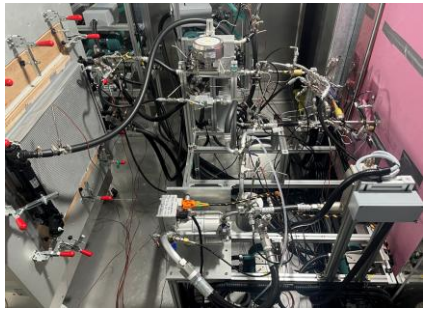
R494B and R4101A are expected to offer superior performance compared to R1234yf under drop-in conditions

System performance test- Hyundai ioniq5 model

Experimental environment

- Evaluation conducted at SK test bench
- System specimen : Hyundai ioniq5 heat pump system
- Except for the expansion valve and accumulator, all components from the Ioniq 5 system were used





	Outdoor conditions				Indoor conditions - Front				Indoor Total
Test Name	Ambient Temp	Vehicle Speed	HX Temp Air In	Max Air Velocity	HX Temp Air In	Relative Humidity[2]	Air Flow Rate	Target Temp at HX Air Off	Resulting Target Capacity - Front only
	[°C]	[km/h]	[°C]	[m/s]	[°C]	[%]	SCMH	[°C]	[kW]
Cooling	45	50	45	2.5	34	25	530	Match to R1234yf Max performance	Match to R1234yf Max performance
Heating -20	-20	50	-20	2.5	-20	U.C.	350		
Heating -7	-7	50	-7	2.5	5	U.C.	350		

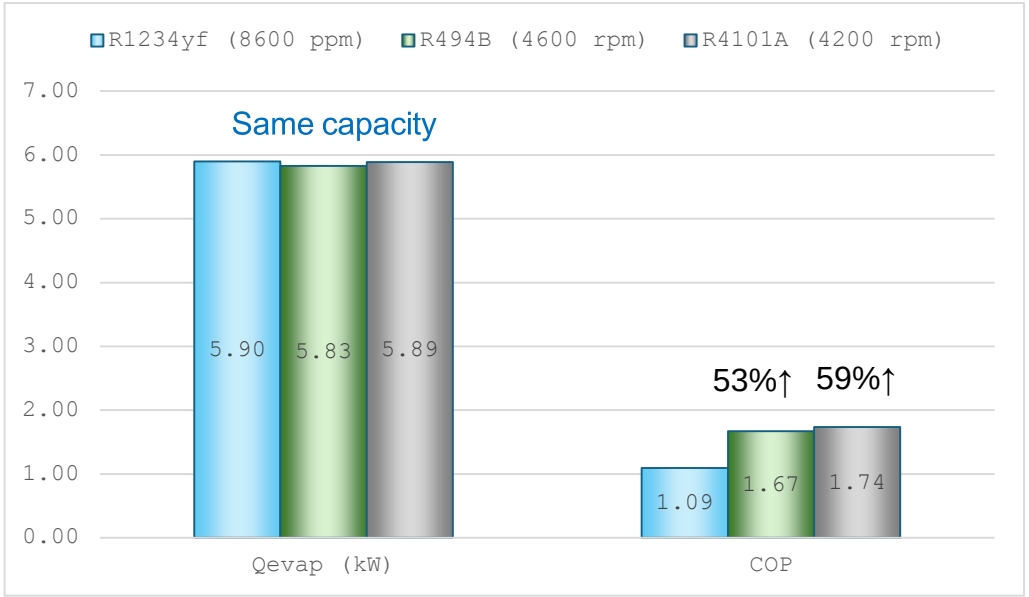
Item	Description	remark
Compressor	45cc E-comp	-
Evaporator	Flat tube microchannel & Fin	-
Inner condenser	Flat tube microchannel & Fin	-
Water condenser	Plate & Fin type	Dual coolant line
Air condenser	Flat tube microchannel & Fin	Subcooled section
Expansion valve for AC	Needle type EXV	-
Expansion valve for HP	Needle type EXV	-
Accumulator	1750cc	-
Refrigerants	R-1234yf (w/ POE oil) R-494B (w/ SK oil) R-4101A (w/ SK oil)	Ref. mass : 1200g Ref. mass : 1420g Ref. mass : 1450g

※ Oil mass is determined based on an oil circulation rate of 4-5%

Cooling Mode Performance (45°C)- Hyundai Ioniq 5

Improved cooling performance with R494B and R4101A

Ambient temperature (45℃)



Cooling Mode Analysis- Hyundai ioniq5 model

Test results

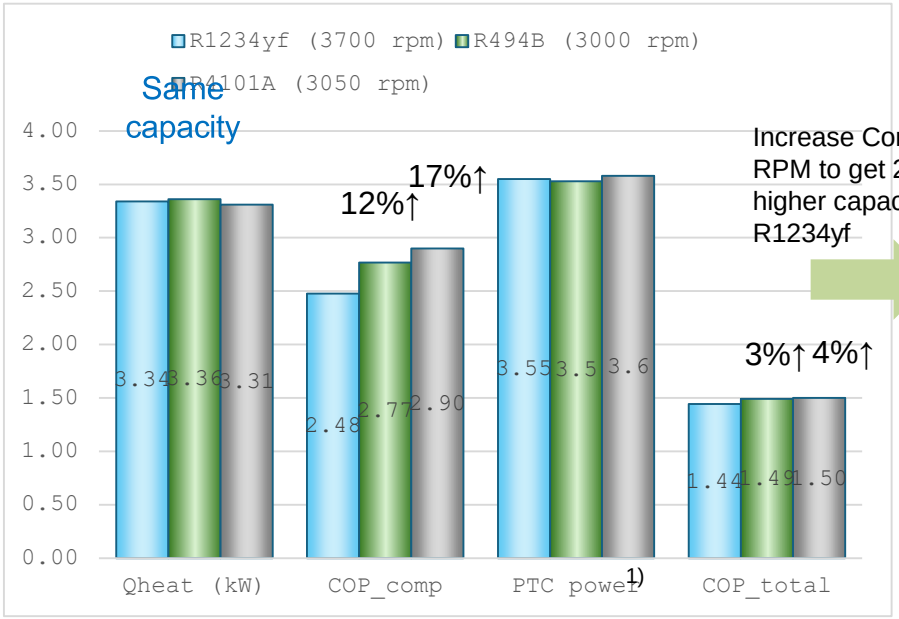
Refrigerant	Q-cooling	Evap. △enthalpy	Mass flow rate	Volumetric capacity	Comp. Speed	Comp. Work	Suction line T-sat. drop
	kW	kJ/kg	Kg/hr	kJ/m^3	RPM	kW	(℃)
R-1234yf	Match	109.6	203.3	960	8600	5.39	13.4
R-494B		139.7 (127%)	160.0 (79%)	1799 (187%)	4600 (53%)	3.49 (65%)	4.6 (34%)
R-4101A		140 (127%)	159.8 (79%)	1972 (205%)	4200 (49%)	3.39 (63%)	4.4 (33%)

- SK refrigerants show lower a mass flow rate and a higher volumetric capacity → Decrease compressor work
- They also have a lower saturation temperature drop in the suction line when used with the R-1234yf base system.

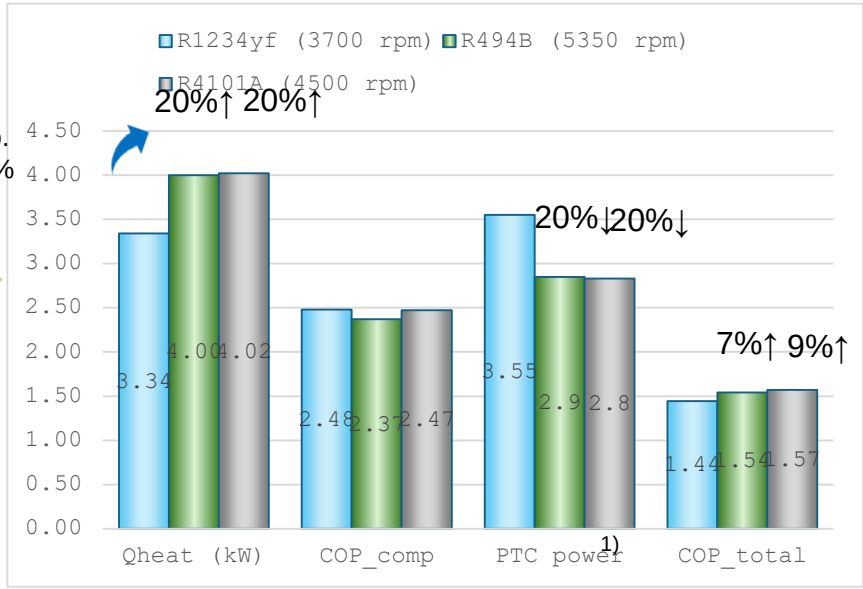
Heating Mode Performance (-7°C)- Hyundai Ioniq 5

Reduced heating power consumption through improved heating performance

Heating (-7°C)



Increase Comp. RPM to get 20% higher capacity R1234yf



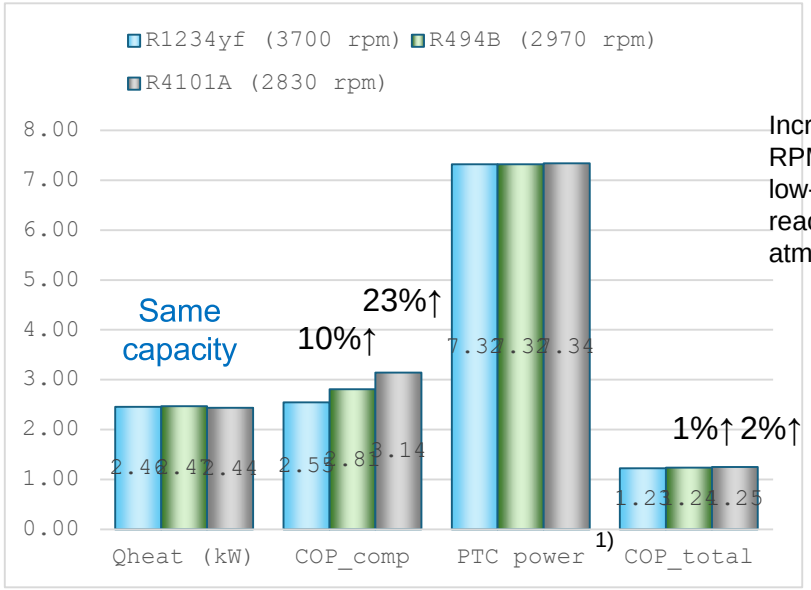
1) Total PTC power consumption for target discharge temperature of 50°C

Heating Mode Performance (-20°C)- Hyundai Ioniq 5

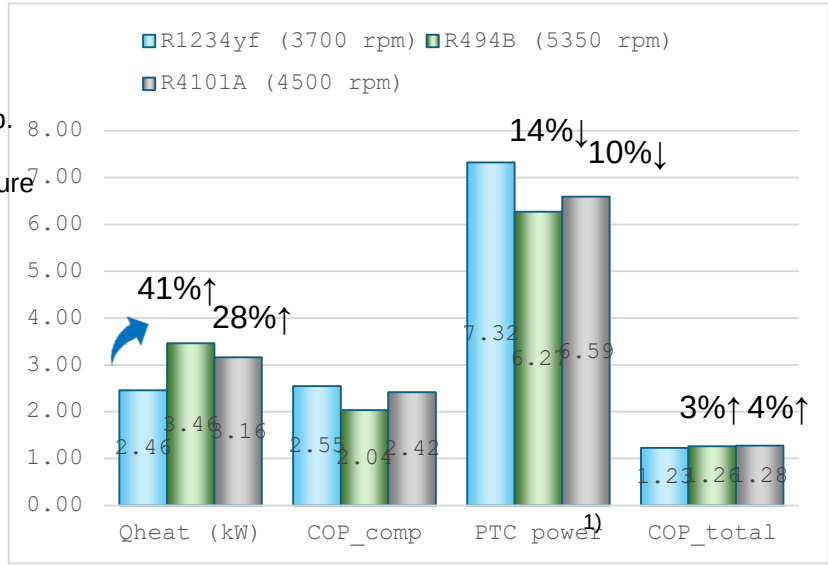
Heating mode

Reduced heating power consumption through improved heating performance

Heating (-20℃)



Increase Comp. RPM until the low-side pressure reaches atmospheric



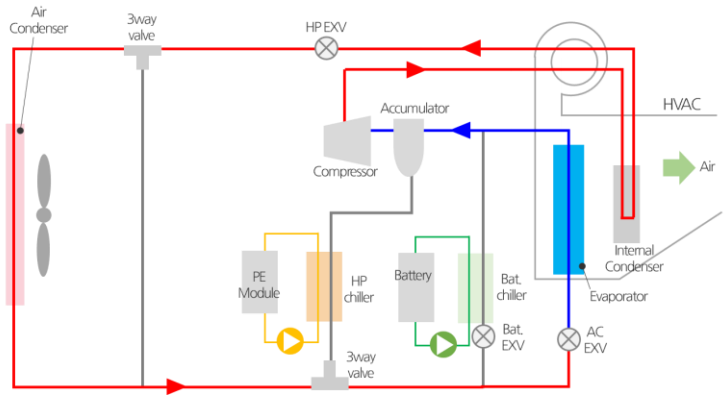
1) Total PTC power consumption for target discharge temperature of 60°C

System performance test- Hyundai KONA EV

Test equipment

- Evaluation conducted at Creative Thermal Solutions (CTS) (partner of SAE CRP)
- Test specimen : Hyundai KONA heat pump system and component.
- e-Compressor : Scroll type, 33cc volume

Heat pump schematic



Test conditions

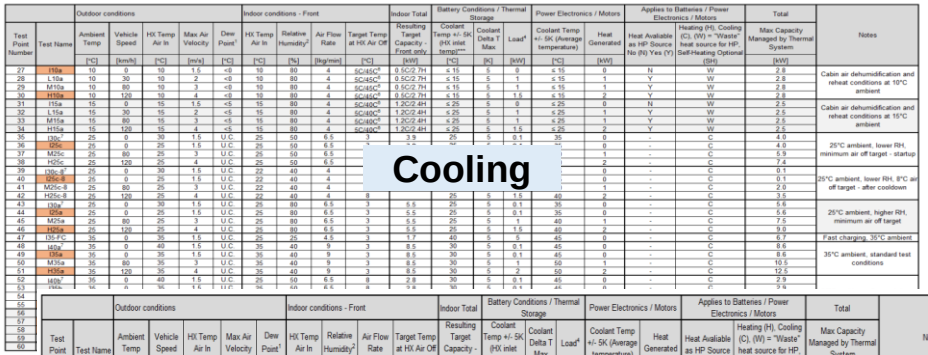
- SAE J 2765 Reduced Matrix
- Cooling and heating mode was conducted respectively

Item	Description	remark
Compressor	33cc E-comp	KONA EV
Evaporator	Flat tube microchannel & Fin	-
Inner condenser	Flat tube microchannel & Fin	-
Water condenser	Plate type	Inside the radiator tank
Air condenser	Flat tube microchannel & Fin	Down flow
Expansion valve for AC	Needle type EXV	-
Expansion valve for HP	Needle type EXV	-
Accumulator	1750cc	-
Refrigerants	R-1234yf (w/ POE oil) R-494B (w/ SK oil)	Ref. mass : 1675g Ref. mass : 2095g

※ Oil mass is determined based on an oil circulation rate of 3-4%

System performance test- Hyundai KONA EV

SAE J2765 Full test matrix



Test Point Number	Test Name	Outdoor conditions: Ambient Temp [°C]	Vehicle Speed [km/h]	HX Temp Air In [°C]	Max Air Velocity [m/s]	Dew Point[1] [°C]	Indoor conditions - Front: HX Temp Air In [°C]	Relative Humidity[2] [%]	Air Flow Rate [kg/min]	Target Temp at HX Air Off [°C]	Indoor Total: Resulting Target Capacity - Front only [kW]	Battery Conditions / Thermal Storage: Coolant Temp +/- 5K (HX inlet temp)*** [°C]	Coolant Delta T Max [K]	Load[4] [kW]	Power Electronics / Motors: Coolant Temp +/- 5K (Average temperature) [°C]	Heat Generated [kW]	Applies to Batteries / Power Electronics / Motors: Heat Available as HP Source No (N) Yes (Y)	Heating (H), Cooling (C), (W) = "Waste" heat source for HP, Self-Heating Optional (SH)	Total: Max Capacity Managed by Thermal System [kW]	Notes
27	I10a	10	0	10	1.5	<0	10	80	4	SC/4SC[3]	0.5C/2.7H	≤ 15	5	0	≤ 15	0	N	W	2.8	Cabin air dehumidification and reheat conditions at 10°C ambient
28	L10a	10	30	10	2	<0	10	80	4	SC/4SC[3]	0.5C/2.7H	≤ 15	5	1	≤ 15	1	Y	W	2.8	
29	M10a	10	80	10	3	<0	10	80	4	SC/4SC[3]	0.5C/2.7H	≤ 15	5	1	≤ 15	1	Y	W	2.8	
30	H10a	10	120	10	4	<0	10	80	4	SC/4SC[3]	0.5C/2.7H	≤ 15	5	1.5	≤ 15	2	Y	W	2.8	
31	I15a	15	0	15	1.5	<5	15	80	4	SC/4SC[3]	1.2C/2.4H	≤ 25	5	0	≤ 25	0	N	W	2.5	Cabin air dehumidification and reheat conditions at 15°C ambient
32	L15a	15	30	15	2	<5	15	80	4	SC/4SC[3]	1.2C/2.4H	≤ 25	5	1	≤ 25	1	Y	W	2.5	
33	M15a	15	80	15	3	<5	15	80	4	SC/4SC[3]	1.2C/2.4H	≤ 25	5	1	≤ 25	1	Y	W	2.5	
34	H15a	15	120	15	4	<5	15	80	4	SC/4SC[3]	1.2C/2.4H	≤ 25	5	1.5	≤ 25	2	Y	W	2.5	
35	I30c	25	0	30	1.5	U.C.	25	50	6.5	3	3.3	25	5	0.1	35	0	-	C	4.0	25°C ambient, lower RH, minimum air off target - startup
36	I25c	25	0	25	1.5	U.C.	25	50	6.5	3	3.3	25	5	0.1	35	0	-	C	4.0	
37	M25c	25	80	25	3	U.C.	25	50	6.5	3	3.3	25	5	1	40	1	-	C	5.9	
38	H25c	25	120	25	4	U.C.	25	50	6.5	3	3.3	25	5	1.5	40	2	-	C	7.4	
39	I20c-8	25	0	30	1.5	U.C.	22	40	4	8	2.2	25	5	0.1	35	0	-	C	0.1	25°C ambient, lower RH, 8°C air off target - after cooldown
40	I25c-8	25	0	25	1.5	U.C.	22	40	4	8	2.2	25	5	0.1	35	0	-	C	0.1	
41	M25c-8	25	80	25	3	U.C.	22	40	4	8	2.2	25	5	1	40	1	-	C	2.0	
42	H25c-8	25	120	25	4	U.C.	22	40	4	8	2.2	25	5	1.5	40	2	-	C	3.5	
43	I30a[5]	25	0	30	1.5	U.C.	25	80	6.5	3	5.5	25	5	0.1	35	0	-	C	5.6	25°C ambient, higher RH, minimum air off target
44	I25a	25	0	25	1.5	U.C.	25	80	6.5	3	5.5	25	5	0.1	35	0	-	C	5.6	
45	M25a	25	80	25	3	U.C.	25	80	6.5	3	5.5	25	5	1	40	1	-	C	7.5	
46	H25a	25	120	25	4	U.C.	25	80	6.5	3	5.5	25	5	1.5	40	2	-	C	9.0	
47	I35-FC	35	0	35	1.5	U.C.	25	25	4.5	3	1.7	40	5	5	45	0	-	C	9.7	Fast charging, 35°C ambient
48	I40a[5]	35	0	40	1.5	U.C.	35	40	9	3	8.5	30	5	0.1	45	0	-	C	8.6	35°C ambient, standard test conditions
49	I35a	35	0	35	1.5	U.C.	35	40	9	3	8.5	30	5	0.1	45	0	-	C	8.6	
50	M35a	35	80	35	3	U.C.	35	40	9	3	8.5	30	5	1	50	1	-	C	10.5	
51	H35a	35	120	35	4	U.C.	35	40	9	3	8.5	30	5	2	50	2	-	C	12.5	
52	I40b	35	0	40	1.5	U.C.	35	50	6.5	8	2.9	30	5	0.1	45	0	-	C	2.9	
53	I40c	40	0	40	1.5	U.C.	40	60	6.5	8	2.9	30	5	0.1	45	0	-	C	2.9	
54																				
55																				
56																				
57																				
58																				
59																				
60																				

Cooling

Test Point Number	Test Name	Outdoor conditions: Ambient Temp [°C]	Vehicle Speed [km/h]	HX Temp Air In [°C]	Max Air Velocity [m/s]	Dew Point[1] [°C]	Indoor conditions - Front: HX Temp Air In [°C]	Relative Humidity[2] [%]	Air Flow Rate [kg/min]	Target Temp at HX Air Off [°C]	Indoor Total: Resulting Target Capacity - Front only [kW]	Battery Conditions / Thermal Storage: Coolant Temp +/- 5K (HX inlet temp)*** [°C]	Coolant Delta T Max [K]	Load[4] [kW]	Power Electronics / Motors: Coolant Temp +/- 5K (Average temperature) [°C]	Heat Generated [kW]	Applies to Batteries / Power Electronics / Motors: Heat Available as HP Source No (N) Yes (Y)	Heating (H), Cooling (C), (W) = "Waste" heat source for HP, Self-Heating Optional (SH)	Total: Max Capacity Managed by Thermal System [kW]	Notes
	I-40a[3]	-40	0	-40	1.5	<-50	-5	U.C.	5.5	55	5.5	≤ -20	5.0	1.5	≤ -20	0	N	H	7.0	Heating passenger compartment and batteries at severe ambient
	M-40a[3]	-40	80	-40	3	<-50	-5	U.C.	5.5	55	5.5	≤ -20	5.0	1.5	≤ -20	0	N	H	7.0	
	H-40a[3]	-40	120	-40	4	<-50	-5	U.C.	5.5	55	5.5	≤ -20	5.0	1.5	≤ -20	0	N	H	7.0	
1	I-30a	-30	0	-30	1.5	<-40	-30	U.C.	4	55	5.7	≤ -20	5.0	1.5	≤ -20	0	N	H	7.2	-30°C startup
2	M-30a	-30	80	-30	3	<-40	-30	U.C.	4	55	5.7	≤ -20	5.0	1.5	≤ -20	0	N	H	7.2	
3	H-30a	-30	120	-30	4	<-40	-30	U.C.	4	55	5.7	≤ -20	5.0	1.5	≤ -20	0	N	H	7.2	
4	I-20a	-20	0	-20	1.5	<-30	-20	U.C.	5.5	55	6.9	U.C.	U.C.	0	≤ -10	0	N	SH	6.9	-20°C startup
5	M-20a	-20	80	-20	3	<-30	-20	U.C.	5.5	55	6.9	U.C.	U.C.	0	≤ -10	0	N	SH	6.9	
6	I-20b	-20	0	-20	1.5	<-30	0	U.C.	4	55	3.7	U.C.	U.C.	0	≤ 0	0	N	SH	3.7	-20°C after partial warmup
7	M-20b	-20	80	-20	3	<-30	0	U.C.	4	55	3.7	U.C.	U.C.	0	≤ 0	0.5	Y	SH	3.7	
8	H-20b	-20	120	-20	4	<-30	0	U.C.	4	55	3.7	U.C.	U.C.	0	≤ 0	1	Y	SH	3.7	
9	I-20c	-20	0	-20	1.5	<-30	10	U.C.	4	55	3.0	U.C.	U.C.	0	≤ 10	0	N	SH	3.0	-20°C after full warmup or immediately following charge
10	L-20c	-20	30	-20	2	<-30	10	U.C.	4						≤ 10	0	N	SH	3.0	
11	M-20c	-20	80	-20	3	<-30	10	U.C.	4						≤ 10	0.5	Y	SH	3.0	
12	H-20c	-20	120	-20	4	<-30	10	U.C.	4						≤ 10	1	Y	SH	3.0	
13	I-10a	-10	0	-10	1.5	<-20	-10	U.C.	5.5						≤ -5	0	N	SH	6.0	-10°C startup
14	M-10a	-10	80	-10	3	<-20	-10	U.C.	5.5	55	6.0	U.C.	U.C.	0	≤ -5	0.5	Y	SH	6.0	
15	I-10b	-10	0	-10	1.5	<-20	5	U.C.	4	55	3.4	U.C.	U.C.	0	≤ 5	0	N	SH	3.4	-10°C after partial warmup
16	M-10b	-10	80	-10	3	<-20	5	U.C.	4	55	3.4	U.C.	U.C.	0	≤ 5	0.5	Y	SH	3.4	
17	H-10b	-10	120	-10	4	<-20	5	U.C.	4	55	3.4	U.C.	U.C.	0	≤ 5	1.5	Y	SH	3.4	
18	I-10c	-10	0	-10	1.5	<-20	15	U.C.	4	55	2.7	U.C.	U.C.	0	≤ 20	0	N	SH	2.7	-10°C after full warmup or immediately following charge
19	L-10c	-10	30	-10	2	<-20	15	U.C.	4	55	2.7	U.C.	U.C.	0	≤ 20	0.5	Y	SH	2.7	
20	M-10c	-10	80	-10	3	<-20	15	U.C.	4	55	2.7	U.C.	U.C.	0	≤ 20	0.5	Y	SH	2.7	
21	H-10c	-10	120	-10	4	<-20	15	U.C.	4	55	2.7	U.C.	U.C.	0	≤ 20	1.5	Y	SH	2.7	
22	I0a	0	0	0	1.5	<-10	0	U.C.	5.5	55	5.1	U.C.	U.C.	0	≤ 5	0	N	SH	5.1	0°C startup
23	M0a	0	80	0	3	<-10	0	U.C.	5.5	55	5.1	U.C.	U.C.	0	≤ 5	1	Y	SH	5.1	
24	I0b	0	0	0	1.5	<-10	10	U.C.	4	55	3.0	U.C.	U.C.	0	≤ 10	0	N	SH	3.0	0°C after partial warmup or immediately following charge
25	M0b	0	80	0	3	<-10	10	U.C.	4	55	3.0	U.C.	U.C.	0	≤ 10	1	Y	SH	3.0	
26	H0b	0	120	0	4	<-10	10	U.C.	4	55	3.0	U.C.	U.C.	0	≤ 10	2	Y	SH	3.0	

Heating

Reduced test matrix

System performance test- Hyundai KONA EV

Reduced test matrix

Cooling (11 conditions)

No.	Test Name	Outdoor		indoor			Bat.
		Amb. Temp	Veh. speed	HX Temp Air in	RH	Target Temp. HX Air Out	Target Load
		℃	Km/h	℃	%	℃	kW
1	I10a	10	0	10	80	5C/45C	0
2	H10a	10	120	10	80	5C/45C	1.5
3	I25c	25	0	25	50	3	0.1
4	I25c-8	25	0	22	40	8	0.1
5	I25a	25	0	25	80	3	0.1
6	H25a	25	120	25	80	3	1.5
7	I35a	35	0	35	40	3	0.1
8	H35a	35	120	35	40	3	2
9	H35b	35	120	25	50	8	2
10	I45	45	0	35	25	3	0.1
11	M45	45	80	35	25	3	1

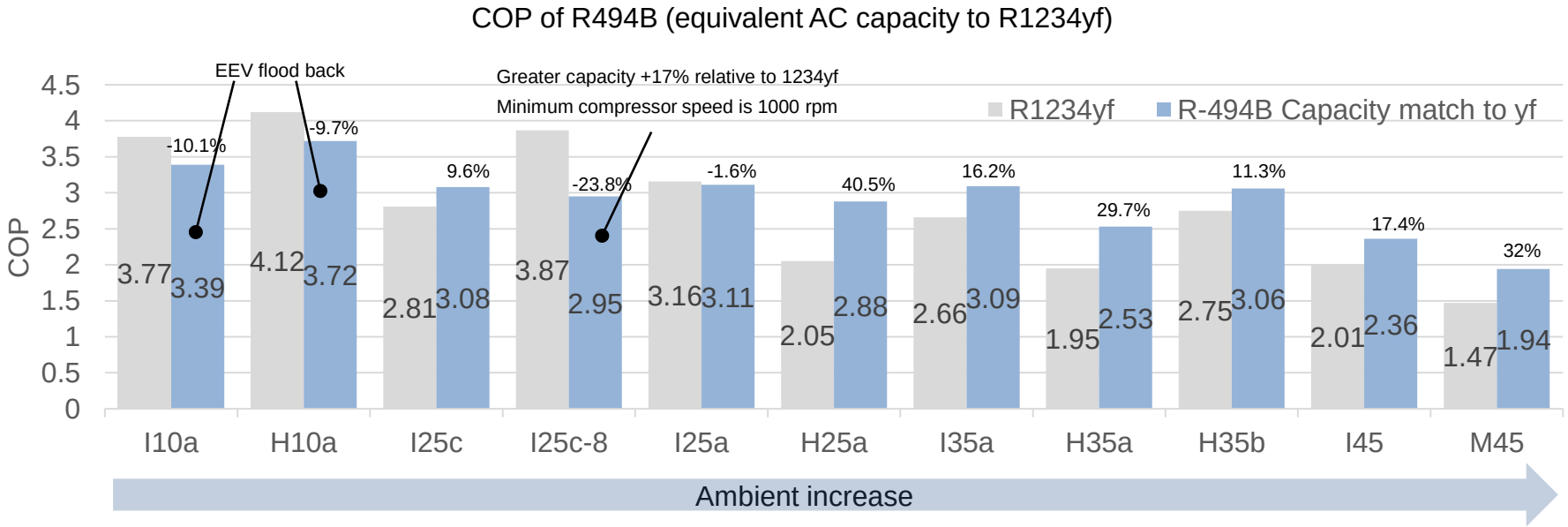
Heating (9 conditions)

No.	Test Name	Outdoor		indoor		
		Amb. Temp	Veh. speed	HX Temp Air in	RH	Target Temp. HX Air Out
		℃	Km/h	℃	%	℃
1	M-20a	-20	80	-20	-	55
2	I-20c	-20	0	10	-	55
3	H-20c	-20	120	10	-	55
4	M-10a	-10	80	-10	-	55
5	I-10c	10	0	15	-	55
6	H-10c	-10	120	15	-	55
7	M0a	0	0	0	-	55
8	I0b	0	0	10	-	55
9	H0b	0	120	10	-	55

System performance test- Hyundai KONA EV model

Cooling test results

Improves COP at the same AC capacity as R1234yf.



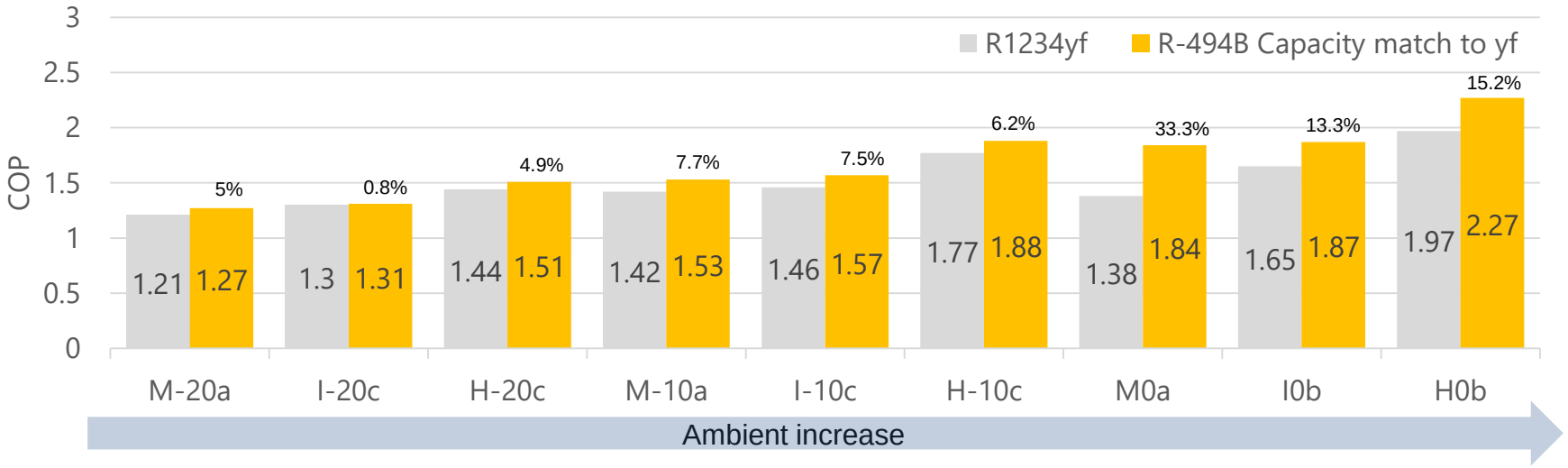
System performance test- Hyundai KONA EV model

Heating test results

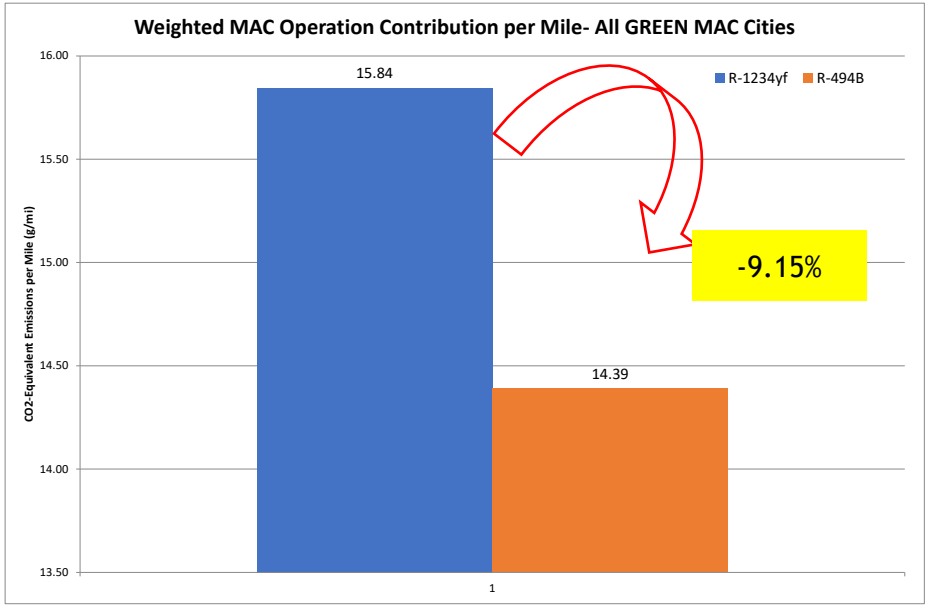
Achieves higher heating capacity than R1234yf in HP mode.

Reduces COP for heating at the same heating capacity as R1234yf.

COP of R494B (equivalent AC capacity to R1234yf)



Weighted MAC Operation Contribution per Mile-All GREEN MAC Cities



All GREEN MAC Cities	
R-1234yf	15.84
R-494B	14.39

GREEN MAC Cities(11) : Boston, Chicago, Fargo, Houston, Los. Angeles, Miami, Phoenix, San. Francisco, Sacramento, San. Diego, WDC

SK Oil solution for Stability

SK Oil has been developed for stability of refrigerant and system.

Reactivity

R-494B	R-4101A
CF3I / R-152a / R-744	CF3I / R-152a / R-32

At high temperatures (>130 ℃), CF3I can decompose to generate by-products which can lead to metal corrosion

Countermeasure

ASHRAE 97 results

14 days at 150℃

		Ref. Oil For R-1234yf	SK oil solution (Oil + additives)
Sludge formation		Solidified	No
TAN (mgKOH/g)	Initial	<0.1	<0.1
	Final	6.5	<0.1

Compressor durability test

Stability verification under compressor operating condition (High Temp.)

Ref. and oil	R-494B, SK oil solution
Test location	Korea Automotive Technology Institute
Compressor	KONA EV 33cc E-comp
Schedule	By mid-November

Conclusion

Regulation	Compliant with GWP and PFAS environmental regulations
Toxicity Flammability	R-494B,R-4101A ASHRAE A2L Approval (Not flammable in nominal composition and WCF[1)] condition)
System compatibility	Operational compatibility confirmed in Kona EV and Ioniq 5 Long-term compressor durability testing in progress
Performance enhancement	Improved cooling and heating performance for HP system with R1234yf

R494B and R4101A offer low GWP and non PFAS alternatives for automotive applications

Thank you