Performance Evaluation and Optimization of Lower GWP Refrigerants in a Residential Heat Pump

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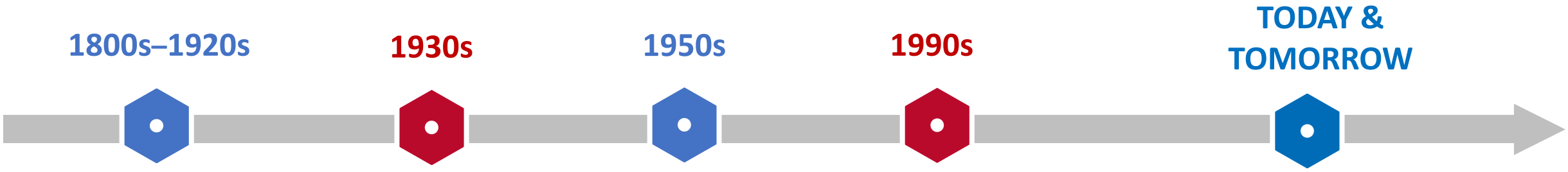
Outline

- Refrigerant change background
- Project Overview
- Chemical Comparison
- Thermodynamic Cycle models
- Test setup and performance testing
- Thermal Stability
- Conclusions and Future Work

Refrigerant Technology Evolution



Industrial Chemicals
(Methyl Chloride, Ammonia, CO2, etc.)

CFCs
(R-12)
Chlorine
Single Bond

High ODP
Highest GWP

HCFCs
(R-22)
Less Chlorine
Single Bond

Lower ODP
High GWP

HFCs
(R-410A)
No Chlorine
Single Bond

No ODP
High GWP

Industrial Chemicals
(CO2, Hydrocarbons, Ammonia)

+

HFOs and HFO Blends
(R-1234yf, R-449A, R-513A, R-454B, etc.)
No Chlorine
Double Bond

No ODP
Very Low GWP

Montreal Protocol

Kigali Agreement

Refrigerant Properties and System Details

Physical and chemical properties, thermal stability, thermodynamic cycle models

Physical and Chemical Properties

	R-410A	R-454B	R-454A	R-454C
Components	R-32/R-125	R-32/R-1234yf	R-32/R-1234yf	R-32/R-1234yf
Composition	50.0/50.0	68.9/31.1	35.0/65.0	21.5/78.5
Molecular Weight	72.59	62.61	80.47	90.78
Normal Boiling Point, °C	-51.36	-49.49	-42.16	-37.75
Sat Vap Pres (kPa) @ 20C	1443	1323	1012	847
Sat Vap Pres (kPa) @ 60C	3834	3541	2793	2368
Critical Temperature, °C	71.3	78.1	81.7	85.7
GWP, AR4 (AR5)	2088 (1924)	465 (467)	239 (238)	148 (146)

Thermodynamic Cycle Models – Air Conditioning

Fluid	R-410A	R-454B	R-454A	R-454C
GWP, AR4 (AR5)	2088 (1924)	465 (467)	239 (238)	148 (146)
Capacity vs. R-410A	-	-4%	-23%	-33%
COP vs. R-410A	-	2%	3%	5%
Evap Glide [K]	0.1	1.1	4.7	6.1
T, Dis [C]	81	87	77	73
P, Dis [kPa]	2801	2615	2131	1842

Air conditioning cycle model conditions

- 10°C evaporator, 9.1 K superheat
- 46.1 °C condenser, 8.3K subcooling
- 70% compressor isentropic efficiency

Can account for lower capacity via system optimization

Thermodynamic Cycle Models – Heating

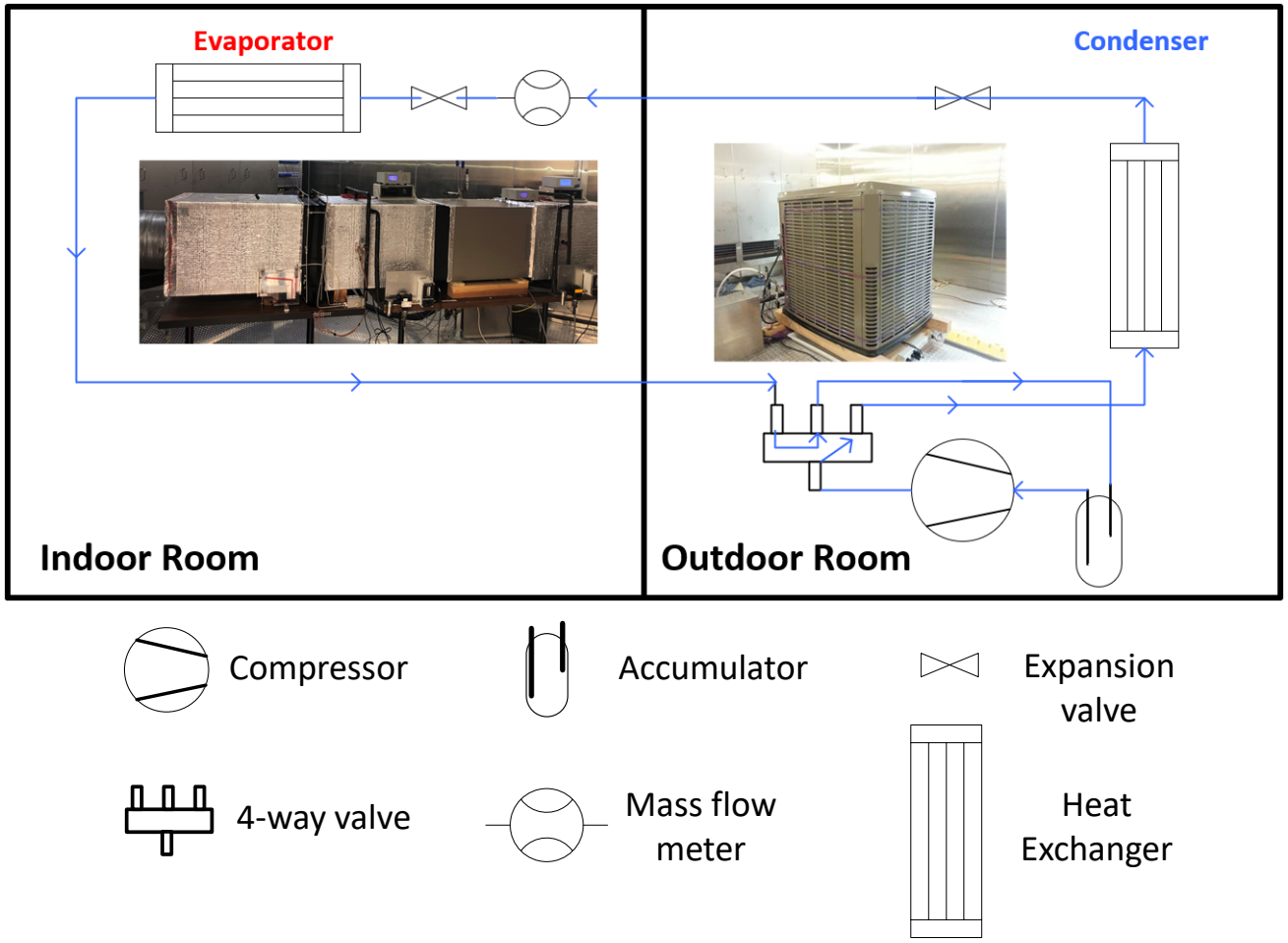
Fluid	R-410A	R-454B	R-454A	R-454C
GWP, AR4 (AR5)	2088 (1924)	465 (467)	239 (238)	148 (146)
Capacity vs. R-410A	-	-1%	-24%	-36%
COP vs. R-410A	-	4%	3%	4%
Evap Glide [K]	0.1	1.0	4.0	4.7
T, Dis [C]	102	111	95	88
P, Dis [kPa]	3435	3207	2615	2261

Heating cycle model conditions

- 0°C evaporator, 10.0 K superheat
- 55.0 °C condenser, 3.0K subcooling
- 70% compressor isentropic efficiency

Can account for lower capacity via system optimization

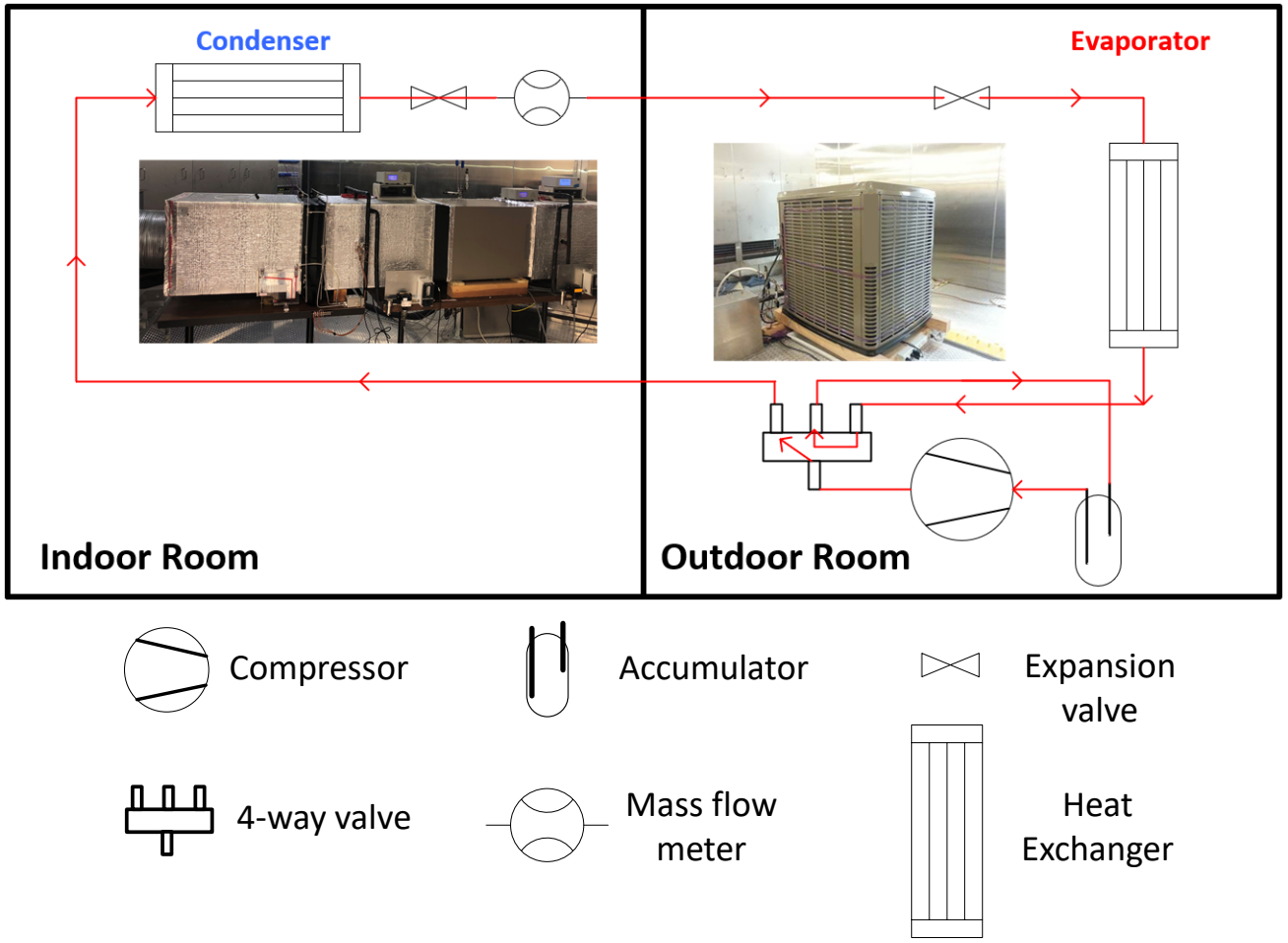
Experimental Setup – Air Conditioning



Residential R-410A Heat Pump

- 8.79kW, 16 SEER ducted split system
- Originally had a single speed compressor
- Replaced with comparable variable speed compressor
- Performance evaluations following ASHRAE Standard 37 and AHRI 210/240
- EEV superheat control
- Dual environmental chambers for maintaining test conditions from ANSI/AHRI Standard 210/240 – 2023 and ISO Standard 5151-2017

Experimental Setup – Heating



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Test Conditions

AC/ Heating	Test Condition	Compressor Speed	Refrigerants	IR DBT [°C]	IR WBT [°C]	OR DBT [°C]	OR WBT [°C]
Air conditioning	Cooling B*	3600 RPM	R-410A, R-454A, R-454C	26.7	19.4	17.8	18.3
Air conditioning	Cooling B*	Matched Capacity	R-454A, R-454C	26.7	19.4	17.8	18.3
Air conditioning	Cooling A*	3600 RPM	R-410A, R-454A, R-454C	26.7	19.4	35.0	23.9
Air conditioning	Cooling A*	Matched Capacity	R-454A, R-454C	26.7	19.4	35.0	23.9
Air conditioning	ISO T3**	3600 RPM	R-410A, R-454A, R-454C	29.0	19.0	46.0	24.0
Air conditioning	ISO T3**	Matched Capacity	R-454A, R-454C	29.0	19.0	46.0	24.0
Heating	H1*	3600 RPM	R-410A, R-454A, R-454C	21.1	15.6	8.3	6.1
Heating	H1*	Matched Capacity	R-454A, R-454C	21.1	15.6	8.3	6.1
Heating	H3*	3600 RPM	R-410A, R-454A, R-454C	21.1	15.6	-8.3	-9.4
Heating	H3*	Matched Capacity	R-454A, R-454C	21.1	15.6	-8.3	-9.4

*ANSI/AHRI 210/240-2023

**ISO Standard 5151-2017

Refrigerant Charge Optimization

Refrigerant	Optimized Charge [kg]	Relative to R-410A [%]	Optimized Charge [kg]	Relative to R-410A [%]	Estimated Charge [kg]	Relative to R-410A
R-410A	5.22	0%	5.22	0%	*5.22*	*0%*
R-454A	4.99	-4%	4.76	-9%	*5.02*	*-4%*
R-454C	5.67	9%	5.22	0%	*5.12*	*-2%*

Estimated charge determined via equivalent refrigerant volume

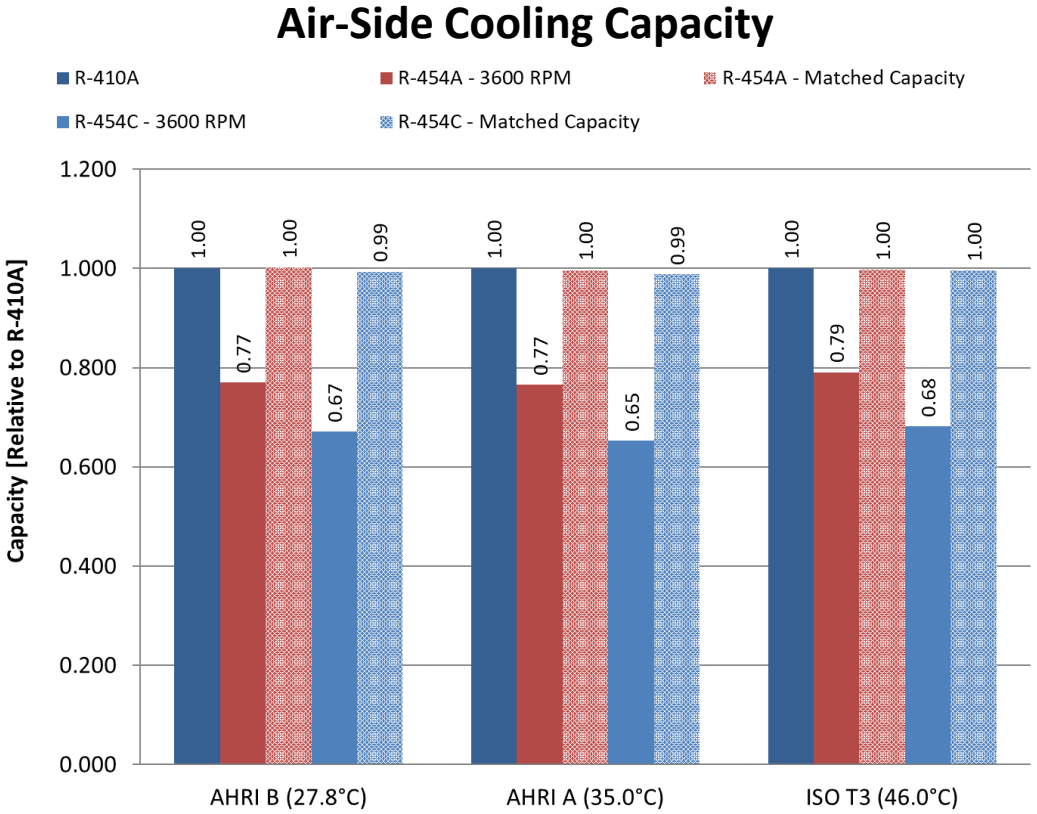
Lower optimized refrigerant charges in heating vs. cooling modes

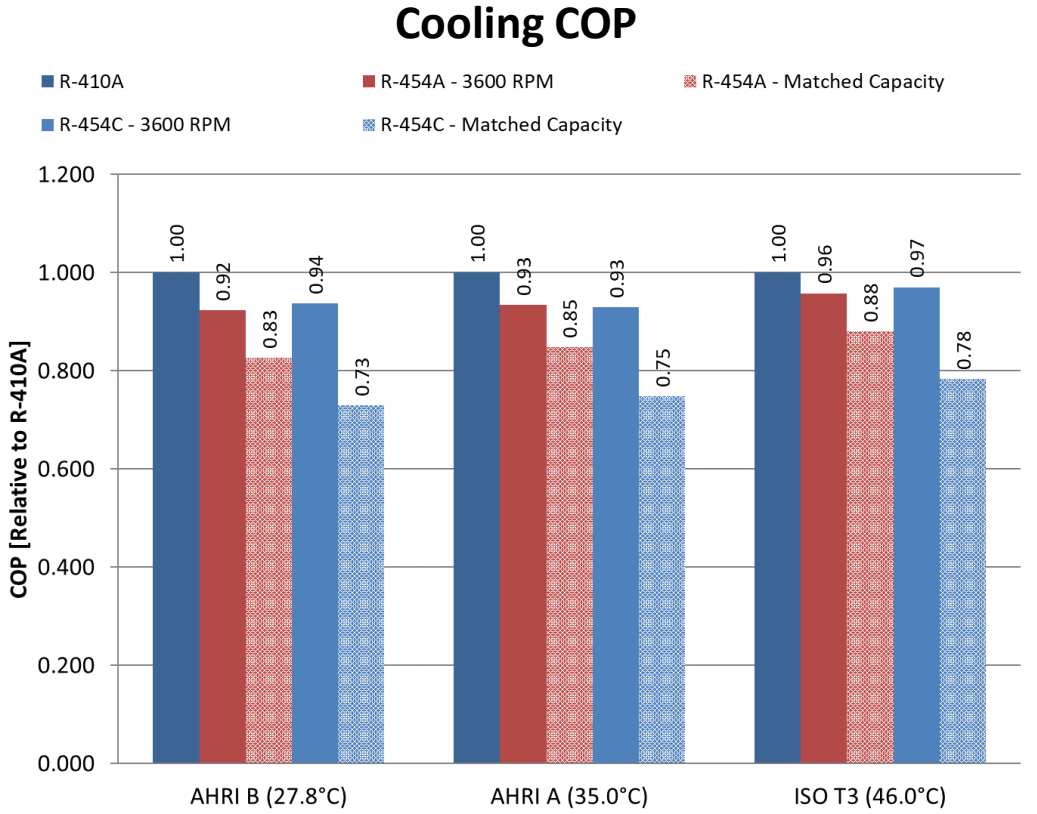
R-454C charge in cooling was about 11% higher than expected charge

Optimized charge for COP at the *Matched Capacity* conditions

Air Conditioning

Air-Side Capacity and COP





3600 RPM (60 Hz) testing was similar to thermodynamic models

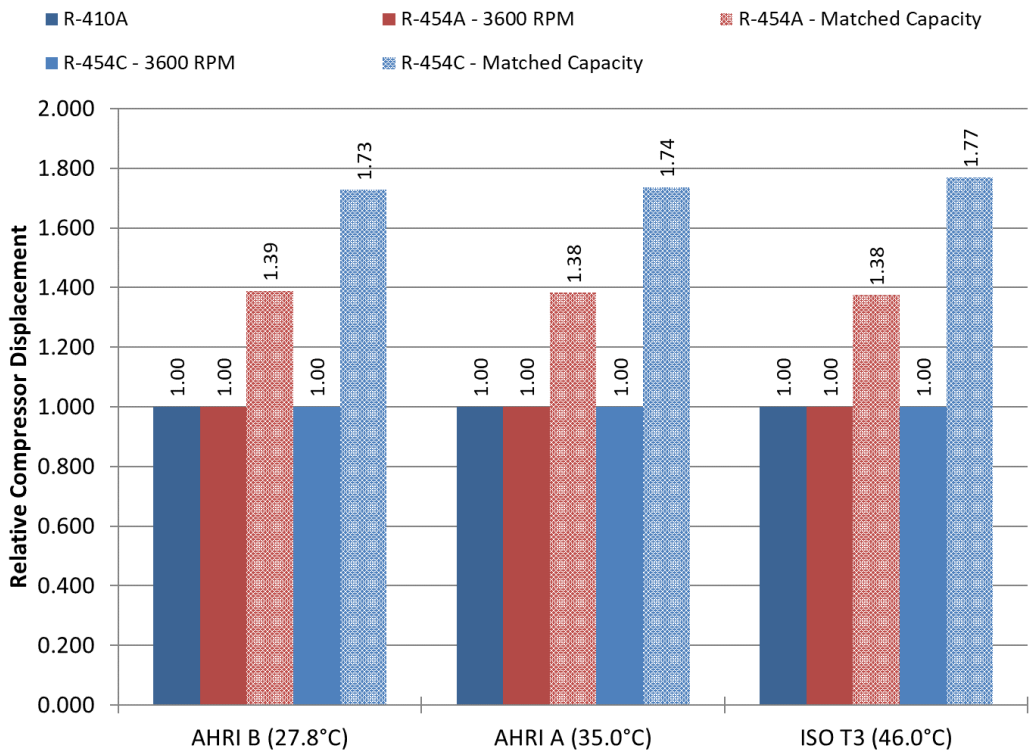
Can achieve similar capacities with increased compressor speeds

Lower COPs at higher compressor speeds

R-410A compressor displacement, higher refrigerant charge (for R-454C)

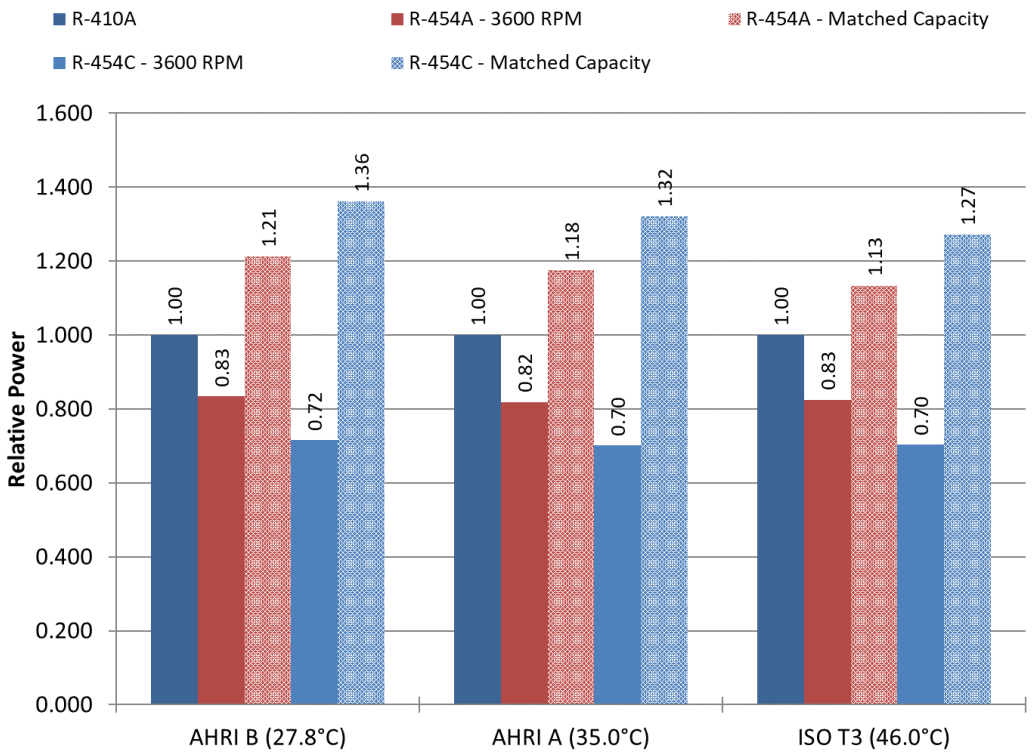
Compressor Displacement and Power Consumption

Compressor Displacement



Compressor displacement increases resulted in higher power consumption

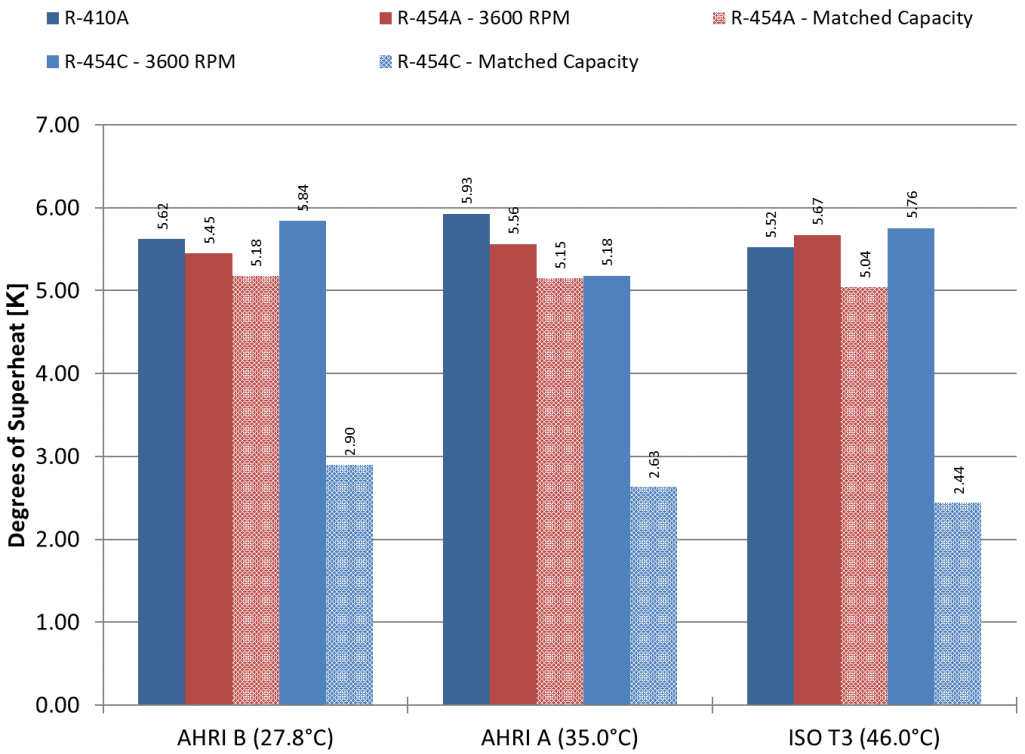
Power Consumption



Lower power consumption for R-454A and R-454C when operating at 3600 RPM

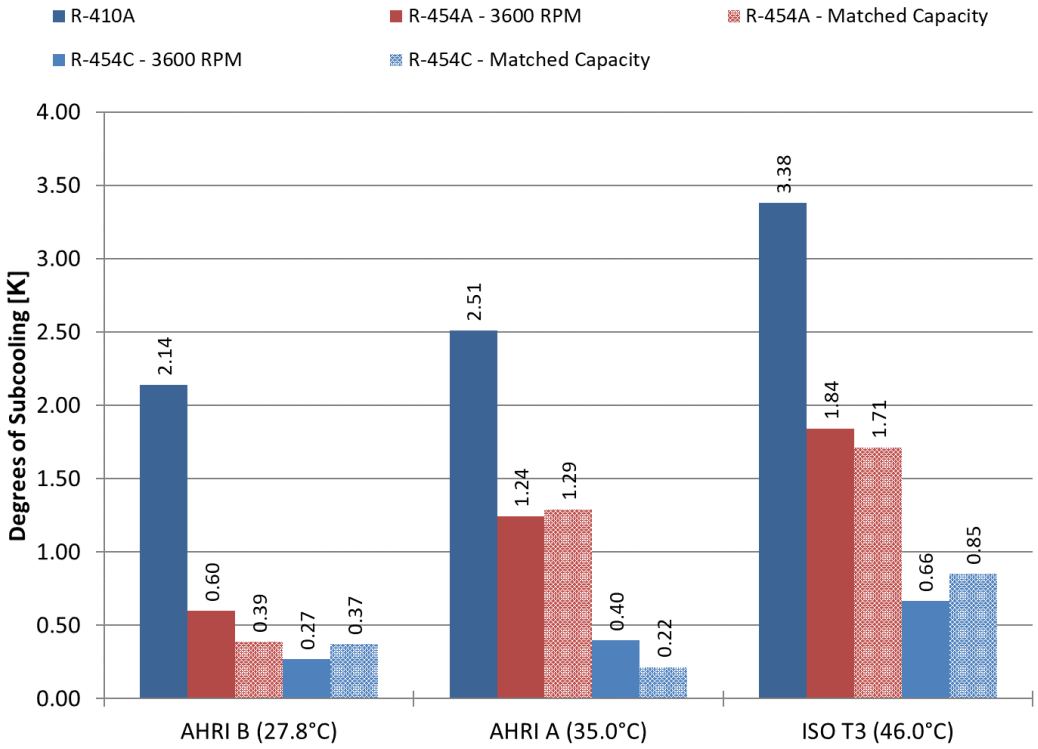
Evaporator Superheat and Subcooling

Evaporator Superheat



Adjusted superheat in *Matched Capacity* test to adjust evaporator temperatures

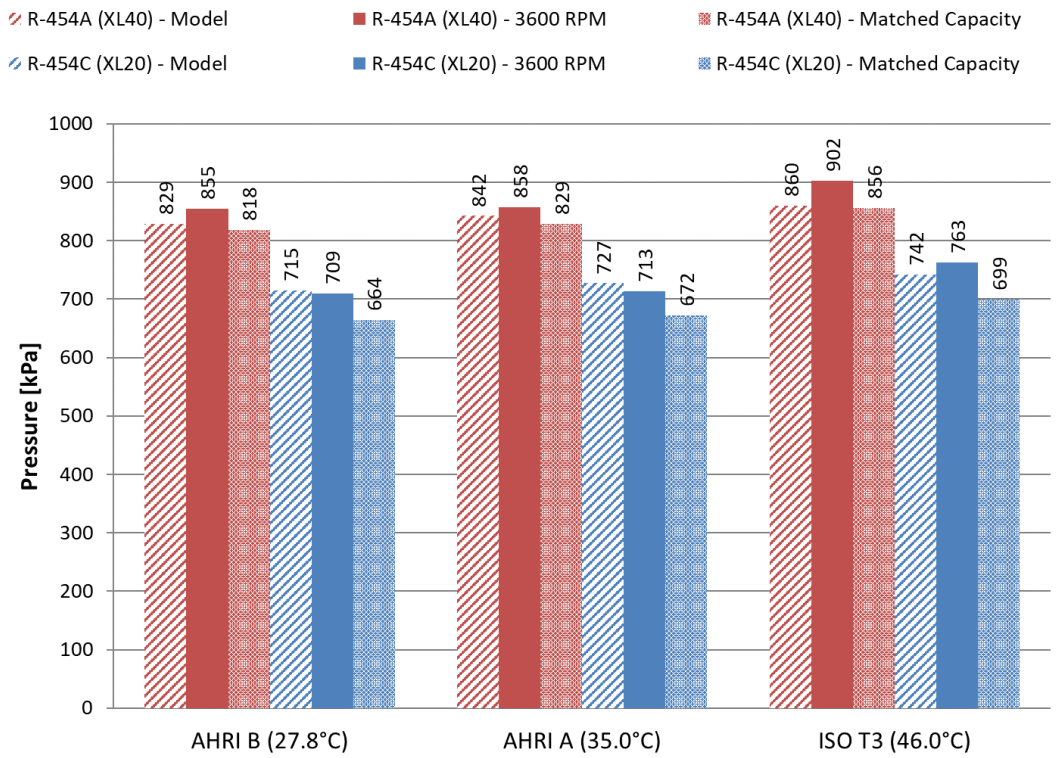
Amount of Subcooling



Low subcooling for R-454C and higher refrigerant charge than predicted (unchanged heat exchangers)

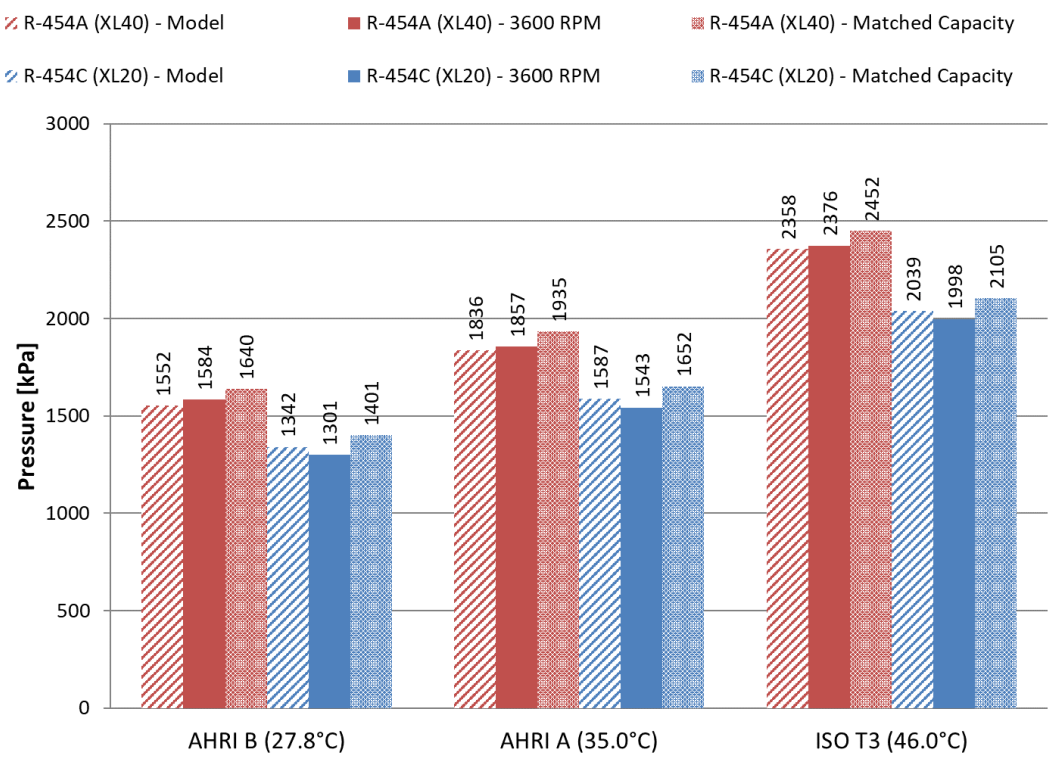
Operating Pressures – Air Conditioning

Evaporator Pressure



Different superheat between 3600 RPM and Matched Capacity tests

Condenser Pressure

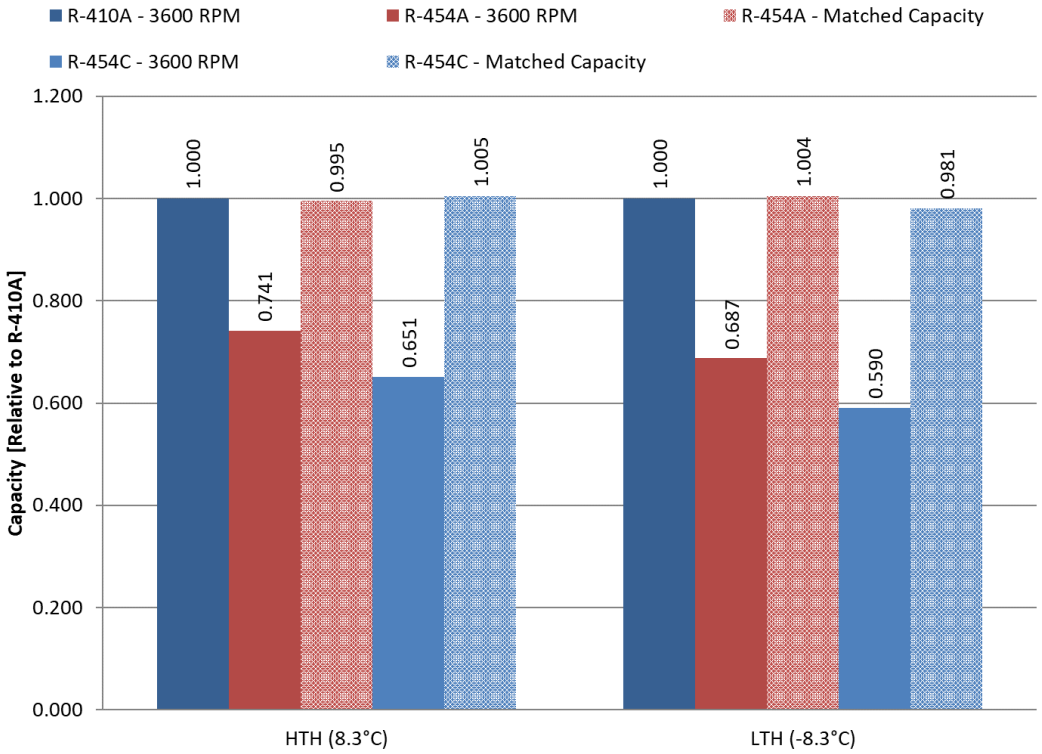


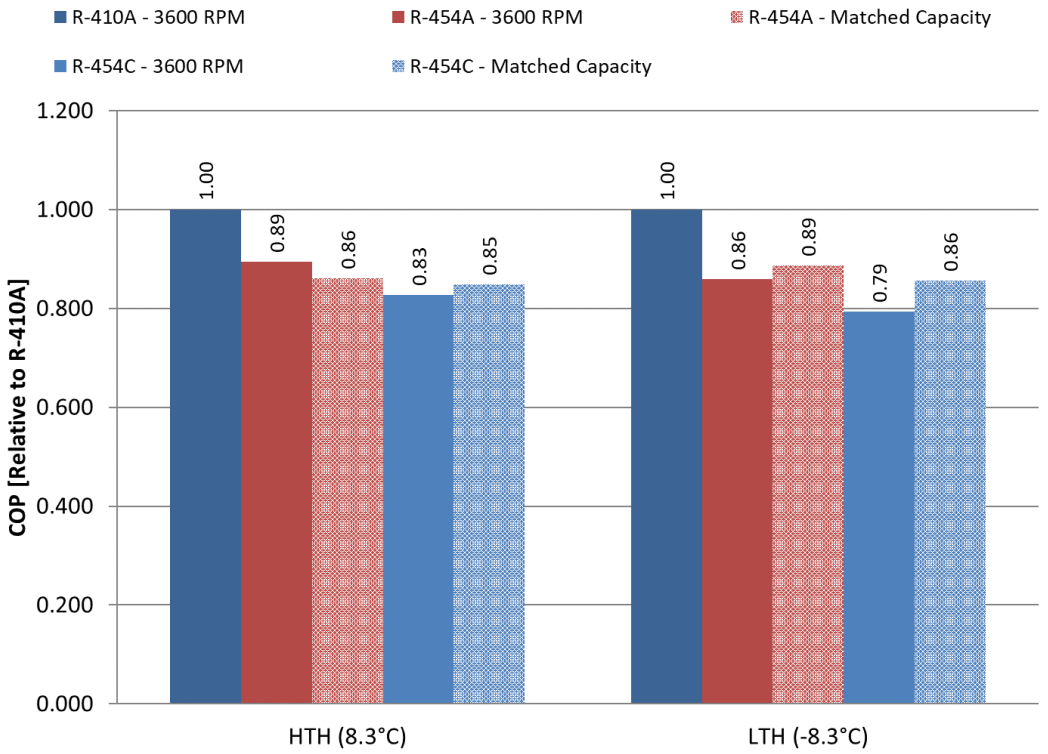
Similar condensing pressures between cycle models and 3600 RPM tests

Increased condensing pressures at higher compressor speeds

Heating

Air-Side Capacity and COP





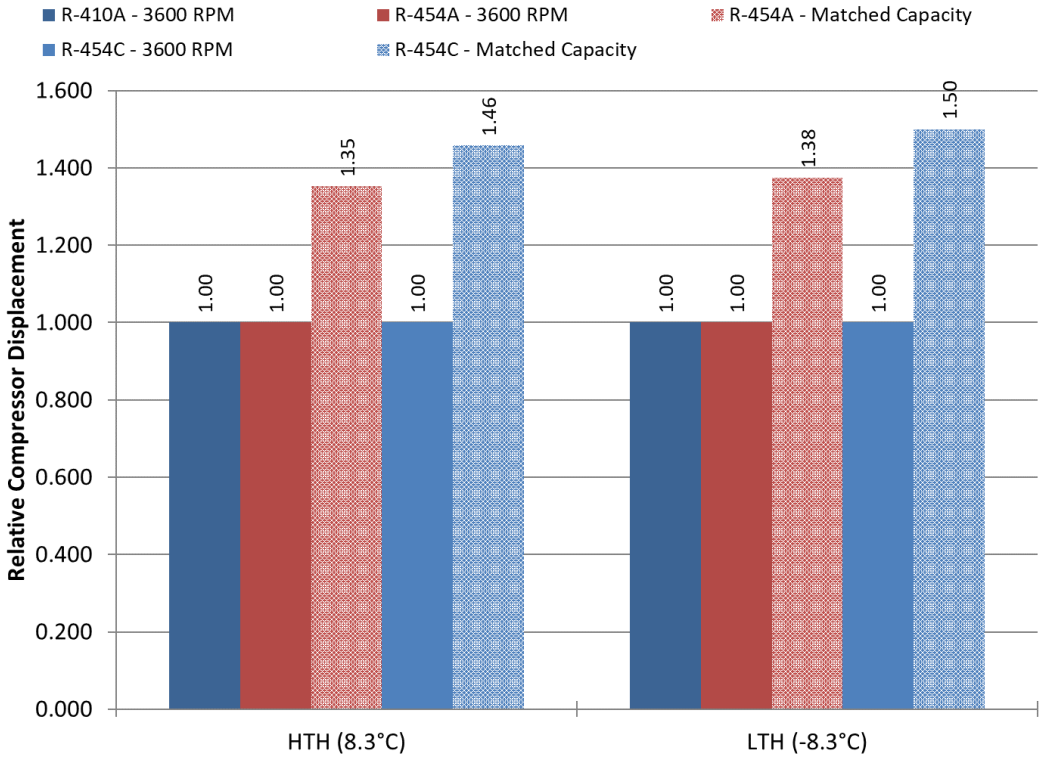
3600 RPM (60 Hz) testing was similar to thermodynamic models

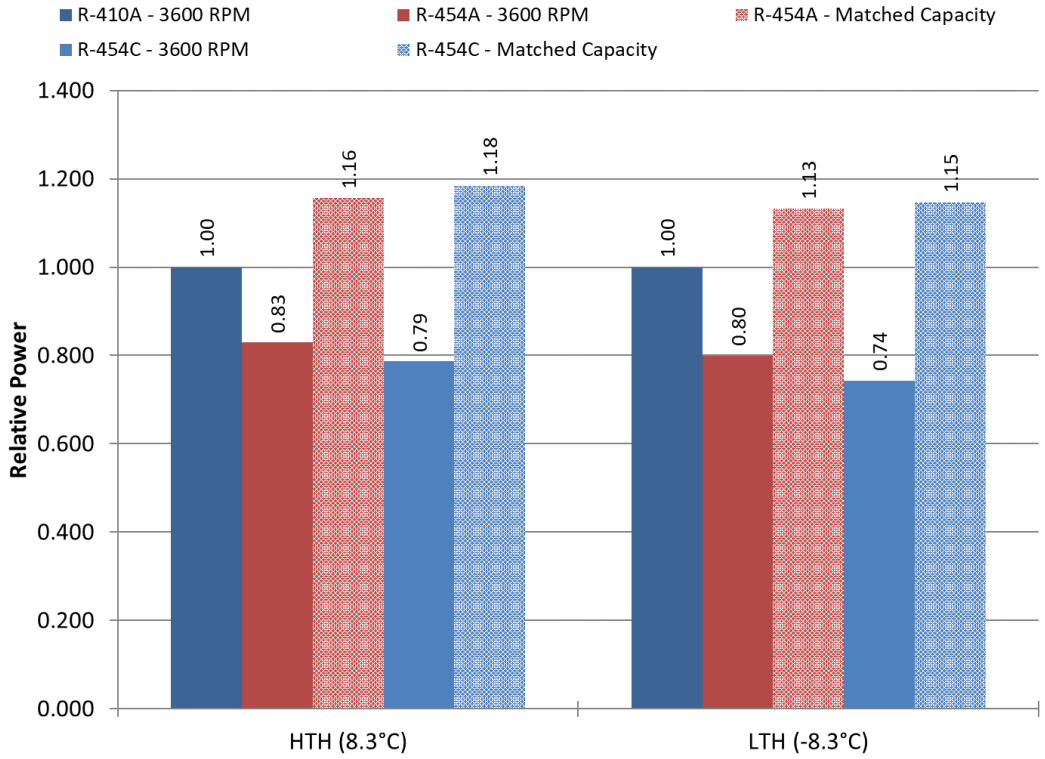
Can achieve similar capacities with increased compressor speeds

Higher COPs at increased compressor speeds

Charge optimization for *Matched Capacity* performance

Compressor Displacement and Power Consumption



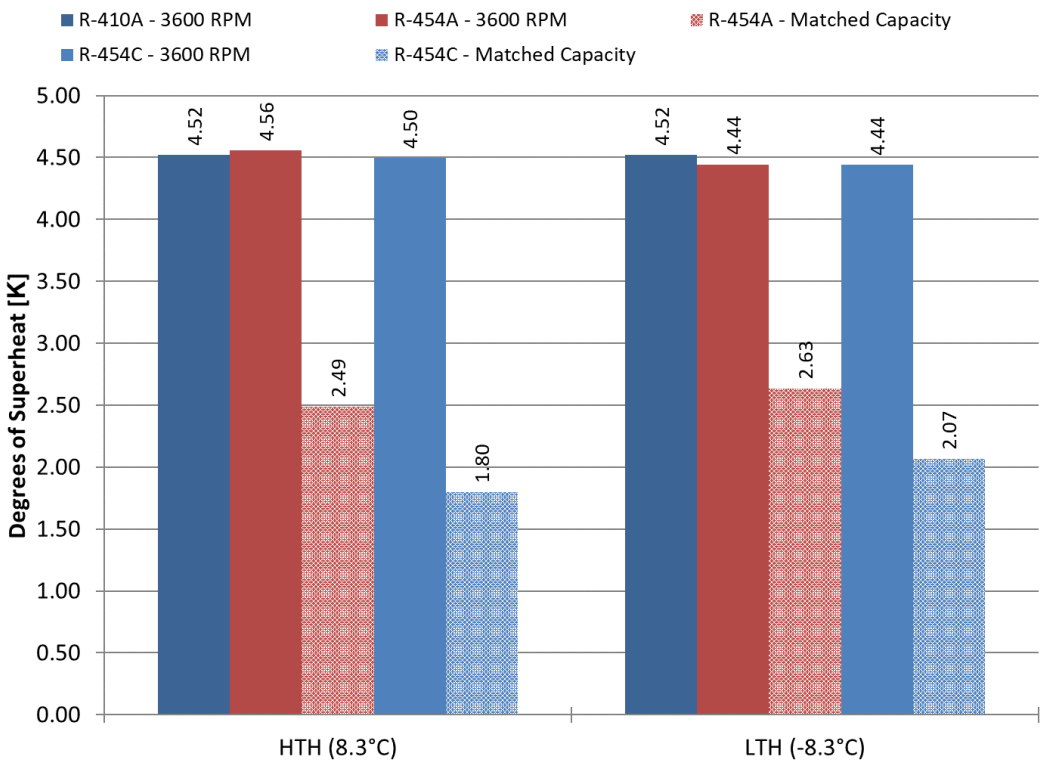


Lower compressor displacement increase for R-454C in heating

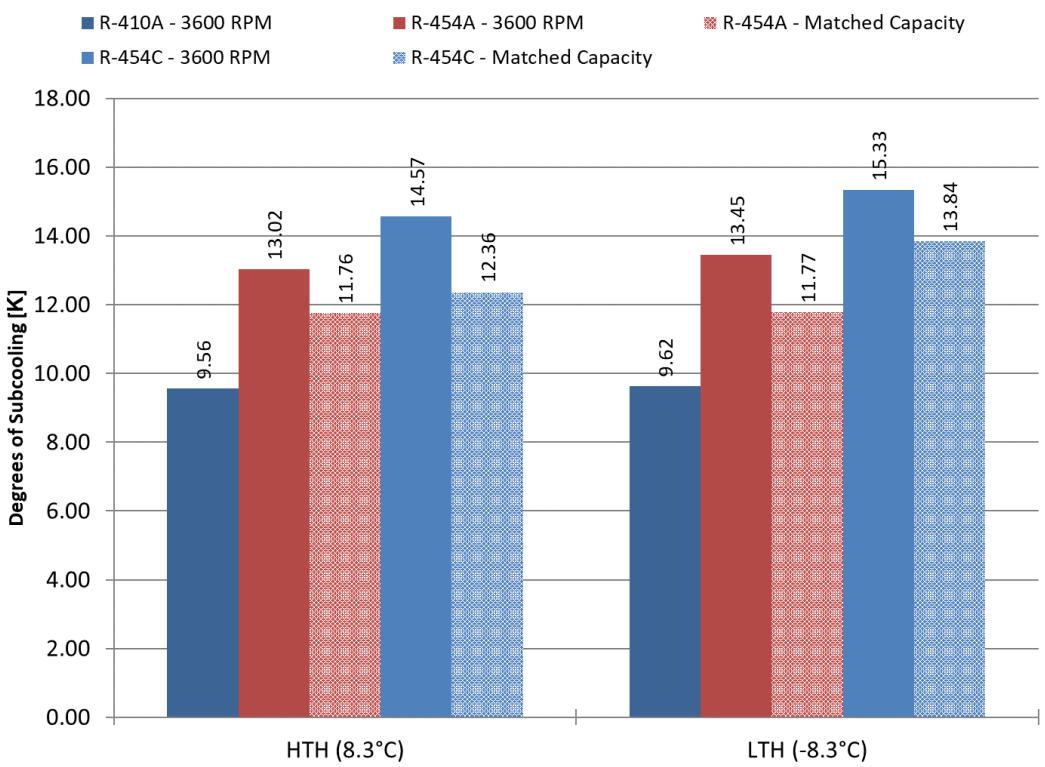
Similar compressor displacement increase for R-454A

Increase in power consumption was *lower* in heating vs. cooling

Evaporator Superheat and Subcooling



Adjusted superheat in *Matched Capacity* test to adjust evaporator temperatures

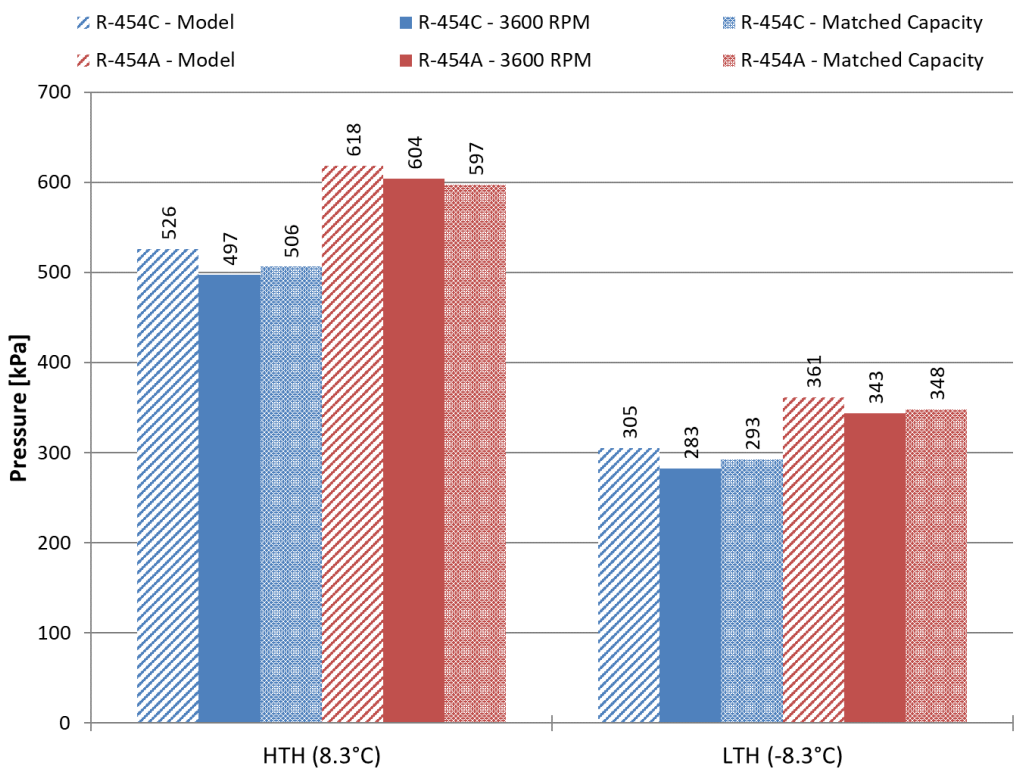


High subcooling for R-454A and R-454C

Optimized charge for *Matched Capacity*, penalized 3600 RPM testing

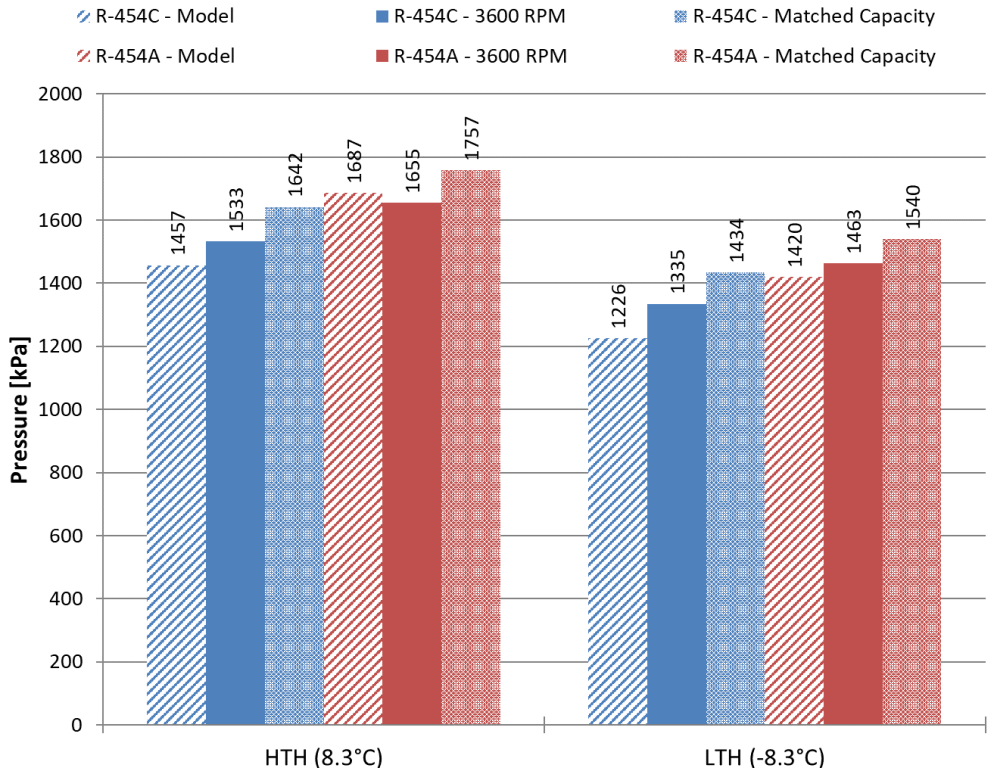
Operating Pressures – Heating

Evaporator Pressure



Different superheat between 3600 RPM and Matched Capacity tests

Condenser Pressure



Higher condensing pressures than cycle model results, indicating high refrigerant charge

Thermal Stability – Test Method

Thermal stability was evaluated using ASHRAE Standard 97 with POE 32 lubricant

Tubes were loaded with carbon steel, copper, and aluminum coupons, then filled with refrigerant and lubricant

Some tubes contained refrigerant with air contamination (2000 ppm) and oil with moisture (500 ppm)

Tubes were sealed and aged at 175 °C for 14 days

Indicators

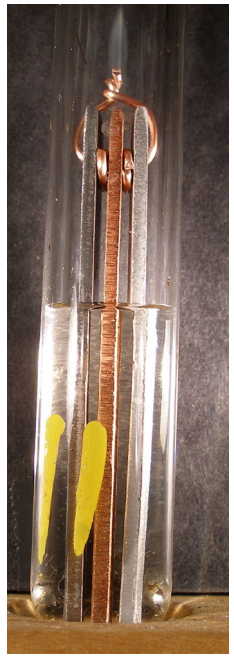
- High concentration of fluoride ions → fluid decomposition
- MDL (minimum detection limite) → fluoride/chlorine ions were below procedure detection limit (MDL = 0.3 ppm)

Thermal Stability

After 14 Days at 175 C

R-410A / oil

Left



R-410A / oil / air / moisture

Right

R-454C / oil

Left

R-454C / oil / air / moisture

Right

No visual changes or differences between coupons exposed to R-410A vs. R-454C

Thermal Stability

Refrigerant	Air (mmHg)	Water (ppm)	Metal Coupons	F^- (ppm)
R-410A	--	--	Yes	6.46
R-410A	7.6	--	Yes	11.70
R-410A	--	500	Yes	2.02
R-410A	7.6	500	Yes	3.07
R-454C	--	--	Yes	< MDL
R-454C	7.6	--	Yes	< MDL
R-454C	--	500	Yes	< MDL
R-454C	7.6	500	Yes	< MDL

R-454C has similar stability to R-410A

Conclusions and Future Work

Performance and Stability

Improved capacity of lower GWP refrigerants via variable speed compressor

Power consumption penalties with increased compressor displacements and higher refrigerant charge

Improved efficiency in heating relative to 3600 RPM testing

Similar thermal stability results as R-410A

Insights and Future Work

Significant performance improvements can be achieved with compressor and heat exchanger optimizations

Additional refrigerant charge optimizations

Heat exchanger optimization (multi-row heat exchangers, more counterflow)

Thank you!

Regulatory Drivers

- Environmental considerations

- Kigali Amendment
  - Global phase-down of HFCs
    - GWP-weight basis
  - Enters into force 1/1/2019

- F-Gas
  - Refrigerant shortages

- US EPA SNAP, CARB