Advisory Board Meeting 5th October 2021

Work Package 3 Parts 1 to 4

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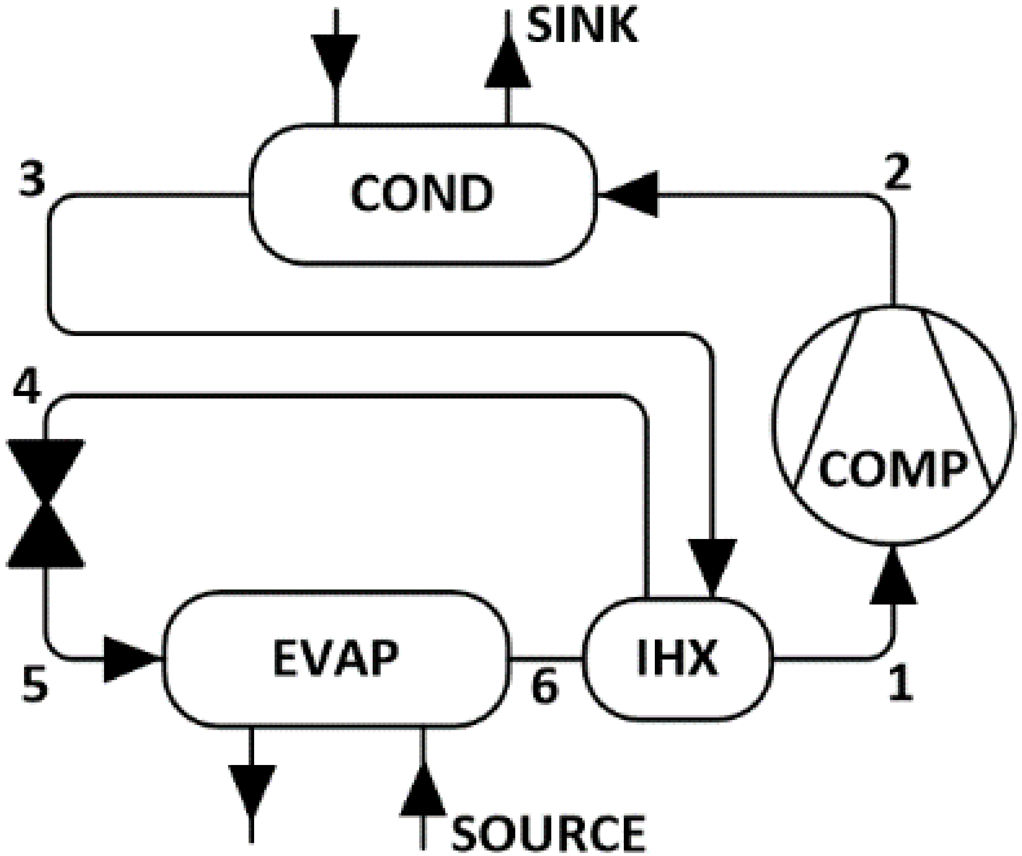
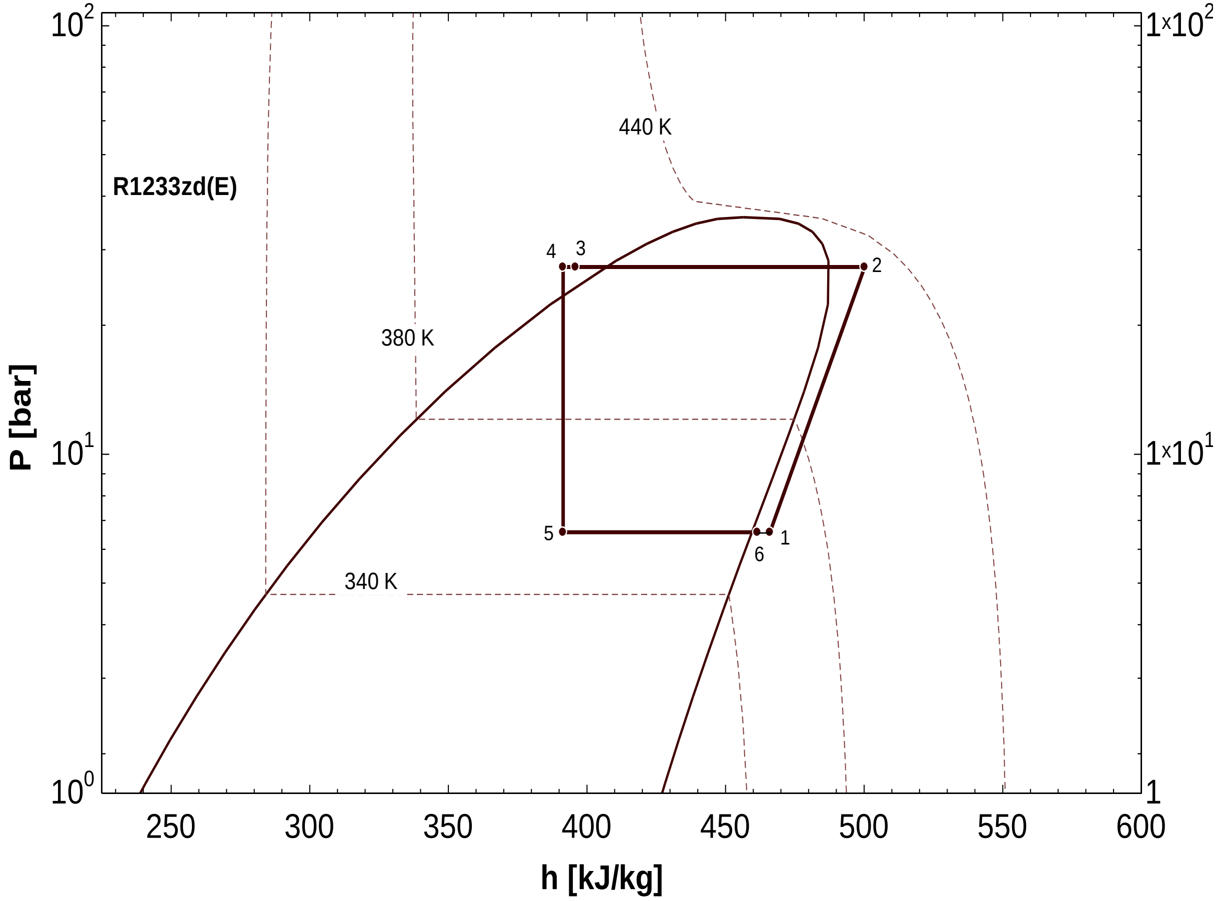
Low Temperature Heat Recovery and Distribution Network Technologies

Work Package 3 Advance performance of energy transformation technologies [UW, UU]

- WP3.1: Low temperature lift, high COP VC heat pump to deliver heat from LT network to load (e.g. lift of 20^{o}C with COP>9, enabling network to supply conventional radiator system)
- WP3.2: VC Heat Pump for Demand Side Management; variable renewable electricity supply will be matched to demands using building/process heating controls in association with variable compressor speed and storage
- WP3.3: High temperature VC heat pumps from network to process heat in commercial or industrial applications.
- WP3.4: Combined heat pump/ORC for heat to electricity or reverse, allowing maximum flexibility between combined (thermal/electricity) energy systems.

WP 3.1 & 3.3 Low Temperature High Lift VC Heat Pump





WP 3.1 & 3.3 VC Heat Pump

	ΔT_{Lift} = 30 & 70 K (T_{Evap}/T_{Cond} = 60°C/90°C & 60°C/130 °C)								ΔT_{Lift} = 30 & 70 K (T_{Evap}/T_{Cond} = 70°C/100°C & 70°C/140 °C)							
Refrigerant	T_{dis}[°C]	COP	VHC $\left[{}^{kJ}/_{m^3}\right]$	$T_{min_{sup}}$[°C]	P_r	$P_{in}[kW]$	IR_{total}	η_{ex}%	T_{dis}[°C]	COP	VHC $\left[{}^{kJ}/_{m^3}\right]$	$T_{min_{sup}}$[°C]	P_r	$P_{in}[kW]$	IR_{total}	η_{ex}%
R1233zd(E)	97	7.927	3316	5.565	2.132	1.955	0.3677	63.23	107	7.815	4110	5.549	2.039	1.973	0.3919	60.81
	137	3.14	2633	6.426	4.881	5.755	0.4103	58.97	147	3.086	3105	6.495	4.483	5.717	0.4387	56.13
R1336mzz(Z)	95	7.996	2273	10.52	2.27	1.951	0.3905	60.95	105	7.875	2886	10.6	2.158	1.97	0.4159	58.41
	135	3.144	1809	20.74	5.52	5.975	0.4815	51.85	145	3.09	2203	21.19	5.016	5.895	0.5437	45.63
R245fa	94.5	7.755	3925	4.837	2.185	2.003	0.4037	59.63	104.5	7.578	4873	4.767	2.081	2.04	0.4342	56.58
	134	2.825	2876	5.689	5.064	6.466	0.5037	49.63	144	2.708	3288	5.497	4.617	6.567	0.5344	46.56
R365mfc	95	8.088	1899	10.55	2.33	1.936	0.3797	62.03	105	8.003	2439	10.73	2.211	1.944	0.4007	59.93
	135	3.214	1560	20.81	5.818	5.957	0.4491	55.09	145	3.138	1948	20.85	5.264	5.893	0.5456	45.44
R1224yd(Z)	95	8.145	3602	6.55	2.113	1.901	0.3632	63.68	105	8.11	4426	6.546	2.021	1.9	0.3756	62.44
	135	2.921	2678	7.704	4.796	6.153	0.4799	52.01	145	2.889	3061	8.096	4.417	6.083	0.447	55.3
R1234ze(Z)	100	7.884	4221	6.331	2.096	1.962	0.3449	65.51	110	7.747	5177	6.419	2.01	1.988	0.3725	62.75
	140	3.097	3174	5.39	4.744	5.786	0.3441	66.59	150	3.003	3589	5.823	4.385	5.841	0.3249	67.51
R600	95	7.624	4633	5.518	1.955	2.015	0.4207	57.93	105	7.606	5540	5.811	1.884	2.011	0.4284	57.16
	135	2.798	3378	7.433	4.117	6.173	0.6055	39.45	145	2.783	3692	8.554	3.844	6.11	0.5125	48.75
R601	95	8.279	1935	9.517	2.183	1.876	0.3602	63.98	105	8.162	2433	9.74	2.085	1.894	0.3845	61.55
	135	3.313	1623	18.69	5.129	5.538	0.4557	54.43	145	3.232	1991	18.88	4.694	5.525	0.5442	45.58

LoT-NET

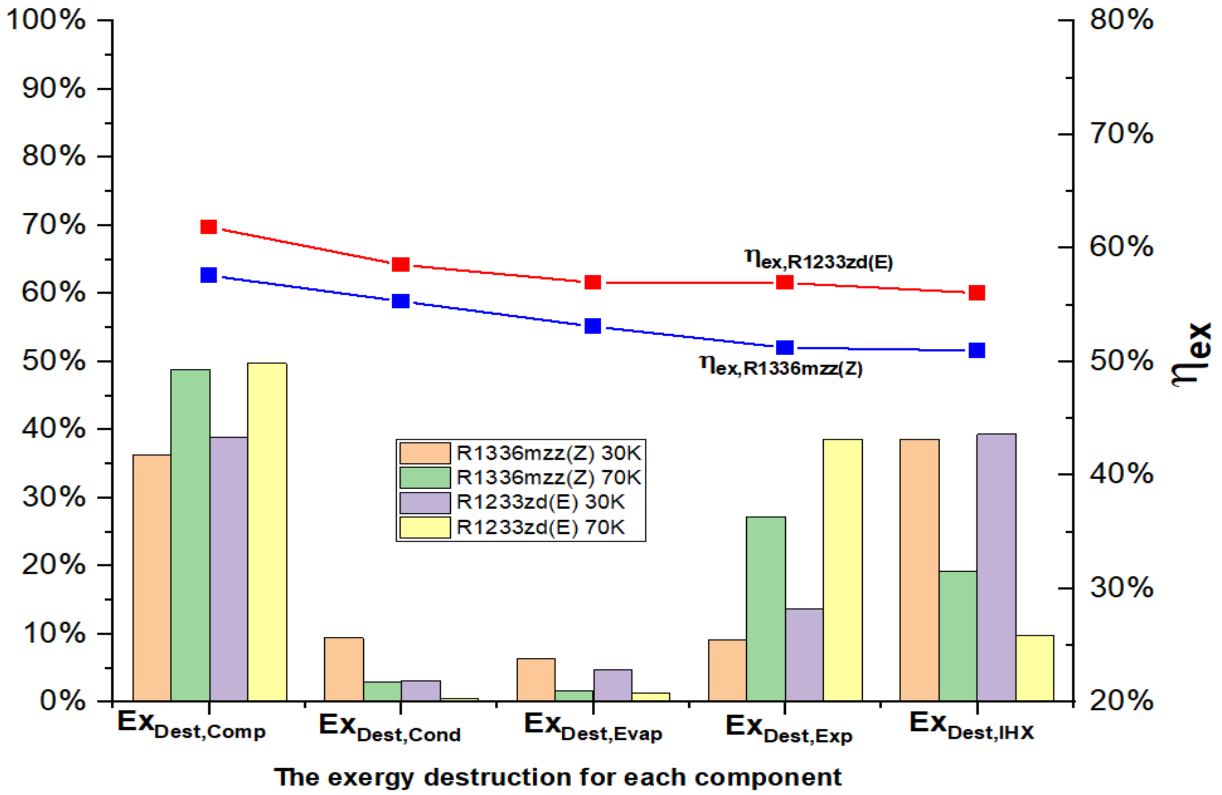
WP 3.1 VC Heat Pump

R1233zd is has a higher exergetic efficiency

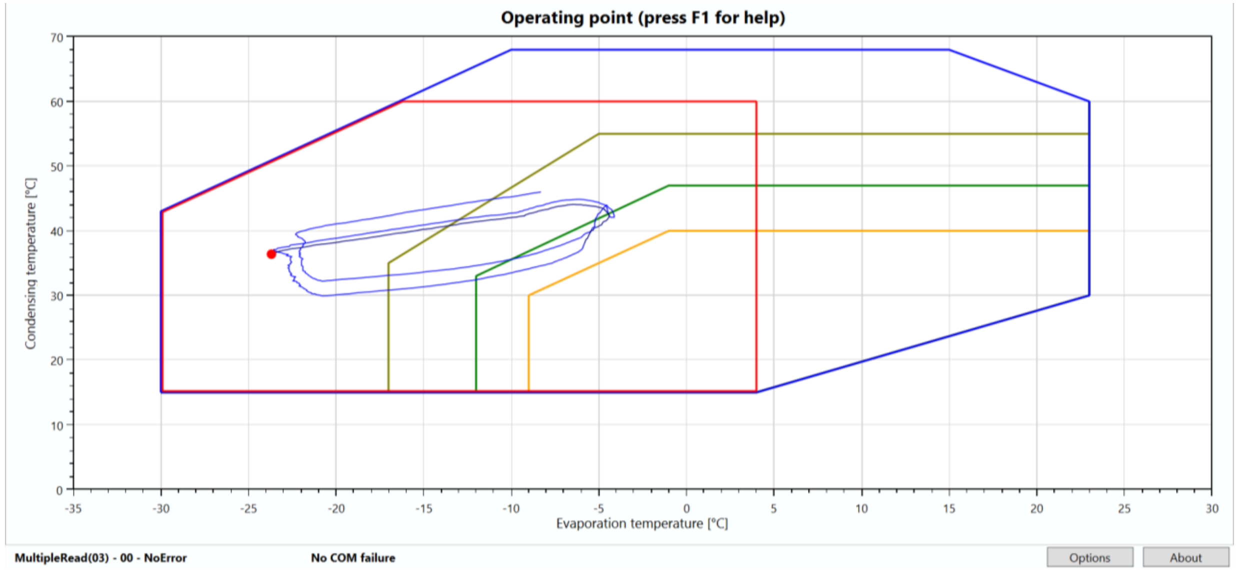
The compressor, followed by the expansion valve, has the biggest loss.

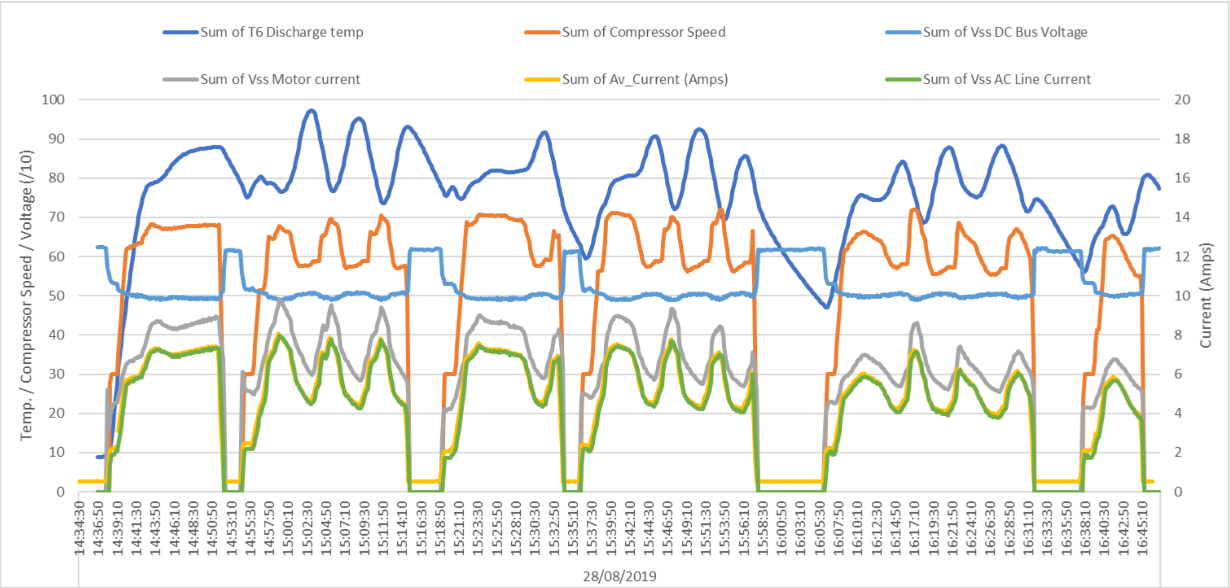
The losses in compression and expansion processes resulting from the dissipative forces.

The losses in heat exchangers are a function of heat transfer temperature gradient



WP 3.2 Heat Pump for Demand Side Management





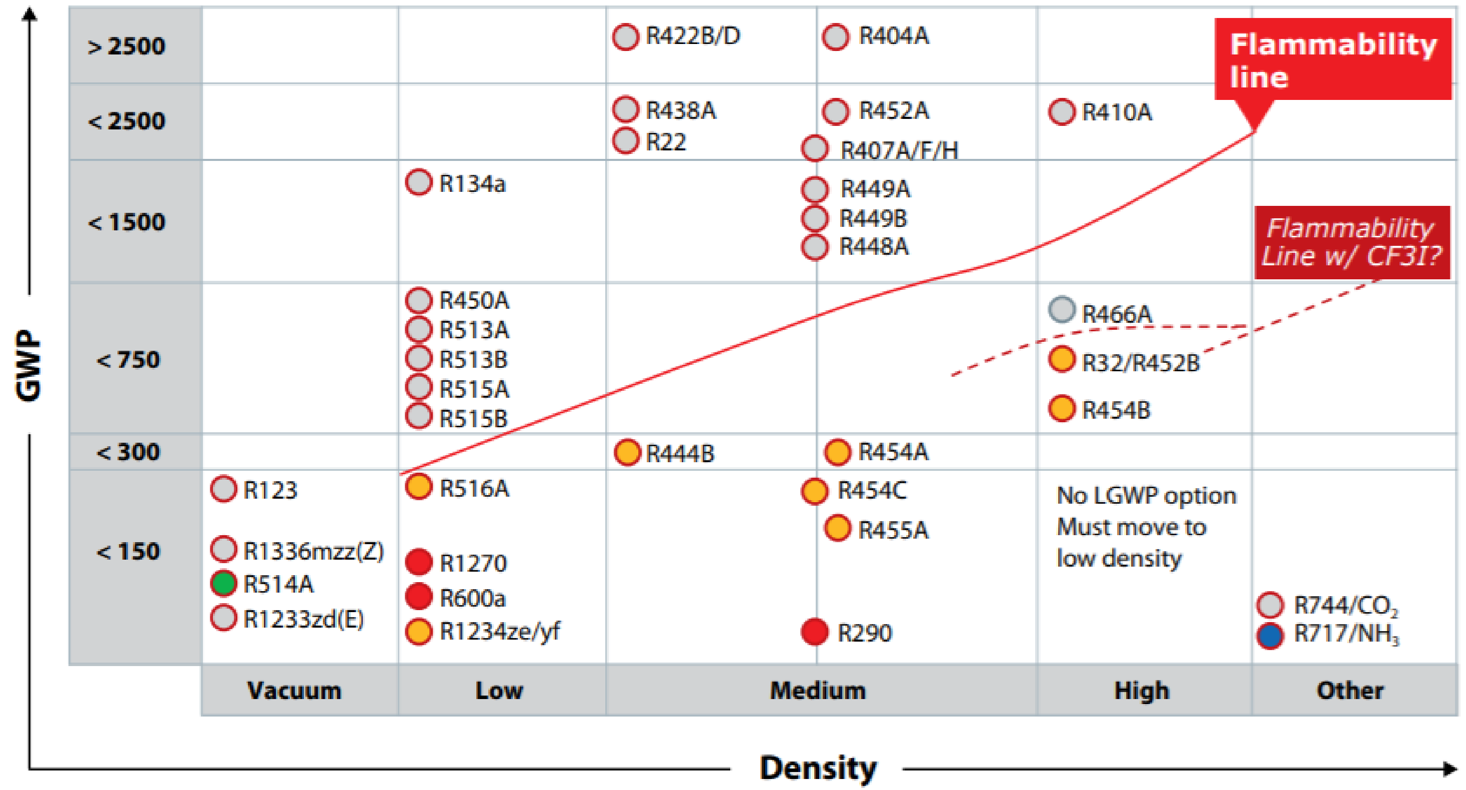
At higher compressor speeds is the inverter maxing out at 8amps input

LoT-NET

WP 3.2 Heat Pump for Demand Side Management

- Non-flammable, low GWP

Main refrigerants at play
A complex picture in continuous evolution



Legend
- A1 – Non-flammable
- A2L – Mildly flammable
- A3 – Highly flammable
- BI – Toxic – non-flammable
- B2L – Toxic – less flammable
- On the market
- Not yet on the market

GWP versus density (pressure) of the main refrigerant groups

LoT-NET

R410A Base Case: $Evap_{in}$ 25°C/$Cond_{out}$ 45°C - COP_h 3.983

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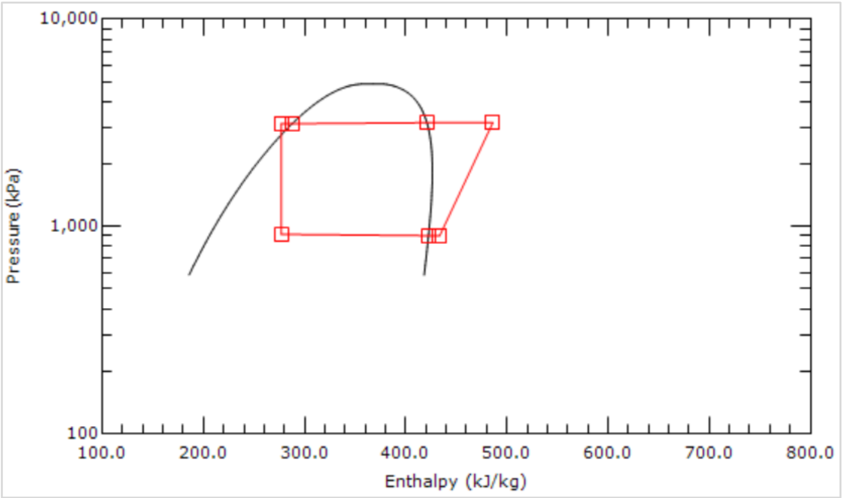
---------------------COMPRESSOR AND SYSTEM RESULTS--------------------------

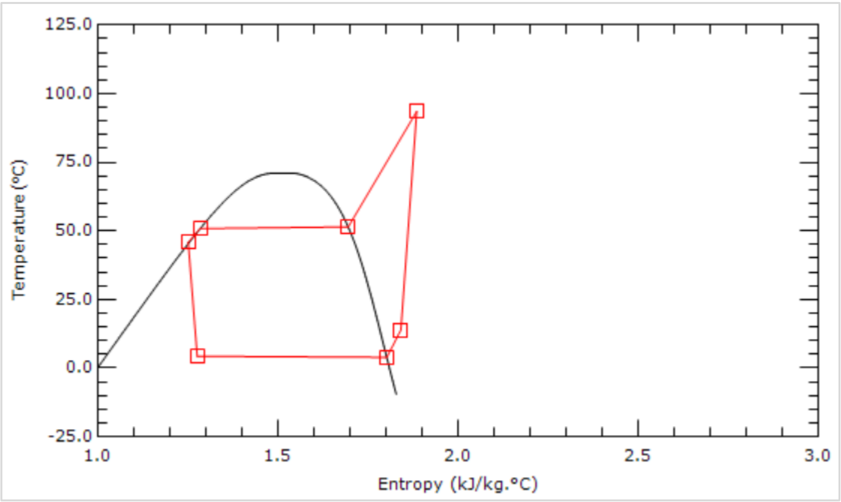
Compressor power            =   4.191 kW
Compressor COP: COPc        =   2.983                   COPh =   3.983
Compr. suc. vol. flow rate  =   8.879 m^3/h

Refrigerant mass flow rate  = 7.9790E-02 kg/s  Total power =   4.191 kW
Cooling capacity: evaporator=  12.500 kW          system   =  12.500 kW
Heating capacity: condenser =  16.691 kW          system   =  16.691 kW
      System COP: COPc,sys  =   2.983             COPh,sys =   3.983
```

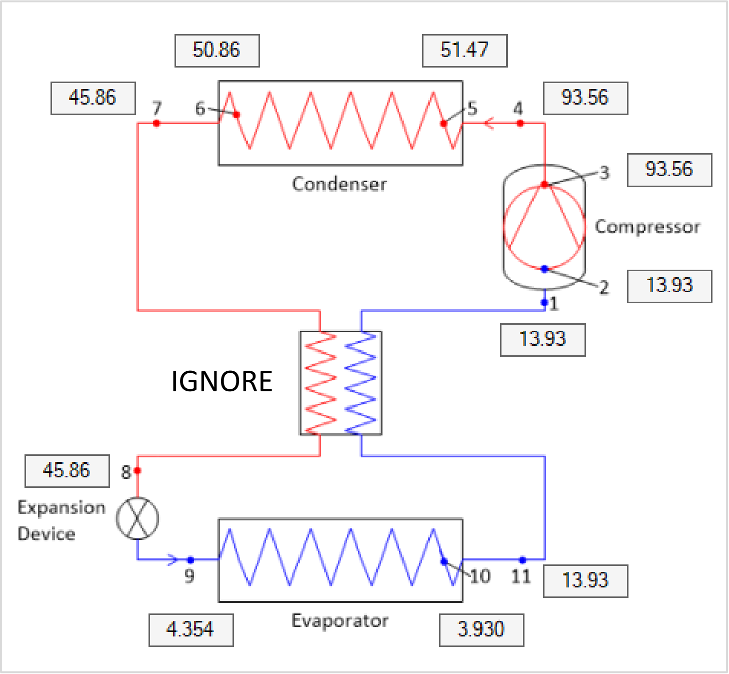
P-h State Diagram



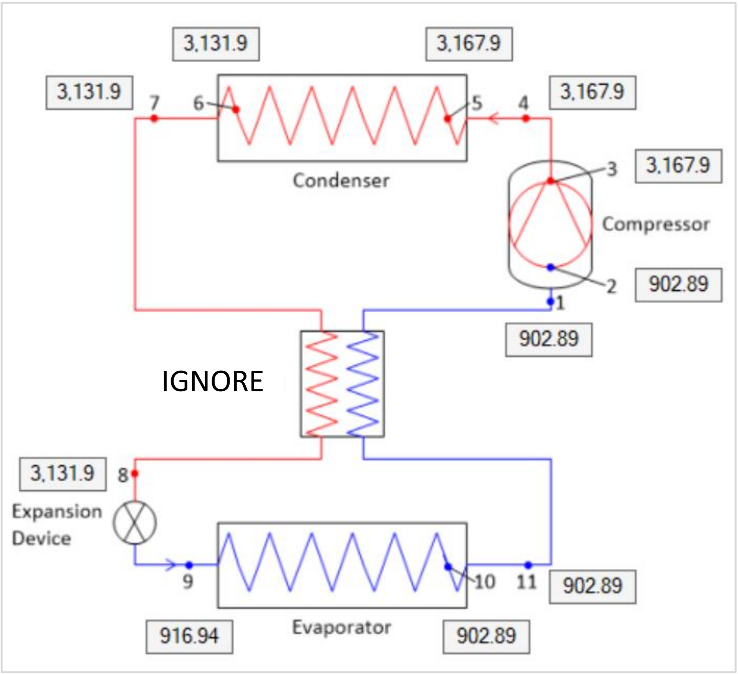
T-s State Diagram



Temperature (°C)



Pressure (kPa) [1 Bar = 100 kPa]



R161: Evap_{in} 25°C/Cond_{out} 45°C – COP_h 4.208

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---------------------COMPRESSOR AND SYSTEM RESULTS--------------------------

Compressor power              =   3.896 kW
Compressor COP: COPc          =   3.208           COPh =   4.208
Compr. suc. vol. flow rate    =  14.207 m^3/h

Refrigerant mass flow rate  = 4.3549E-02 kg/s  Total power =   3.896 kW
Cooling capacity: evaporator=  12.500 kW          system   =  12.500 kW
Heating capacity: condenser =  16.396 kW          system   =  16.396 kW
      System COP: COPc,sys  =   3.208             COPh,sys =   4.208
```
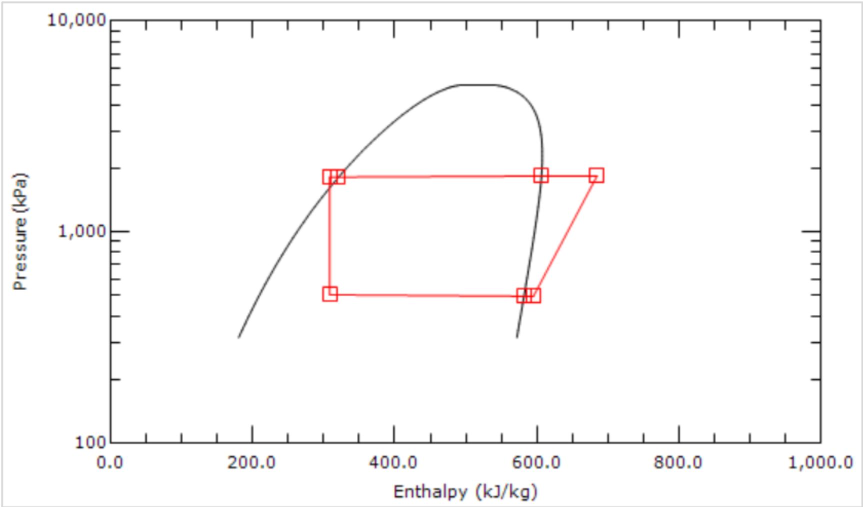
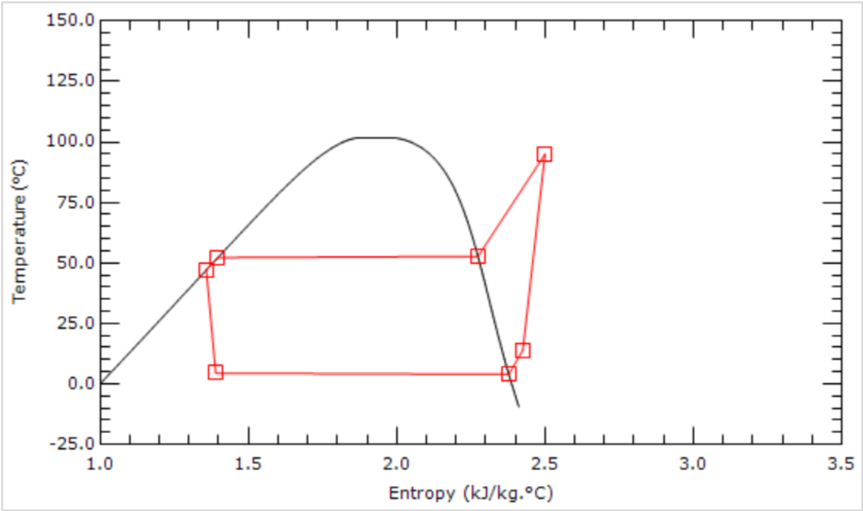
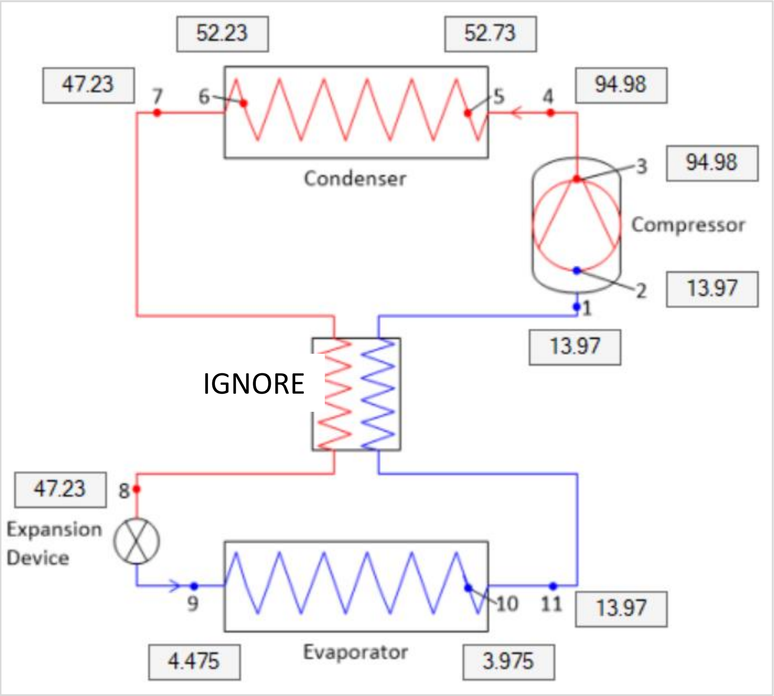

P-h State Diagram



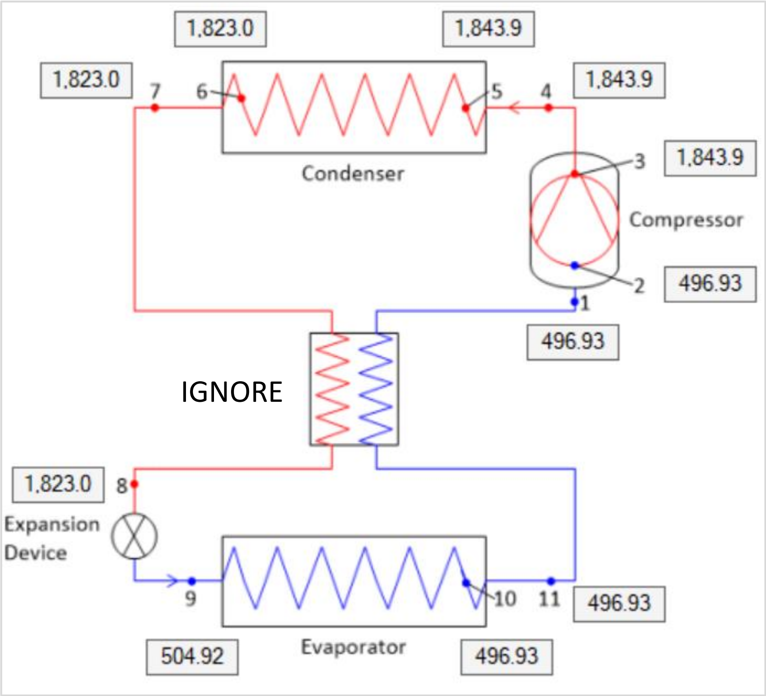
T-s State Diagram



Temperature (°C)



Pressure (kPa) [1 Bar = 100 kPa]



R466A: Evap$_{in}$ 25°C/Cond$_{out}$ 45°C – COP$_h$ 4.017

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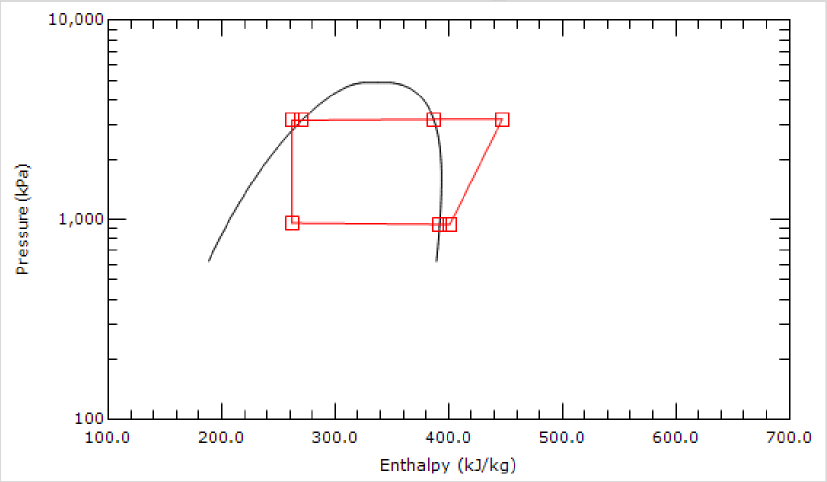
---------------------COMPRESSOR AND SYSTEM RESULTS-------------------------

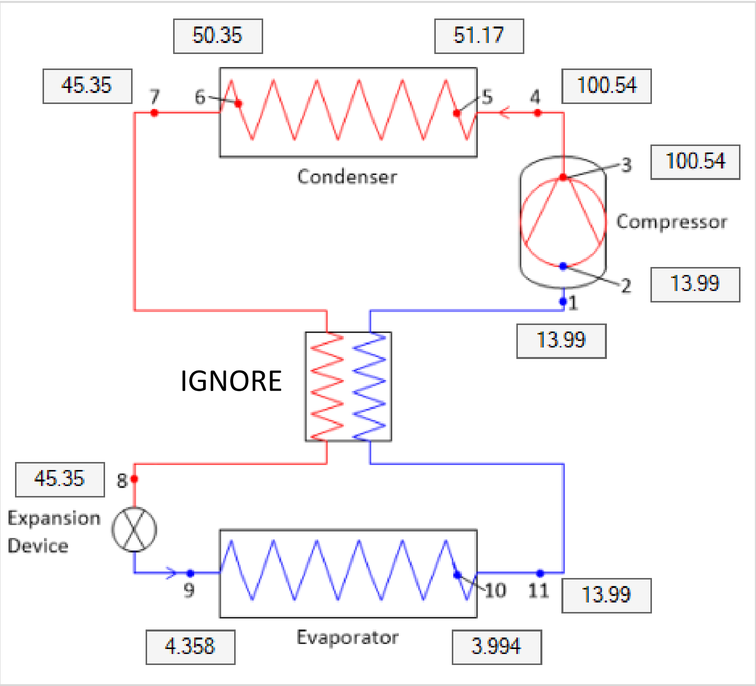
Compressor power              =   4.143 kW
Compressor COP: COPc          =   3.017                 COPh =   4.017
Compr. suc. vol. flow rate    =   8.475 m^3/h

Refrigerant mass flow rate    = 8.9724E-02 kg/s  Total power =   4.143 kW
Cooling capacity: evaporator=  12.500 kW            system   =  12.500 kW
Heating capacity: condenser =  16.643 kW            system   =  16.643 kW
      System COP: COPc,sys  =   3.017              COPh,sys =   4.017
```

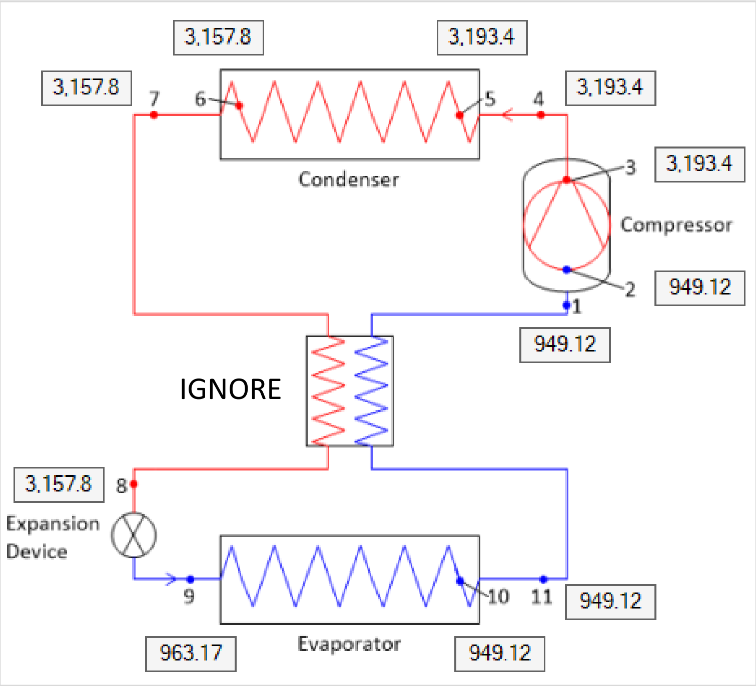
P-h State Diagram



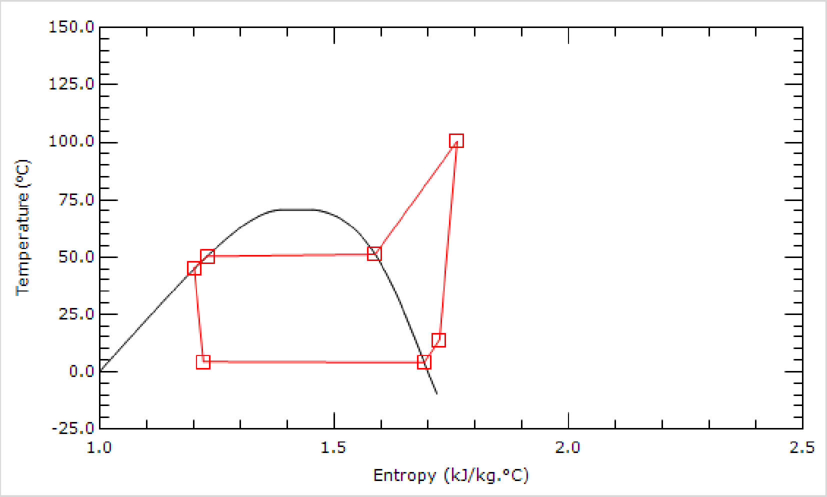
Temperature (°C)



Pressure (kPa) [1 Bar = 100 kPa]



T-s State Diagram



R470A (RS-53) – Unable to evaluate

Mixture Components

In addition to the relatively small amount of CO_2 (10%), it blends the R410A components, R32 (17%) and R125 (19%), with R134a (7%), HFO1234ze(E) (44%) and a small amount of the less common HFC R227ea (3%)

Performance Characteristics

- Low direct GWP Drop-in replacement for R410A
- Similar energy efficiency to R410A
- Close match for R410A in cooling capacity
- Similar discharge pressure to R410A
- No changes to hardware required during retrofitting
- Compatible with lubricants commonly used with R410A
- Replaces R410A in air conditioning and refrigeration applications
- Similar flow rate to R410A
- Zero Ozone Depletion Potential
- Non-flammable & low toxicity

https://www.refsols.com/RS-53.html

RS-53 (R-470A)

PHYSICAL PROPERTIES

Property		RS-53	R410A
Molecular Mass		84.43	72.6
Boiling point (1 atm) (1)	°C	-62.7	-51.4
	°F	-80.8	-60.5
Critical Temperature	°C	88.7	71.3
	°F	191.7	160.4
Critical Pressure	bara	55.91	49.00
	psia	810.8	710.6
Liquid Density (25°C) (1)	kg/m3	1101	1059
Density of saturated vapour (25°C) (1)	kg/m3	61.47	64.87
Latent Heat of Vaporisation at boiling point (3)	kJ/kg	268.5	273.0
Heat capacity constant volume Cv (25°C & 1bara)	kJ/kg.K	0.749	0.700
Heat capacity constant pressure Cp (25°C & 1bara)	kJ/kg.K	0.854	0.823
Cp/Cv (25°C & 1 bara)		1.141	11.755
Vapour Pressure (25°C) (1)	bara	18.43	16.57
	psia	267.3	240.4
Vapour Viscosity (25°C & 1 bara)	cP	0.0130	0.0133
Liquid Viscosity (25°C) (1)	cP	0.139	0.118
Liquid Thermal Conductivity (25°C)	W/m.K	0.0846	0.0892
Surface Tension (25°C) (1)	N/m	0.00623	0.00521
Specific heat of liquid (25°C) (1)	kJ/kg.K	1.58	1.71
Global Warming Potential AR5	GWP	909	1924
Flammability limit in air (1 atm)	vol%	none	none
Inhalation exposure (8 hour day & 40 hour week)	ppm	1000	1000

FEATURES

- Zeotropic mixture of HFC's / HFO / CO_2
- R410A Drop-in
- Compatible POE lubricants
- Similar discharge pressure to R410A
- Similar cooling and heating capacity to R410A
- No changes in hardware needed for retrofitting
- GWP 909 (AR5)
- ODP = 0
- Non flammable

APLICATIONS

Air conditioning

Commercial refrigeration

Industrial refrigeration

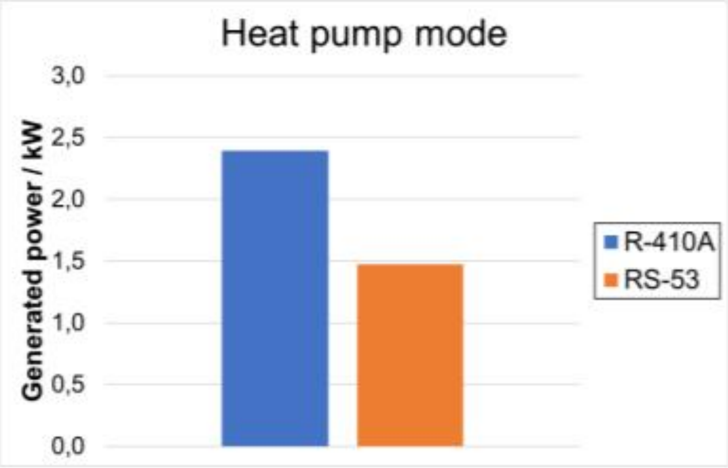
https://www.refsols.com/files/RS-53/RS-53_GRIT_Case_Study.pdf

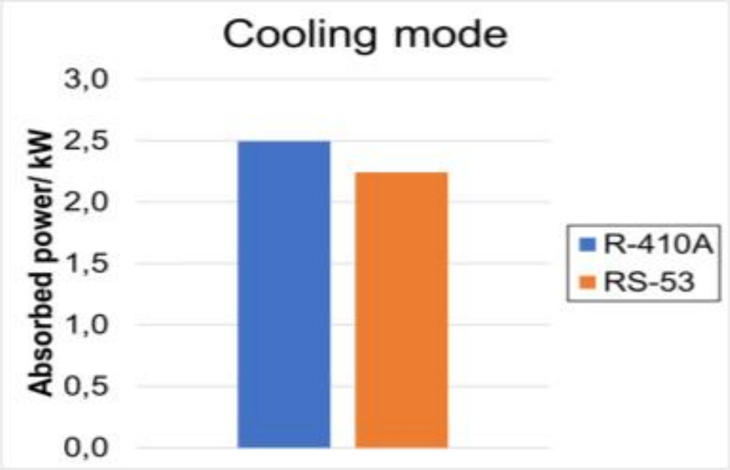
RS-53 (R-470A)

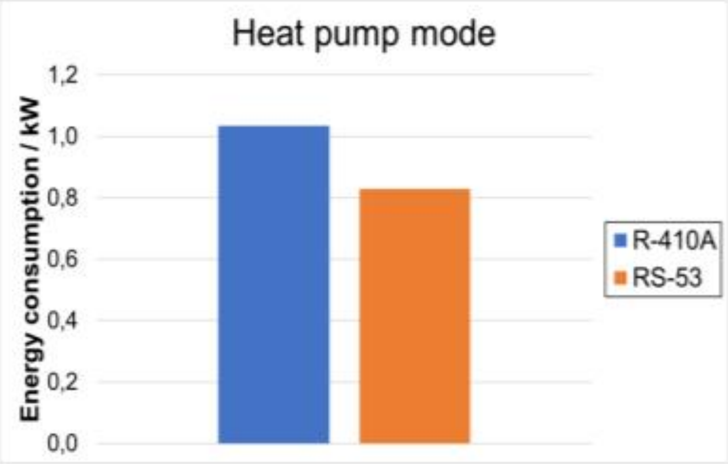
CASE STUDY
R410A SPLIT A/C RETROFIT
(Barcelona)

Benefits shown after the case study:

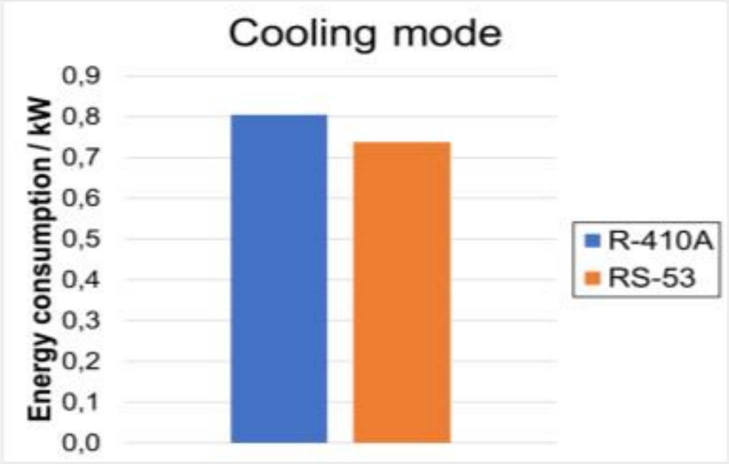
- Any change needed to do the retrofit. Just change the gas and start working
- Similar working conditions
    - Suction / discharge pressure
    - Temperatures
    - Same oil
- RS-53 has lower heating and cooling capacity but its consumption is lower than R410A
- Equipment working with RS-53 since summer 2019 without any maintenance issues







Test done at 15ºC (59ºF) ambient temperature



Test done at 30ºC (86ºF) ambient temperature

https://www.refsols.com/files/RS-53/RS-53_GRIT_Case_Study.pdf

R454B: $Evap_{in}$ 25°C/$Cond_{out}$ 45°C – COP_h 4.083

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---------------------COMPRESSOR AND SYSTEM RESULTS------------------------

Compressor power             =   4.055 kW
Compressor COP: COPc         =   3.083              COPh =    4.083
Compr. suc. vol. flow rate   =   9.046 m^3/h

Refrigerant mass flow rate   = 6.4650E-02 kg/s  Total power =    4.055 kW
Cooling capacity: evaporator=  12.500 kW           system   =  12.500 kW
Heating capacity: condenser =  16.555 kW           system   =  16.555 kW
      System COP: COPc,sys  =   3.083              COPh,sys =    4.083
```
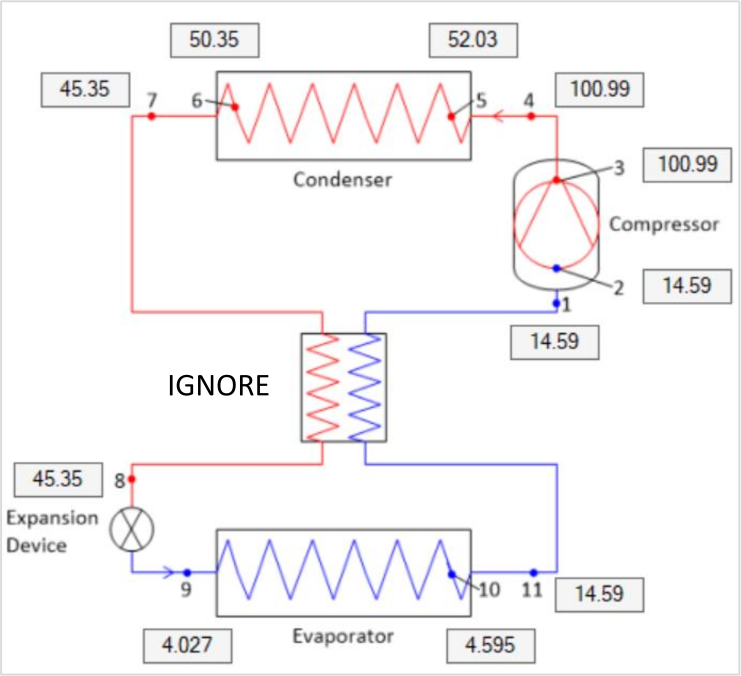
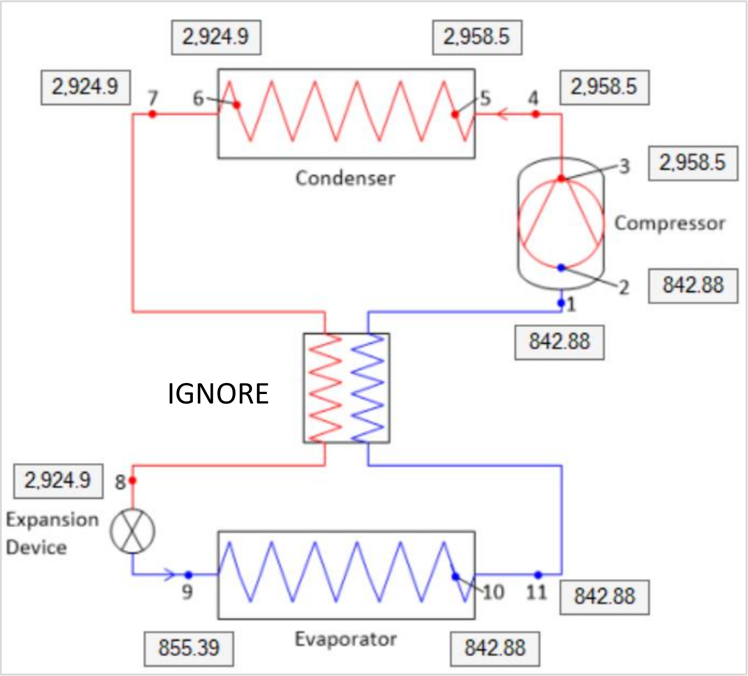
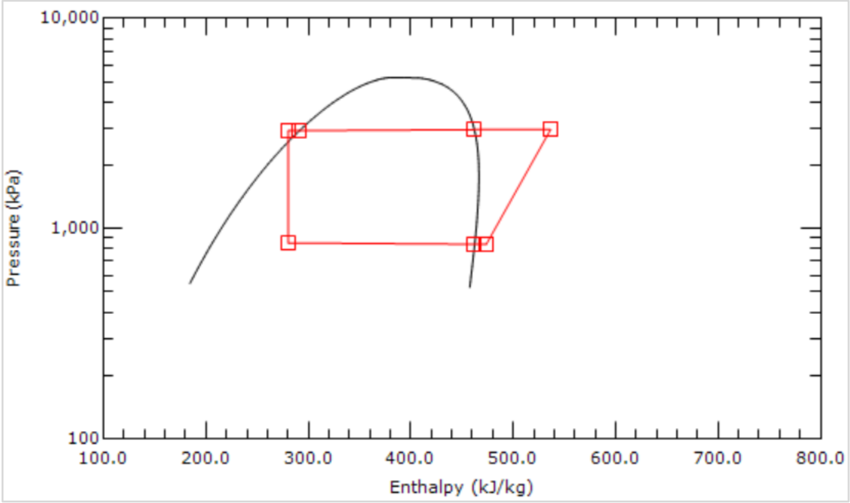

Temperature (°C)



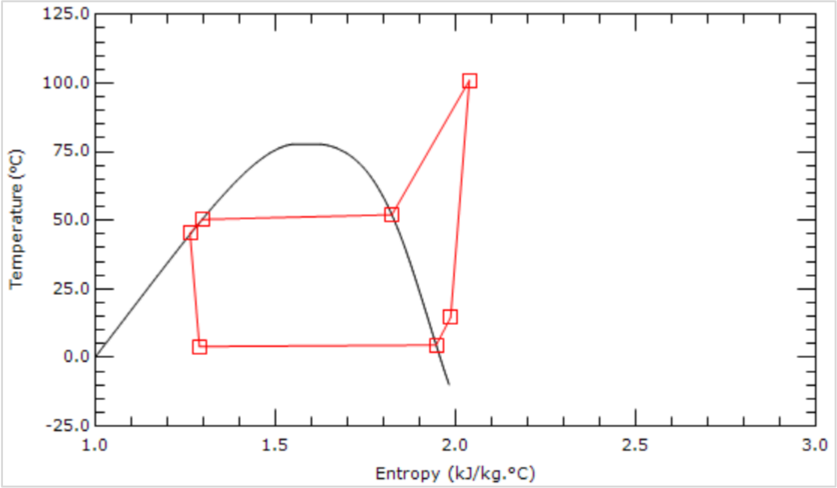
Pressure (kPa) [1 Bar = 100 kPa]



P-h State Diagram



T-s State Diagram



R452B: $Evap_{in}$ 25°C/$Cond_{out}$ 45°C – COP_h 4.072

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--------------------COMPRESSOR AND SYSTEM RESULTS---------------------

Compressor power             =   4.069 kW
Compressor COP: COPc         =   3.072               COPh =   4.072
Compr. suc. vol. flow rate   =   8.986 m^3/h

Refrigerant mass flow rate   = 6.6025E-02 kg/s  Total power =   4.069 kW
Cooling capacity: evaporator=  12.500 kW          system    =  12.500 kW
Heating capacity: condenser =  16.569 kW          system    =  16.569 kW
      System COP: COPc,sys  =   3.072             COPh,sys  =   4.072
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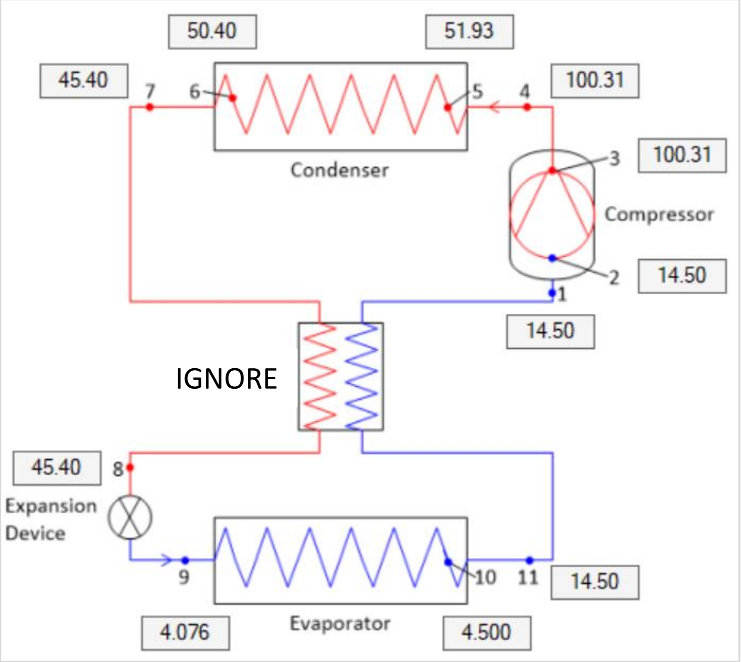
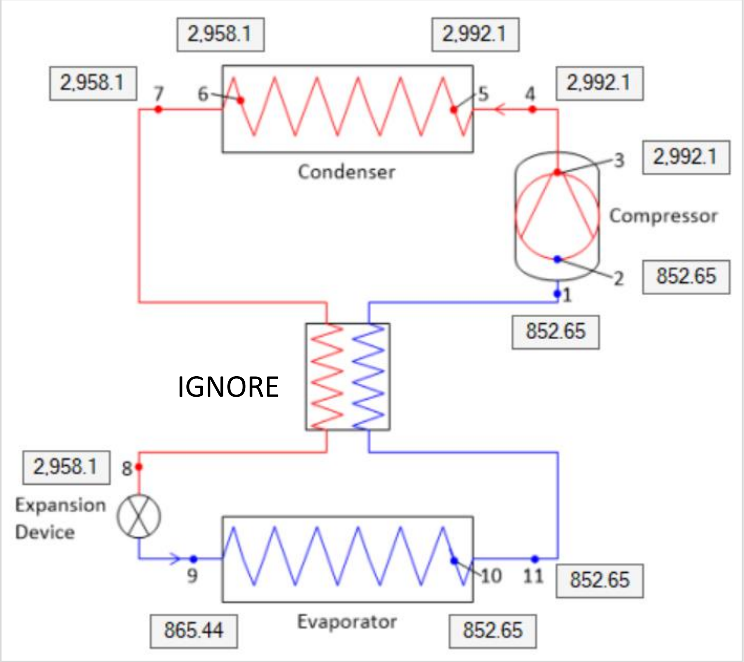
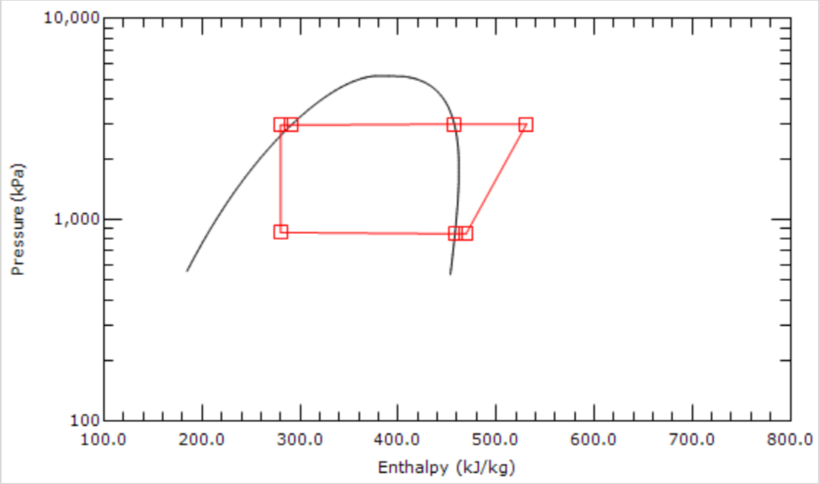
Temperature (°C)



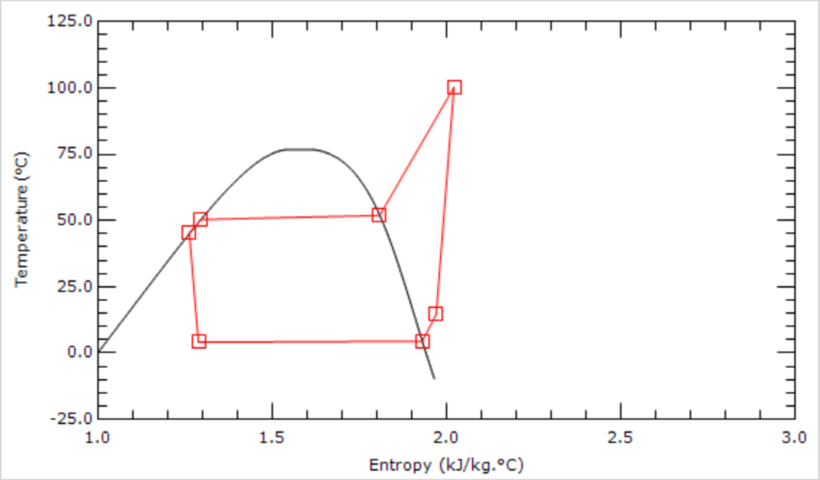
Pressure (kPa) [1 Bar = 100 kPa]



P-h State Diagram



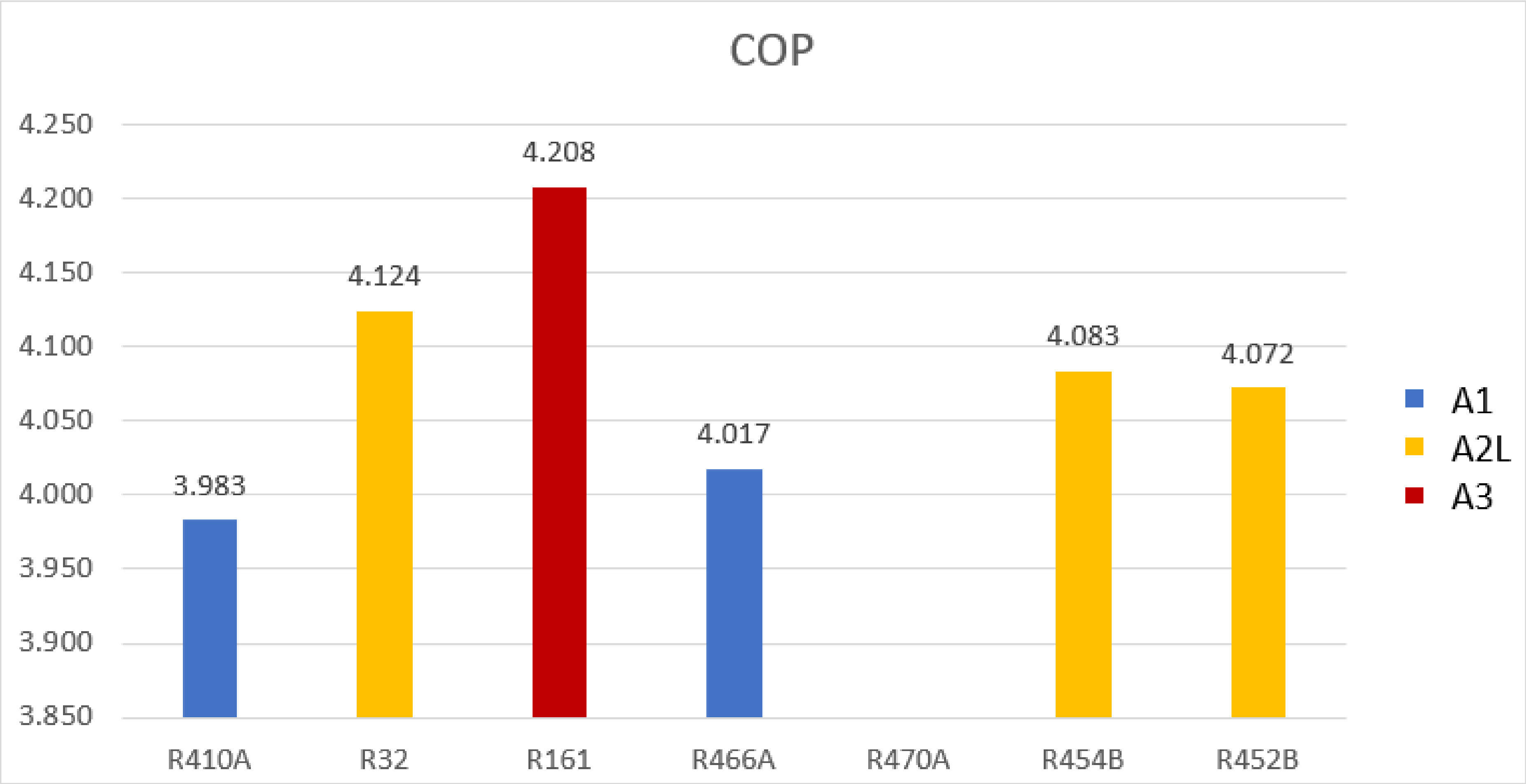
T-s State Diagram



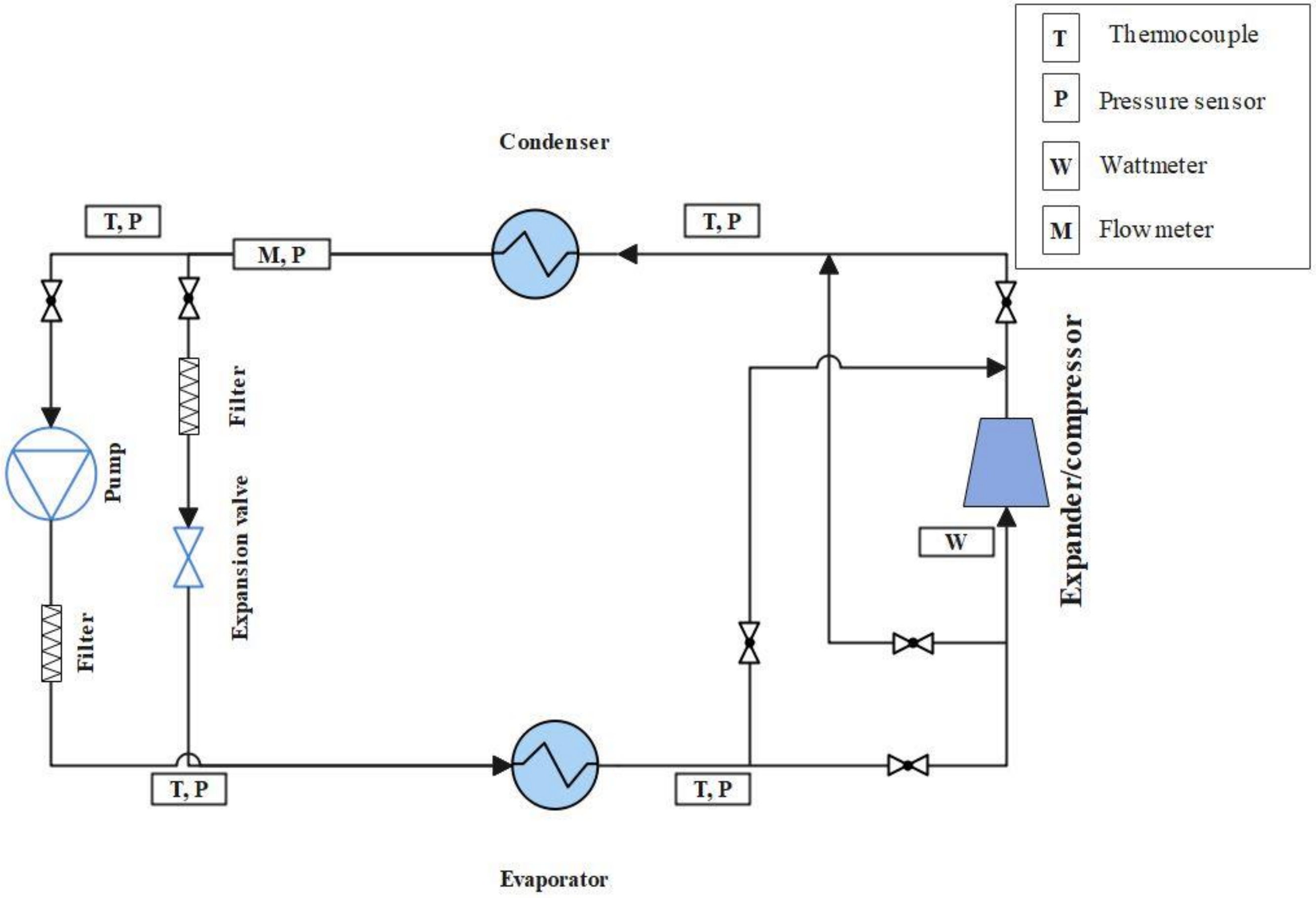
Summary Table

Refrigerant	COP	COP / COP_{R410A}	Discharge Temp. (°C)	Volumetric Capacity (kJ/m³)	Volumetric Capacity / Volumetric Capacity R410A	Notes
R410A	3.983	1.00000	93.6	6767.7	1.00000	
R32	4.124	1.03540	114.9	7478.4	1.10501	High discharge temp. - early compressor failure?
R161	4.208	1.05649	95.0	4154.8	0.61392	
R466A	4.017	1.00854	100.5	7069.2	1.04455	
R470A						Couldn't define blend due to 5 component limit in cycle d-hx
R454B	4.083	1.02511	101.0	6588.1	0.97346	
R452B	4.072	1.02234	100.3	6638.1	0.98085	

Summary - COP


COP
4.250
4.200
4.150
4.100
4.050
4.000
3.950
3.900
3.850
3.983
4.124
4.208
4.017
4.083
4.072
R410A
R32
R161
R466A
R470A
R454B
R452B
A1
A2L
A3

WP 3.4 Reversible Heat Pump-Organic Rankine Cycle



WP 3.4 Reversible Heat Pump-Organic Rankine Cycle

ORC mode

- Heat source temperature 90-120 C
- Condensing temperature 60-30C
- Evaporator heat transfer 13-7kW
- Condenser heat transfer 11-6kW

- HP mode

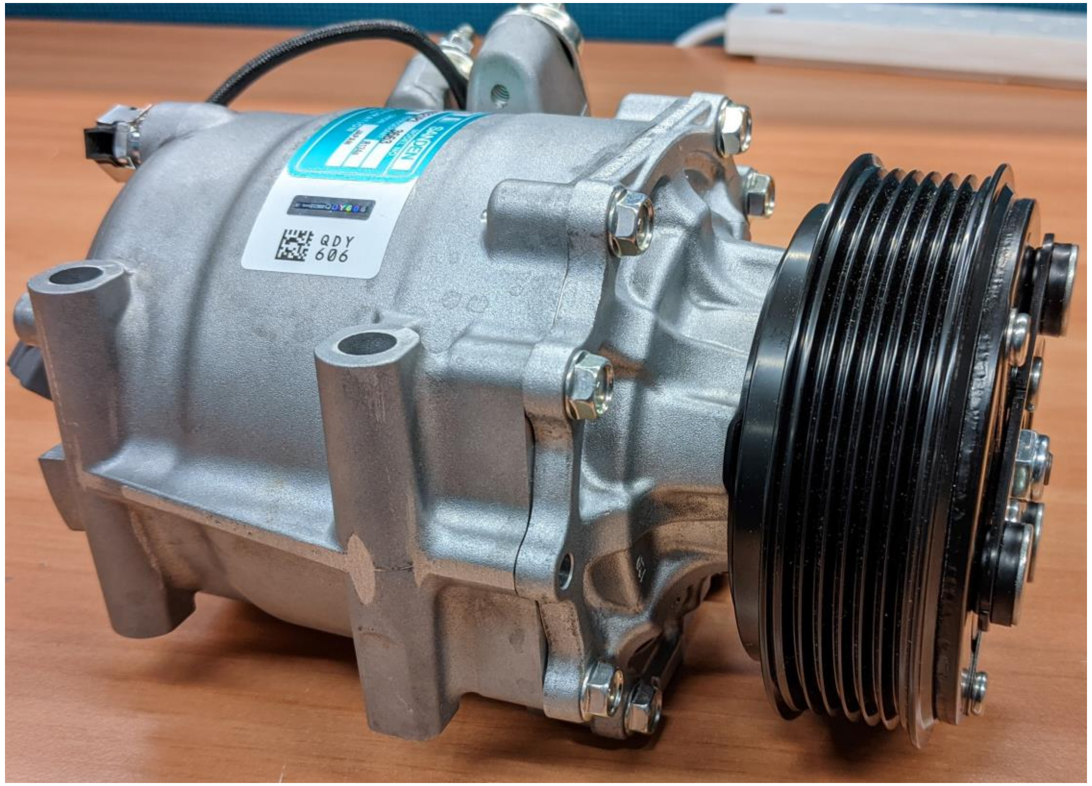
- Evaporating temperature 70-90 C
- Condensing temperature 110-130 C
- Evaporator heat transfer 10-7kW
- Condenser heat transfer 8-12kW

WP 3.4 Reversible Heat Pump-Organic Rankine Cycle

Open drive scroll compressor (as compressor in HP mode and as expander in ORC mode)

SANDEN TRSA09 (displacement 85.7 cc and built in volume ratio 1.9)

Suitable for small scale applications



WP 3.4 Reversible Heat Pump-Organic Rankine Cycle

SWEP B85Hx20 as evaporator in both ORC and HP modes

SWEP B25Tx26 as condenser on both ORC and HP modes

Specified heat exchangers suitable for handling the required heat transfer rates for reversible HP-ORC system

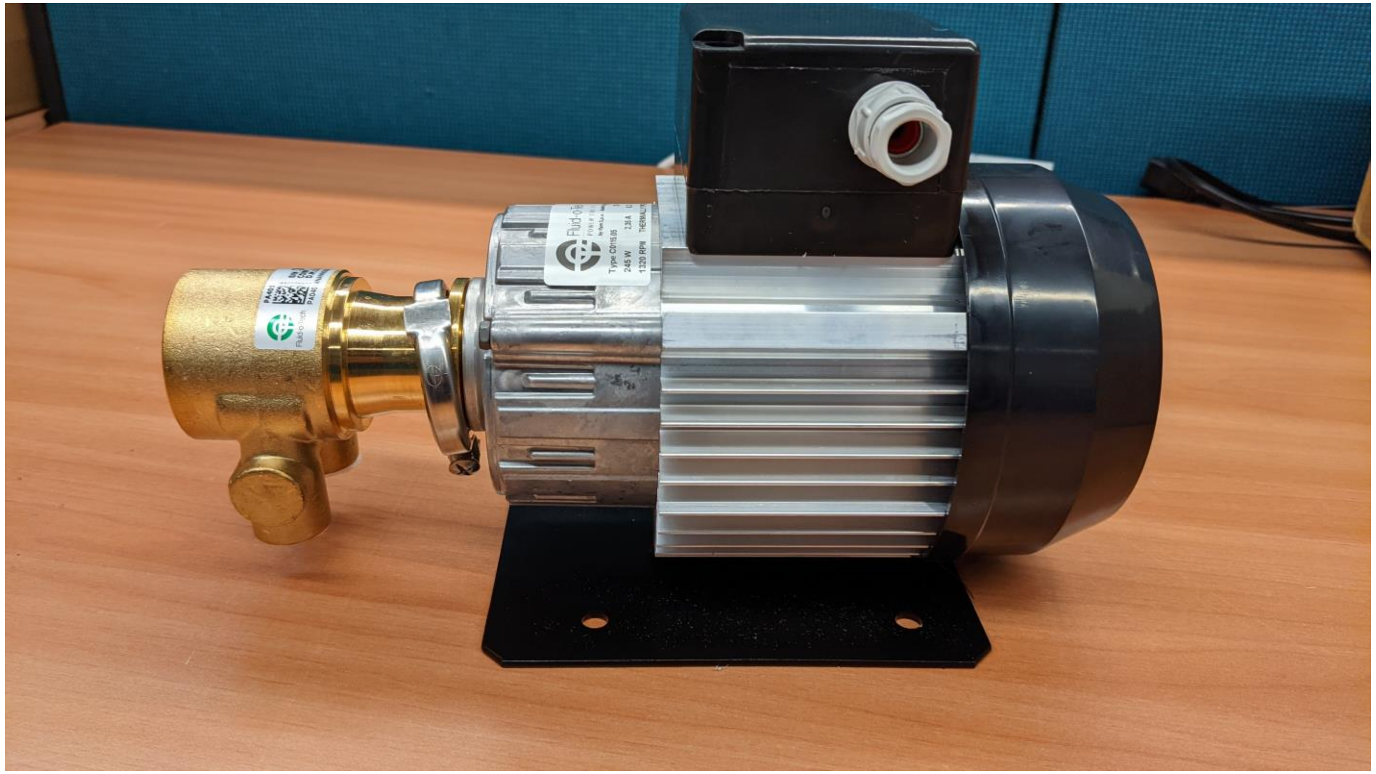
WP 3.4 Reversible Heat Pump-Organic Rankine Cycle

ORC pump

Vane pump is suitable for small scale ORC systems

Fluid-o-Tech FP0401

Suitable for pumping R1233zde at flow rates ranging **0.02 - 0.1 kg/s**



Vane pump with motor

WP 3.1 to WP3.4 Summary

WP 3.1 and WP 3.3 – We have discovered that similar system improvements apply to both systems

WP 3.2 – New working fluids can replace existing choices typical in heat pumps

WP 3.4 – System development is underway