LIFE CYCLE PERFORMANCE OF REFRIGERATION SYSTEMS IN THE DUTCH SUPERMARKET SECTOR

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Supermarket sector

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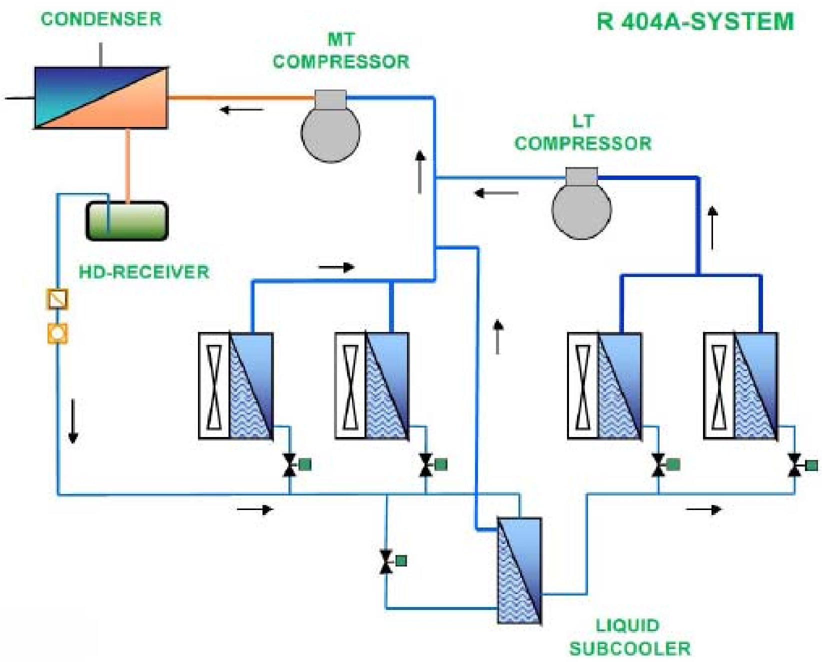


Example of the lay-out of a R404A system for supermarket applications.

Supermarket Sector in NL

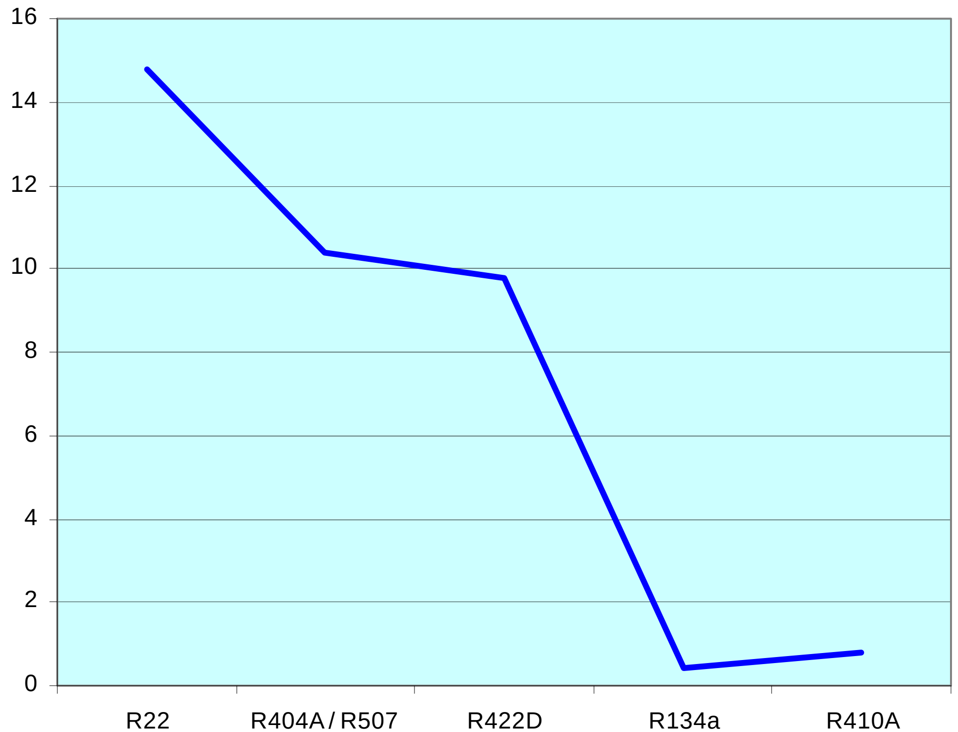
Sector information

Average operating hours per year [h]	Installed cooling capacity [kW]	Installed freezing capacity [kW]		Percentage R404A/ R507 plants [%]	Percentage R22 plants [%]	Percentage R410A plants [%]	Percentage R134a plants [%]	Percentage R422D plants [%]		kg refrigerant/ kW cooling
6132	100	20		84	9	4	2	1		2.7

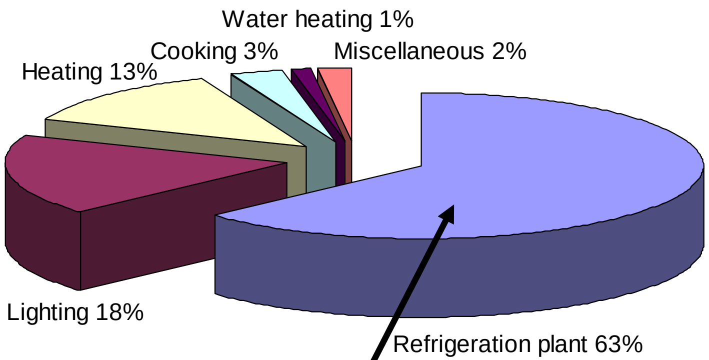
Pennartz and van den Bovenkamp (2011)

Supermarket Sector in NL

Sector information



Leakage rate of refrigerants in sector [%]



Compressor shaft 3 PJ

Losses power plant 4 PJ

Refrigeration 7 PJ
Total sector 11 PJ

Pennartz and van den Bovenkamp (2011)

Supermarket Sector in NL

Current size of sector

	Area [m2]	Number of shops
Hypermarkets	**>2500**	**65**
Supermarkets	**1350**	**1379**
Discounters	**<1000**	**2879.0**
Total sector	**3.8x10^6**	**4323**
MT range (-10°C)	**74 W/m2**	**100 kW**
LT range (-32°C)	**15 W/m2**	**20 kW**

Zadelhoff (2012)

Supermarket Sector in NL

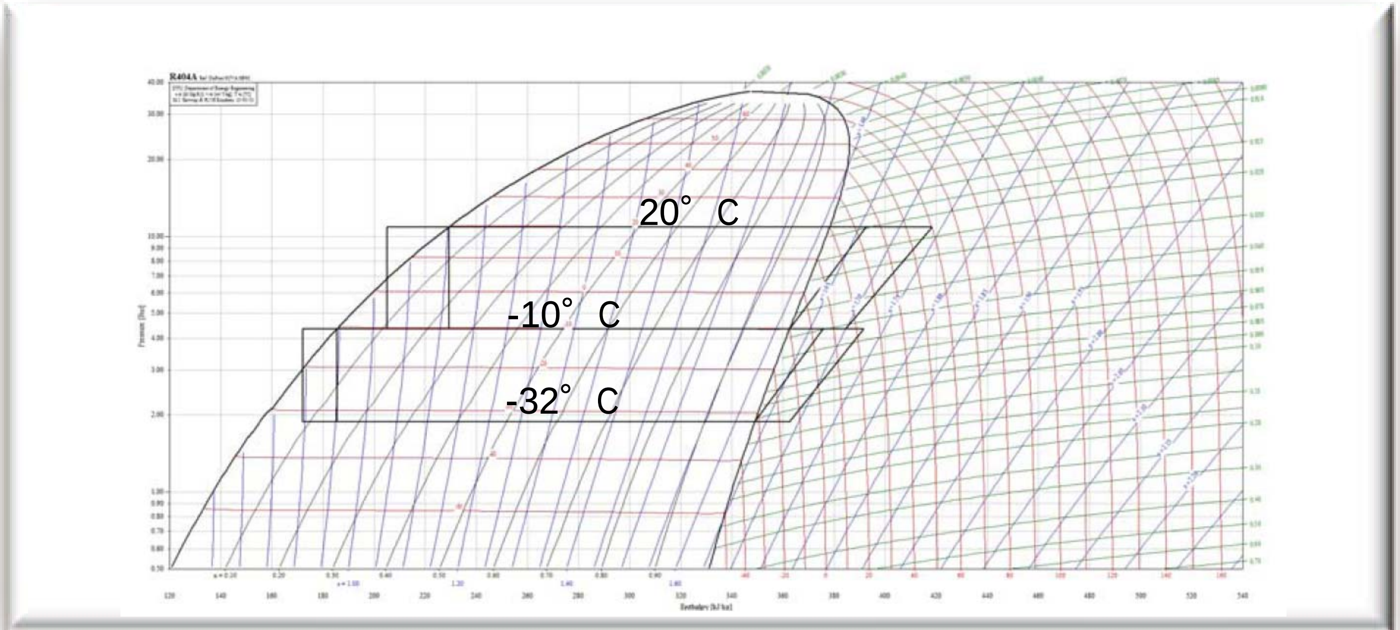
Used refrigerants and leakage rates (based on 34 supermarket plants)

	R404A/R507	R22	R422D	R134a	R410A
Percentage of total refrigerant weight [%]	94.8	4.4	0.5	0.2	0.1
Percentage of total shops [%]	83.5	9.0	0.7	1.7	4.1
Refrigerant leakage [%]	10.4	14.8	9.8	0.4	0.8
GWP [kg CO_2] 100 yr	3700/3800	1790	2700	1370	2100

Jans (2010)

Supermarket application

Cooling capacity = 100 kW (MT) / 20 kW (LT)
Evaporation temperature MT = -10° C (indirect = -17° C)
Evaporation temperature LT = -32° C (indirect = -39° C)
Condensation temperature = 40° C (no heat recovery: variable)
Isentropic efficiency compressor = 0.613 (ammonia = 0.700)
Running time: 6132 hours/year
Minimum temperature difference in hex = 5 K



Supermarket application

Alternative systems considered

	System	Refrigerant inventory
1	Reference: Booster with direct evaporation of R404A	324 kg R404A
2	Booster with direct evaporation of R404A and internal heat exchangers	324 kg R404A
3	Booster with direct evaporation of HFO1234yf	324 kg HFO1234yf
4	Booster with direct evaporation of R744	324 kg CO2
5	Direct evaporation of R404A (MT) with R744 cascade (LT)	162 kg R404A + 162 kg CO2
6	Direct evaporation of HFO1234yf (MT) with R744 cascade (LT)	162 kg HFO1234yf + 162 kg CO2
7	Booster with R717 and secondary fluid for distribution (potassium formate)	24 kg R717
8	Booster with R290 and secondary fluid for distribution (potassium formate)	24 kg R290
9	R717 with R744 cascade, MT distribution with R744	24 kg R717 + 324 kg CO2
10	R290 with R744 cascade, MT distribution with R744	24 kg R290 + 324 kg CO2
11	Direct evaporation HFO1234yf (MT) and R404A (LT)	162 kg HFO1234yf + 162 kg R404A
12	Booster with R717 and secondary fluid for distribution (CO2)	24 kg R717 + 324 kg CO2

Plant characterization – Energetic performance

$$COP = \frac{\dot{Q}_{LT} + \dot{Q}_{MT}}{\dot{W}_{LT} + \dot{W}_{MT}}$$

$$P_{cond\_fan} = 0.027 * (\dot{Q}_{LT} + \dot{Q}_{MT} + \dot{W}_{LT} + \dot{W}_{MT})$$

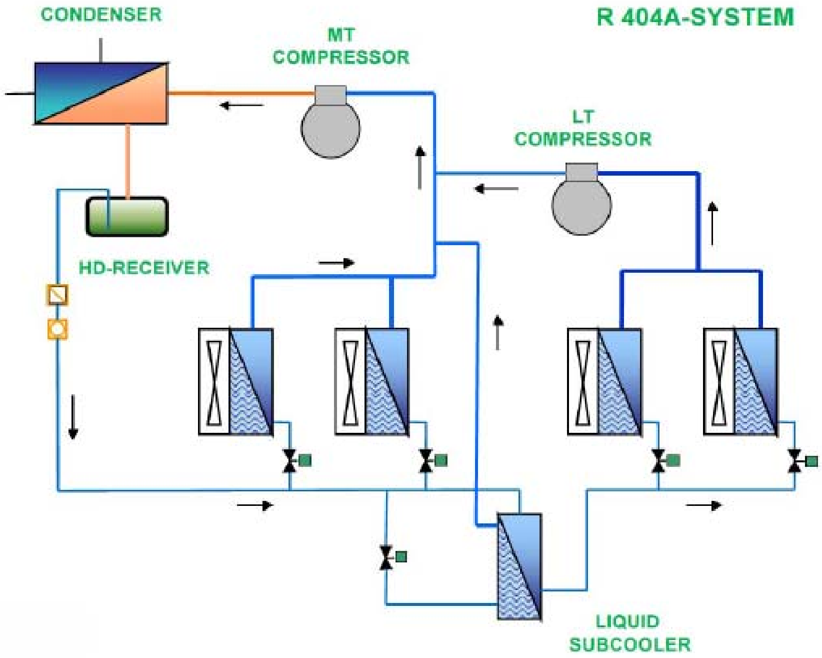
$$P_{evap\_fan} = 0.04 * (\dot{Q}_{LT} + \dot{Q}_{MT})$$

$$P_{defrost} = 0.03 * (\dot{Q}_{LT} + \dot{Q}_{MT})$$

$$P_{anti-sweat} = 0.02 * (\dot{Q}_{LT} + \dot{Q}_{MT})$$

$$COPS = \frac{\dot{Q}_{LT} + \dot{Q}_{MT}}{\dot{W}_{LT} + \dot{W}_{MT} + P_{cond\_fan} + P_{evap\_fan} + P_{defrost} + P_{anti-sweat}}$$

$$PEU = \frac{\dot{Q}_{LT} + \dot{Q}_{MT}}{COPS} * 8760 * (\text{Refrigeration\_load\_ratio}) * \frac{1}{\eta_{elec}}$$



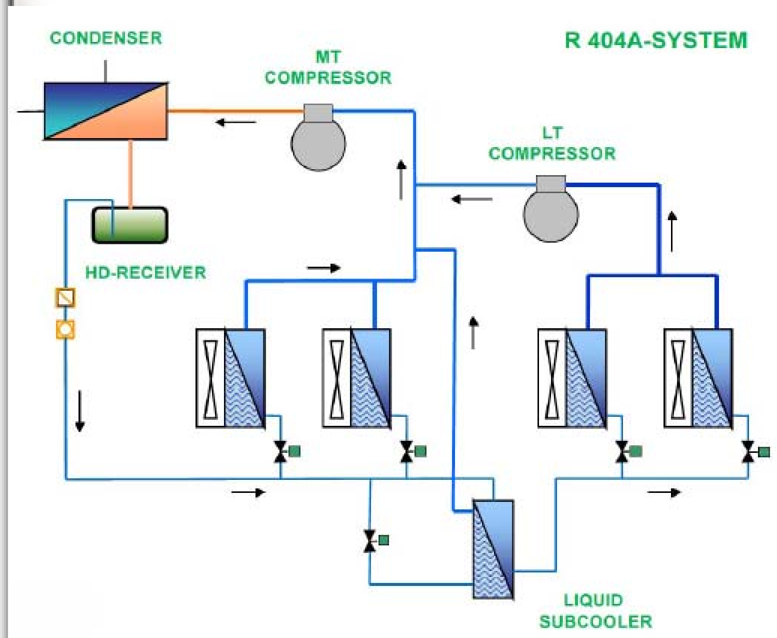
Plant characterization – Global warming / cost estimation

$$TEWI = GWP\ L_{annual}\ m_{charge}\ n + GWP\ m_{charge}\ (1-\alpha_{recovery}) + n\ E_{annual}\ \beta$$

$$Cost = a * \dot{Q}^{b}$$

	Compressors				Condensers	
	R404A	HFO1234yf	CO2	R717	R404A	R717
a	824	1231	3827	1225	83.217	378.27
b	-0.4017	-0.4674	-0.7195	-0.4148	-0.0032	-0.2171

Cost=Cost(compressor+condenser)*3.5



Supermarket application

Seasonal averaged

Altern.	$\dot{W}_{LT}$ [kW]	$\dot{W}_{MT}$ [kW]	Q_{cond} [kW]	P_{cond_fan} [kW]	P_{aux} [kW]	COP [-]	COPS [-]	PEU [TJ]	TEWI [ktonCO2 eq.]	TEWI [%direct emissions]	System costs [kEuro]	TCO [kEuro/year]
1	3.3	38.0	161.3	4.3	15.1	3.2	2.2	2.95	4.65	44.9	144.80	68.56
2	3.3	36.0	159.3	4.3	15.1	3.3	2.3	2.86	4.55	45.6	143.40	66.78
3	3.3	33.8	157.0	4.3	15.0	3.5	2.4	2.72	2.59	0.1	161.90	66.50
4	3.7	49.0	172.7	4.7	15.5	2.5	1.9	3.59	3.13	0.0	214.58	87.80
5	4.8	36.4	161.1	4.3	15.1	3.1	2.2	2.96	3.62	29.0	172.20	71.95
6	4.8	34.2	158.9	4.3	15.1	3.3	2.3	2.82	2.48	0.0	141.50	65.93
7	3.0	37.1	160.1	4.3	17.9	3.1	2.1	3.01	2.67	0.0	207.90	76.93
8	3.4	42.4	165.8	4.5	18.0	2.8	1.9	3.35	2.94	0.0	145.10	75.54
9	4.7	35.4	159.9	4.3	15.4	3.1	2.2	2.88	2.54	0.0	225.70	76.76
10	4.8	41.9	166.7	4.5	15.5	2.7	2.0	3.29	2.86	0.0	174.10	77.86
11	3.3	33.8	157.1	4.2	15.0	3.5	2.4	2.72	3.43	30.5	155.50	65.82
12	3.0	34.9	157.9	4.3	15.4	3.3	2.3	2.79	2.44	0.0	207.00	72.89

TCO (Total Cost of Ownership):
Depreciation period: 15 years
Interest: 8%
Energy costs: 150 €/MWh

Supermarket application

Ranking of systems

No condenser heat recovery					Condenser heat recovery				
Altern.	CSR [ktonCO2 eq.]	TCO [k€/year.]	Safety [Class.]	Total score	Altern.	CSR [ktonCO2 eq.]	TCO [k€/year.]	Safety [Class.]	Total score
6	11.8	11.9	6.2	8.9	6	11.6	12.0	6.2	8.9
3	11.3	11.7	4.7	8.4	3	12.0	11.8	4.7	8.7
12	12.0	8.5	5.7	7.8	12	12.0	9.9	5.7	8.2
11	7.1	12.0	7.7	7.6	8	9.4	8.2	12.0	7.8
8	9.5	7.1	12.0	7.5	11	7.4	12.0	7.7	7.7
9	11.5	6.5	5.7	6.9	9	11.7	8.5	5.7	7.7
10	9.9	6.0	6.0	6.3	7	11.0	8.1	1.0	6.5
5	6.1	8.9	7.7	6.3	5	6.2	9.3	7.7	6.4
7	10.9	6.4	1.0	5.9	10	9.3	6.9	6.0	6.4
2	1.5	11.5	7.7	5.6	2	2.0	11.2	7.7	5.7
1	1.0	10.6	7.7	5.1	1	1.0	9.5	7.7	4.8
4	8.5	1.0	7.7	4.5	4	6.8	1.0	7.7	3.9

CSR (Corporate Social Responsability):
based on TEWI: lowest 12; highest 1
Safety (safety class & amount of refrigerant)
Total: (CSR+TCO+0.5*Safety)/3.0

Supermarket application

Ranking of systems

With heat recovery

Condenser heat recovery						
Altern.	CSR [ktonCO2 eq.]	TCO [k€/year.]	Safety [Class.]	Total score		
6	11.6	12.0	6.2	8.9	6	Direct evaporation of HFO1234yf (MT) with R744 cascade (LT)
3	12.0	11.8	4.7	8.7	3	Booster with direct evaporation of HFO1234yf
12	12.0	9.9	5.7	8.2	12	Booster with R717 and secondary fluid for distribution (CO2)
8	9.4	8.2	12.0	7.8	8	Booster with R290 and secondary fluid for distribution (potassium formate)
11	7.4	12.0	7.7	7.7	11	Direct evaporation HFO1234yf (MT) and R404A (LT)
9	11.7	8.5	5.7	7.7	9	R717 with R744 cascade, MT distribution with R744
7	11.0	8.1	1.0	6.5	7	Booster with R717 and secondary fluid for distribution (potassium formate)
5	6.2	9.3	7.7	6.4	5	Direct evaporation of R404A (MT) with R744 cascade (LT)
10	9.3	6.9	6.0	6.4	10	R290 with R744 cascade, MT distribution with R744
2	2.0	11.2	7.7	5.7	2	Booster with direct evaporation of R404A and internal heat exchangers
1	1.0	9.5	7.7	4.8	1	Reference: Booster with direct evaporation of R404A
4	6.8	1.0	7.7	3.9	4	Booster with direct evaporation of R744

CSR (Corporate Social Responsability):
based on TEWI: lowest 12; highest 1
Safety (safety class & amount of refrigerant)
Total: (CSR+TCO+0.5*Safety)/2.5

Comparison with previous studies

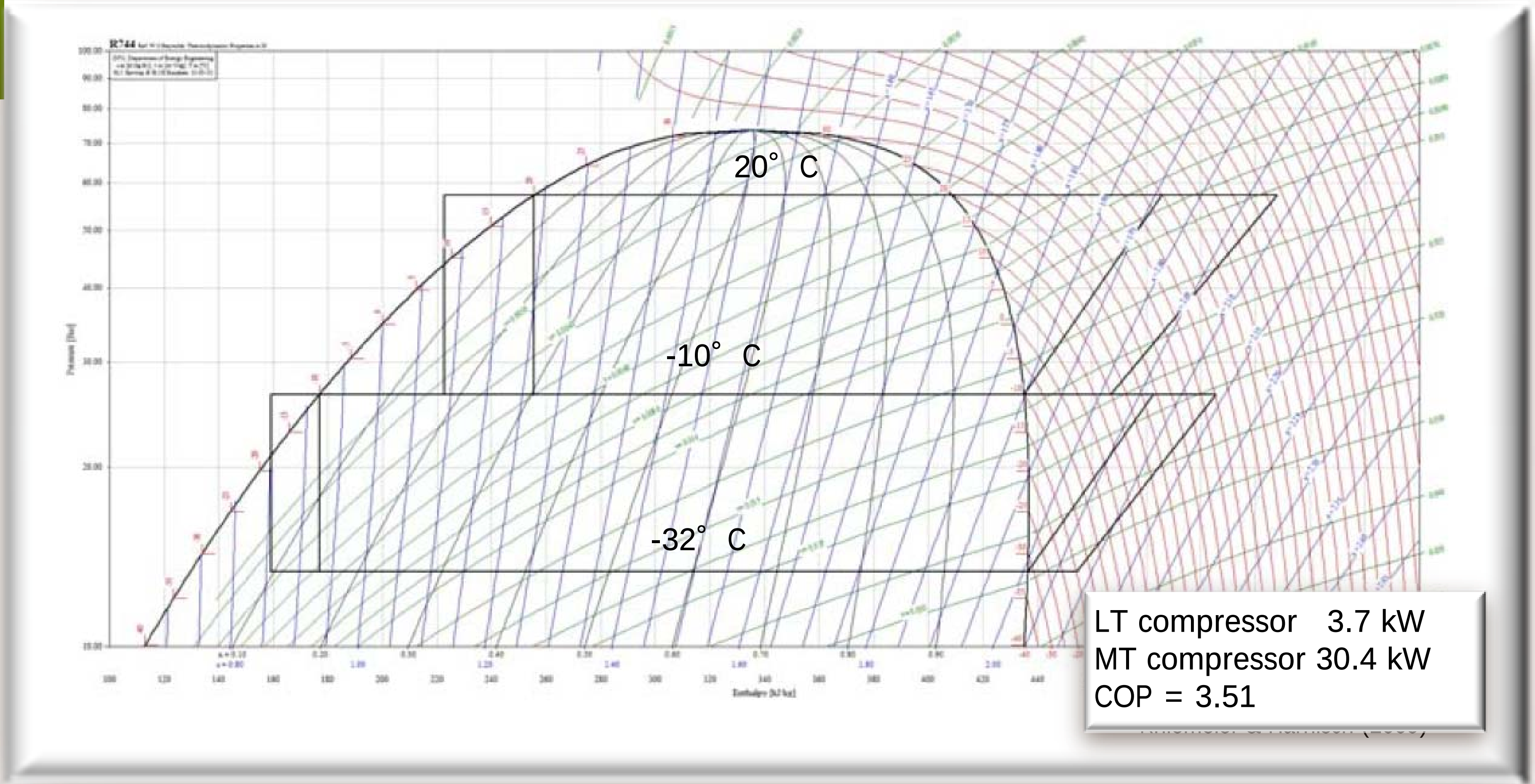
Major difference for CO2 system

Altern.	PEUrelat [%] This study	PEUrelat [%] Rhiemeier	Ratio [-]
1	100	100	1.0
2	97		
3	92		
4	121	100	1.2
5	100	100	1.0
6	96	93	1.0
7	102	115	0.9
8	113		
9	98	87	1.1
10	111	100	1.1
11	92	93	1.0
12	94		

Rhiemeier & Harnisch (2009)

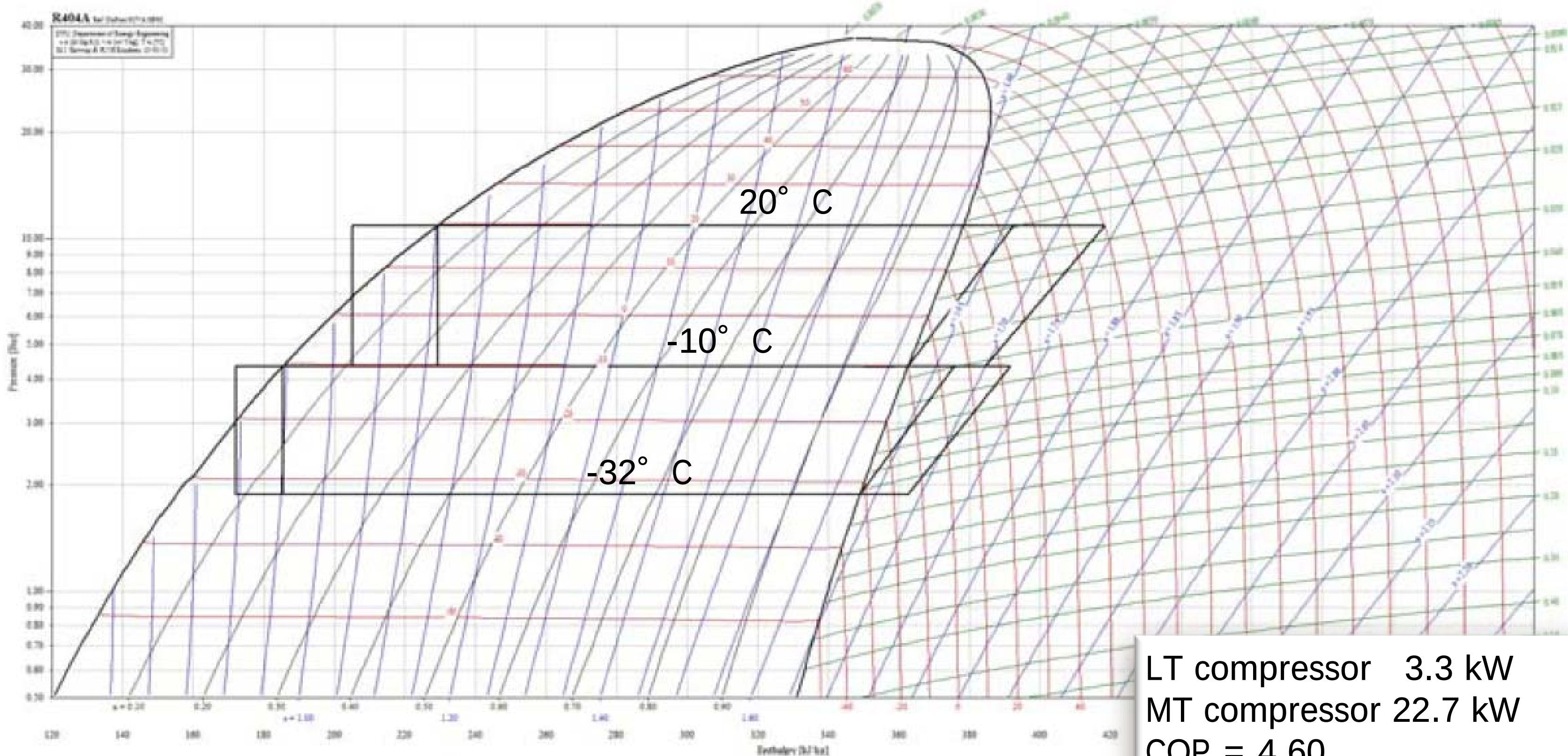
Comparison with previous studies

Major difference for CO2 system: CO2 system



Comparison with previous studies

Major difference for CO2 system: R404A system



LT compressor 3.3 kW
MT compressor 22.7 kW
COP = 4.60

Conclusions

Energy & Emissions (Reference is R404A)

Energetic performance:	
Direct evaporation of HFO1234yf	8% savings
Direct evaporation of HFO1234yf (MT) + direct evaporation of R404A (LT)	8% savings
Ammonia with CO_2 distribution	5% savings
Emission reduction:	
Ammonia with CO_2 distribution	48% reduction
Direct evaporation of HFO1234yf (MT) + CO_2 cascade (LT)	47% reduction
Ammonia with CO_2 distribution (MT) + CO_2 cascade (LT)	45% reduction