THE USE OF AMMONIA & CO_2 HEAT PUMPS IN FOOD PROCESSING

By KLAAS VISSER
L. AIRAH, Hon M.IIR, M. Inst. R, M. eurammon, Aff. CIBSE
PRINCIPAL
KAV CONSULTING Pty. Ltd
P.O. BOX 1146, KANGAROO FLAT, Vic 3555 AUSTRALIA
Tel:- +61 3 54 479 436, Fax:- +61 3 54 479 805
kavconsult@bigpond.com

KAV CONSULTING PTY LTD
Advisers to the Refrigerated Food Industries

IOR ior.org.uk

KAV CONSULTING PTY LTD Advisers to the Refrigerated Food Industries

iif iir

Table 1. Some Food Processes Requiring Simultaneous Heating and Cooling

PROCESSING TYPE	TYPE OF HEATING APPLIED			TYPE OF COOLING APPLIED			
	Warm Water	Hot Water	Product Heating	Product Chilling	Product Freezing	Chilled Water	Space Cooling
Beef slaughter	✓	✓	Decontamination	✓	✓		✓
Sheep slaughter	✓	✓	Decontamination	✓	✓		✓
Pig slaughter	✓	✓	Scalding	✓	✓		✓
Chicken processing	✓	✓	Scalding	✓	✓	✓	✓
Milk processing		✓	Pasteurizing	✓	✓	✓	✓
French fries			Drying		✓		
Vegetables		✓	Blanching	✓	✓	✓	
Beer brewing		✓	✓	✓		✓	

IOR ior.org.uk · KAV CONSULTING PTY LTD Advisers to the Refrigerated Food Industries · iif iir

Table 2. Specific utilities consumption Australian red meat industry, 1978 (Graham, 1979)

	UTILITY TYPE	SPECIFIC UTILITY CONSUMPTION		
No.	Description	Min	Max	Avg
1	Electricity consumption – MJ/tonne HSCW			
	.1 Range and average	170	2,100	1,030
	.2 No rendering, no cold store			420
	.3 Rendering, no cold store			842
	.4 No rendering, cold store			837
	.5 Rendering, cold store			1,083
2	Fuel consumption – MJ/tonne HSCW			
	.1 Range and average	460	10,510	4,120
	.2 Water heating only			1,090
	.3 Rendering with waste heat recovery			4,440
	.4 Rendering with no waste heat recovery			5,140
3	Total energy consumption – MJ/tonne HSW			
	Electricity plus gas	630	12,610	5,150
4	Water consumption – M^3/tonne HSCW			
	Range and average	4.1	43	16.6

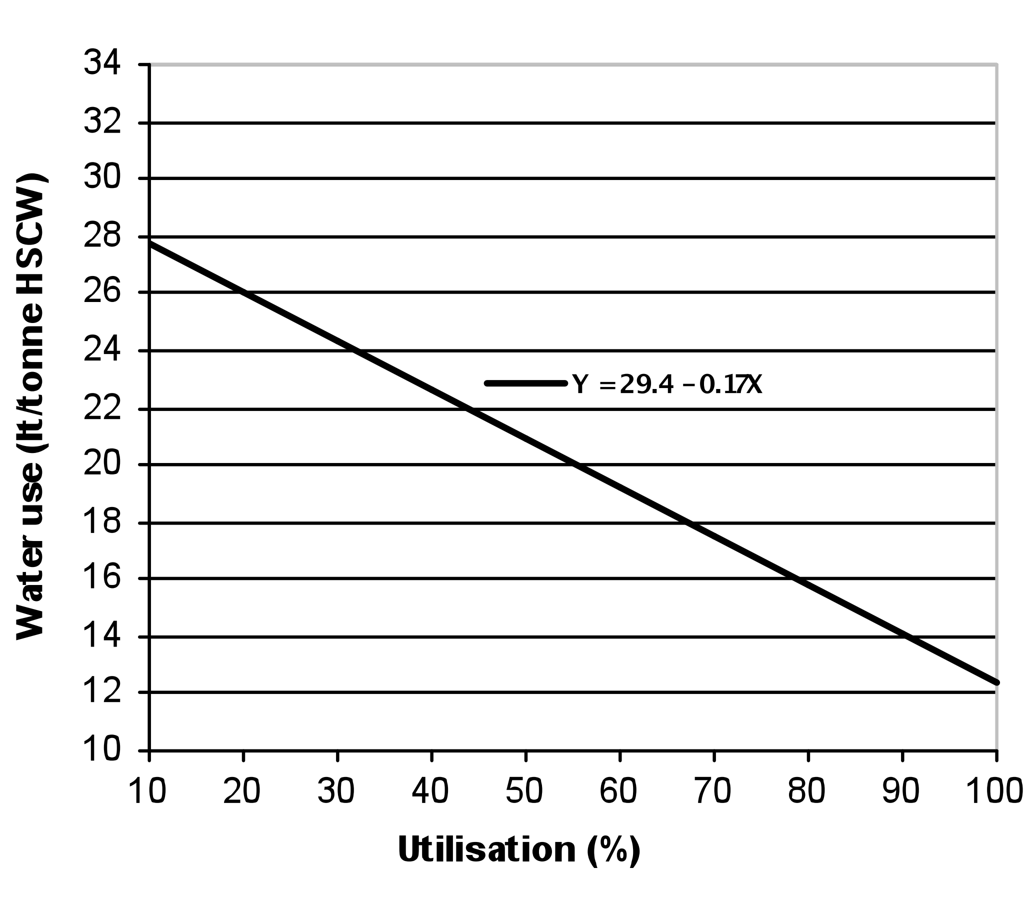


Figure 1. The influence of plant utilisation on volume of water used per tonne dressed carcass weight processed – Graham (1979)

IOR ior.org.uk

KAV CONSULTING PTY LTD Advisers to the Refrigerated Food Industries

iif iir

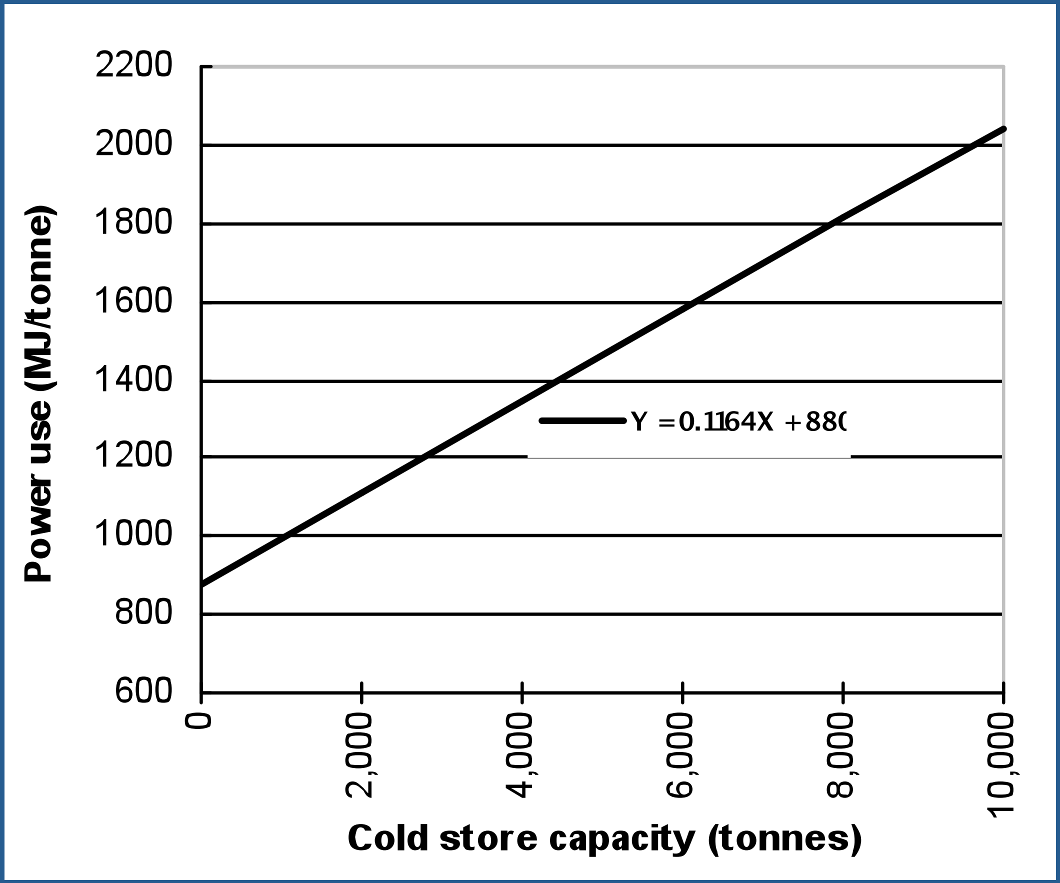


Figure 2. The influence of cold store capacity on power used per tonne of dressed carcass weight processed

Table 3. Approximate utility consumption Australian export meat processing industry

	UTILITY TYPE	SPECIFIC UTILITY CONSUMPTION		
No.	Description	1978[1]	1998[2]	Future[2]
1	Water – lt/tonne HSCW[3]			
	.1 Range	4.1 - 43	9 - 14	4 - 5
	.2 Average	16.6	12	4.5
2	Electricity, GJ/tonne HSCW			
	.1 Range	0.2 - 2.1	0.85 - 1.1	0.75 - 1.0
	.2 Average	1.03	1.0	0.9
3	Fuel, GJ/tonne HSCW			
	.1 Range	0.46 - 10.5	3.0 - 5	2.5 - 3.0
	.2 Average	4.12	3.5	2.9
4	Energy total, GJ/tonne HSCW			
	.1 Range	0.66 - 12.6	3.4 - 5.4	3.25 - 4.0
	.2 Average	5.15	4.5	3.8

[1] **From Table 2** [2] **Visser (1998)** [3] **HSCW = Hot Standard Carcase Weight**

Table 4. Energy Consumption of Three Processing Plants

No	PARAMETER DESCRIPTION	PLANT BY SPECIES PRODUCT TYPE					
1	Livestock converted	Pigs [1]		Chickens		Beef - Proposed [2]	
2	Type of plant	Chilled carcases [3]		Full service [4]		Full service [5]	
3	Type of refrigeration plant and condenser type	Single stage NH_3, evap. condenser		Two stage NH_3, evap. condenser		Two stage transcritical CO_2, adiabatically assist. gas cooler	
4	Type of water heating	Gas	NH_3 heat pump & gas	Gas	NH_3 heat pump & gas	Gas	Transc. CO_2 & gas
5	Annual Dressed Weight, (tonnes)	15,000		47,500		22,500	
6	Annual electrical energy cons. kWhs/1000	1,800	2,186[6]	15,000	16,761[6]	3,600	4,000[7]
7	Annual electrical energy cons. GJ	6,480	7,855	54,000	60,340	12,960	14,400
8	Specific elect. energy cons. kWhr/t	120	146	316	353	160	178
9	Specific elect. energy cons. GJ/t	0.43	0.53	1.14	1.27	0.58	0.64
10	Gas consumption, GJ	18,250	7,000[6]	56,905	5,000[6]	18,037	5,175[7]
11	Specific gas consumption, GJ/t	1.22	0.47	1.18	0.11	0.8	0.23
12	Total spec. energy cons. (9+11) GJ/t	1.67	1.0	2.32	1.38	1.38	0.87
13	Electrical CO_2 emissions, tonne 1.2kg/kWhr	2,160	2,618	18,000	20,113	4.320	4,800
14	Gas CO_2 emissions, tonne 56.3 Kg/GJ	1,027	394	3,204	282	1,015	291
15	Total CO_2 emissions, (13+14)	3,087	3,012	21,209	20,395	5,335	5,091
16	Specific CO_2 emissions, t/tonne (15÷5)	0.206	0.201	0.447	0.429	0.237	0.226
17	Reduction in specific energy cons. GJ/t	-	0.67		0.094		0.51
18	Reduction in specific energy cons. %	-	40		40.5		37.0
19	Reduction in specific emissions, t/t		0.005		0.018		0.011
20	Reduction in specific emissions, %		2.5		4		4.6

(1) Actual existing plants with gas water heating and calculated heat pumps.
(2) This superior prime beef plant did not proceed due to competition from ethanol production for feed grain.
(3) Plant produced chilled carcases only and has no freezing or cold store.
(4) Plant produces mostly fresh products for same day delivery but uses low temp. blast chilling. Also has small amount of blast freezing and cold storage.
(5) Plant would produce high value chilled beef with little freezing and a small cold store.
(6) Based on a COP of 5.55 with liquid sub-cooling and heat recovery from high stage discharge and 10% losses between metering point and consumer. Assumed gas heater efficiency 80%. See Item 37.3 Table 7.
(7) 11% extra transcritical running. Plant would run transcritically during part of the year due to hot climate.

IOR ior.org.uk

KAV CONSULTING PTY LTD
Advisers to the Refrigerated Food Industries

Table 5. Calculation of NH_3 heat pump power consumption to generate 68°C hot water

	PARAMETER	PIG PLANT	CHICKEN PLANT
No	DESCRIPTION	VALUE	VALUE
1	Amount of heat required, GJ Table 4, Item 10	18,250	56,905
2	Heat supplied by gas, GJ Table 4, Item 10	7,000	5,000
3	Heat from heat pump, GJ	11,250	51,905
4	Nett heat from heat pump, GJ @ 80% gas heater efficiency	9,000	41,524
5	Total kWhrs @ 277.77 kWhr/GJ, x 1,000	2,500	11,534
6	COP including high stage compressor desuperheat and liquid sub-cooling	5.55	5.55
7	Electrical power consumption, 6 ÷ (+ 1)	382	1,761
8	Base power consumption, Item 6, Table 4, kWhrs x 1,000	1,800	15,000
9	Power consumption with heat pump, these are the values for Item 6 in the heat pump columns in Table 4 above, kWhrs x 1,000	2,182	16,761

IOR ior.org.uk

KAV CONSULTING PTY LTD Advisers to the Refrigerated Food Industries

iif iir

Table 6. Heat Pump Performance of a 330m3/hr swept Volume High Pressure Ammonia Compressor

SST ^{0}C	Qe kW	N BkW	Qc kW	COP	Parameter	
25.0	579.1	136.1	709.6	4.25	Sat. suction temperature	30
27.5	635.3	138.3	769.7	4.60	Condensing temperature, ^{0}C	73
28.4	657.0	138.6	795.6	4.74	Water inlet temp, ^{0}C	20
30.0	**695.2**	**139.4**	**832.7**	**4.99**	Water outlet temp, ^{0}C	68
32.5	758.7	140.4	898.6	5.41	Water temp rise, K	48
35.0	826.1	140.8	966.9	5.87	Condenser liquid subcool, K	5.0

In both cases a "reverse cascade" CO_2 heat pump is also calculated. In this case the NH_3 compressor would run at –10 SST/ +15°C SCT with a COP of 7.2. See Fig. 4. The CO_2 heat pump compressor at +10°C SST, and 80 bar discharge pressure for 68°C water and 100 bar for 80°C water. In all cases the gas cooler CO_2 exit temperature would be +20°C. From Fig. 3 we note the COP's at 20°C gas cooler exit are 4.85 at +10 SST and 80 bar and 3.9 at +10/100 bar. See Item 15, Table 7. It is clear that the reverse cascade CO_2 heat pump using the discharge of a high stage ammonia compressor is more efficient when generating both 68°C and 85°C hot water. The efficiency is in all cases enhanced by extracting heat from the 1st stage compressor discharge.

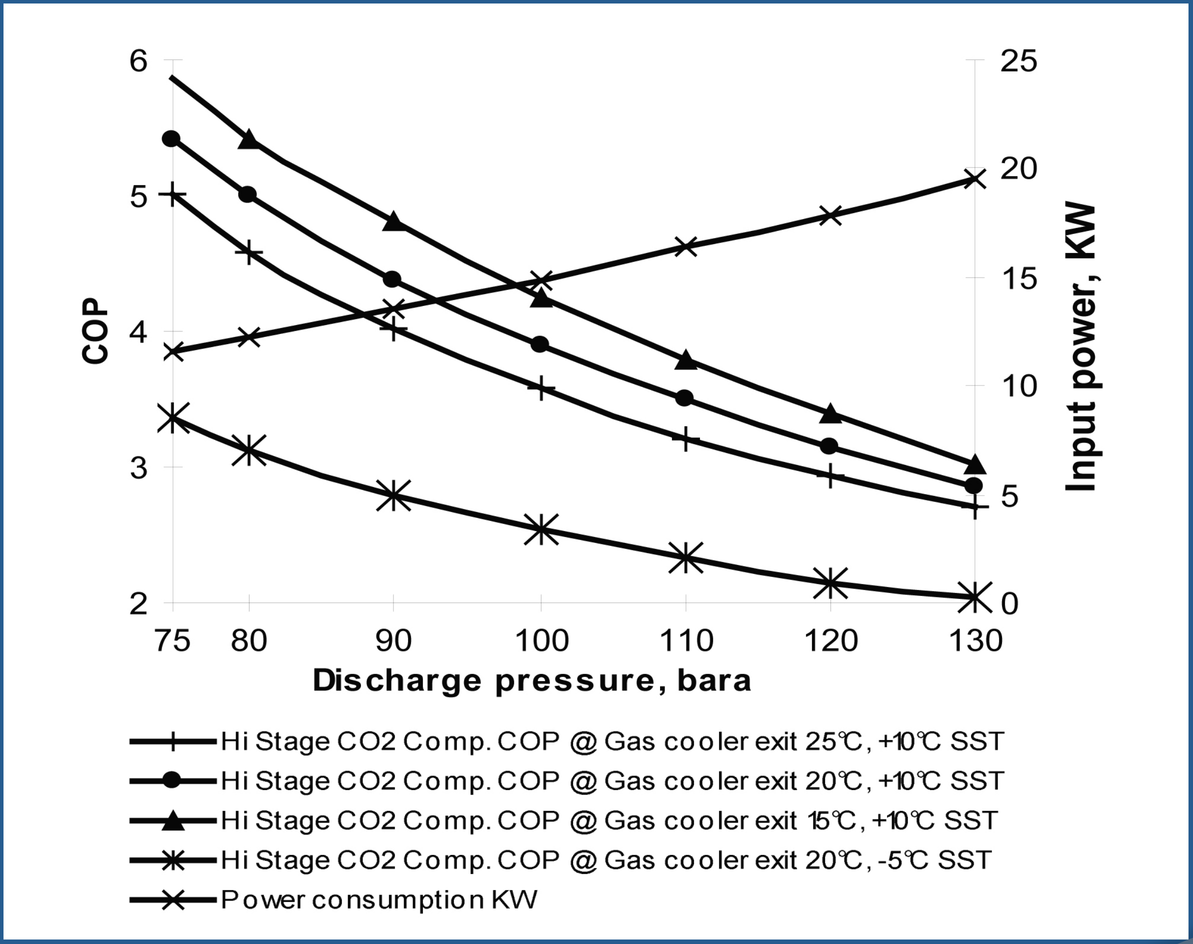


Figure 3. COP and Power Consumption Variation with Discharge Pressure and CO_2 Gas Cooler Exit Temperature

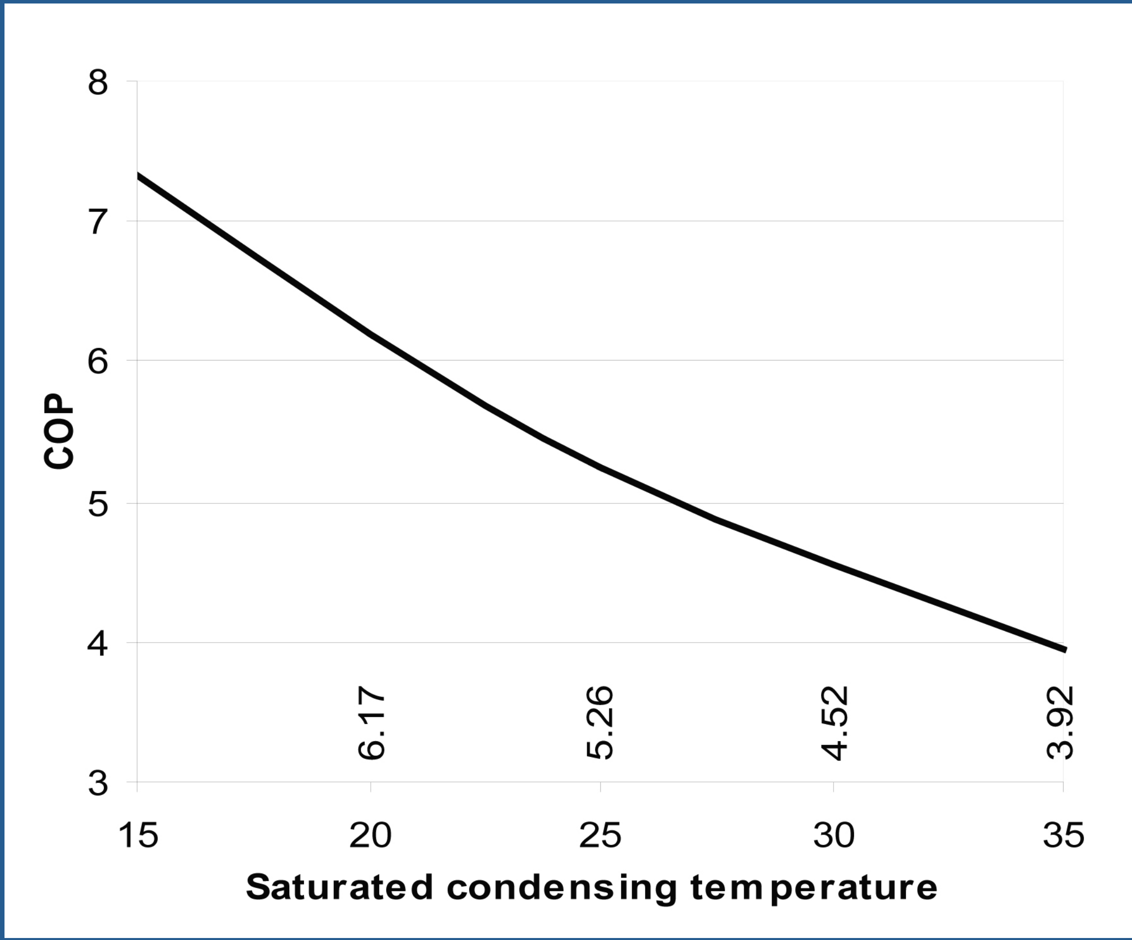


Figure 4. Ammonia Compressor COP Variation with Sat. Condensing Temperature at -10°C Saturated Suction. N.B. Based on BKW

IOR ior.org.uk | KAV CONSULTING PTY LTD Advisers to the Refrigerated Food Industries | iif iir

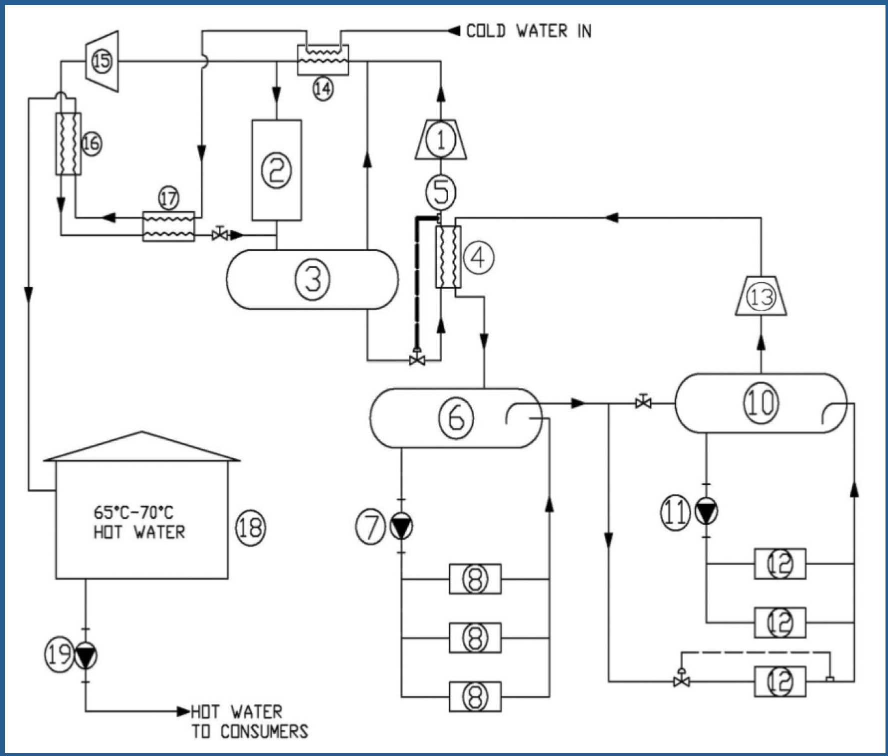
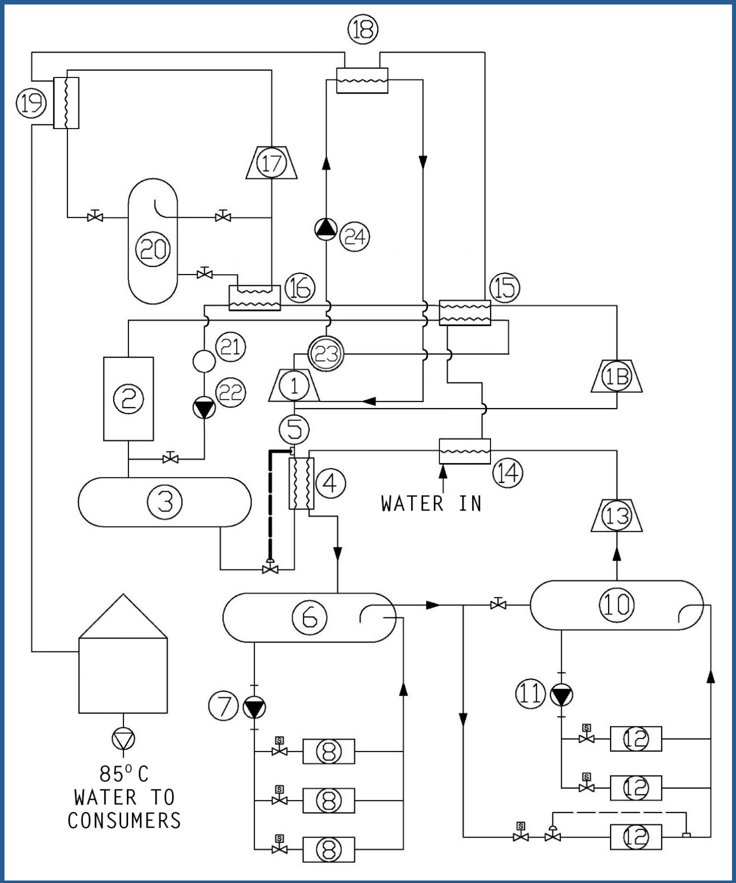


Figure 5. Ammonia CO_2 Cascade System with NH_3 Heat Pump for Process Water Heating. (Visser 2009)

Legend Figure 5

Item No	Description
1	Ammonia high stage compressor
2	Condenser
3	Liquid receiver
4	Cascade CO_2 condenser
5	Suction trap
6	High stage CO_2 pump accumulator
7	High stage CO_2 liquid pump
8	High stage chilling and cooling including high occupancy areas
9	Low temp cold store on DX
10	Low temp CO_2 pump accumulator
11	Low temp CO_2 liquid pump
12	Process freezing loads with LR CO_2 evaporators
13	CO_2 compressor
14	Compressor discharge gas de-superheater
15	High pressure NH_3 heat pump compressor
16	Ammonia condenser
17	Water cooled liquid NH_3 sub-cooler
18	Hot water storage
19	Hot water circulation pump



Legend Figure 6

Item No	Description
1-13	See Figure 5 in previous slide
1B	High stage compressor matched to CO_2 compressor item 17
14	1st stage water heater from booster discharge
15	2nd stage water heater from 1B discharge
16	Ammonia cascade condenser/CO_2 evaporator
17	Transcritical single stage CO_2 compressor + 10/105 bar
18	Compressor oil cooling – stage 3 water
19	CO_2 water heater – stage 4
20	CO_2 expansion vessel
21	Ammonia liquid receiver
22	Liquid Ammonia transfer pump
23	Screw compressor oil separator
24	Screw compressor oil pump

Figure 6. Schematic diagram of a CO_2/NH_3 cascade system with pumped CO_2 on high and low stages and also DX on low stage

IOR ior.org.uk

KAV CONSULTING PTY LTD
Advisers to the Refrigerated Food Industries

Table 7. Comparison of 1,000 kW Heating Capacity Ammonia and CO_2 Heat Pumps to Deliver 68°C and 85°C Hot Water from a Mains Water Temperature of +15C

	PARAMETER	WATER TEMP.			
No.	DESCRIPTION	+68°C		+85°C	
1	**Heat pump type**	NH_3 (1)	CO_2 (2)	NH_3 (1)	CO_2 (2)
2	Heat pump capacity, kW	1,000	1,000	1,000	1,000
3	Initial water temp., °C	15	15	15	15
4	Final water temp., °C	68	68	85	85
5	Water temperature rise, K	53	53	70	70
6	Water flow rate, litres/second	4.5	4.5	3.4	3.4
7	Max. water temp. from heat pump, °C	68	68	68	85
8	Heat from heat pump, kW	1,000	1,000	757	1,000
9	Heat from gas, kW	0	0	243	0
10	Heat from 1st stage compressor superheat, kW (3)	70	40	53	40
11	Heat from liquid sub cooling, kW (4)	93	0	70	0
12	Heat rejected by heat pump compressor, kW	837	960	634	960
13	Heat pump Sat. Suction Temperature, °C	+30	+10	+30	+10
14	Heat pump cond. temp./press., °C/bara	+73	80 bar	+73	100 bar
15	Heat pump 's from Figs. 3 & 4	4.99 (5)	4.85 (6)	4.99 (5)	3.9 (6)
16	Heat pump compressor power 12 ÷ (15 + 1)	140	164	106	196
17	Heat load to heat pump comp. 15x16	697	796	528	764
18	Ammonia 1st stage compressor SST, °C	–10	–10	–10	–10
19	Ammonia 1st stage compressor SCT, °C	+30	+15	+30	+15
20	NH_3 1st stage compressor 's from Fig. 4 (7)	4.55	7.2	4.55	7.2
21	NH_3 hi stage compressor superheat, %	10	5	10	5
22	Hi stage compressor liquid sub-cooling, %	0	0	0	0
23	Superheat from hi st compress. disch., kW (8)	70	40	53	40

IOR ior.org.uk

KAV CONSULTING PTY LTD Advisers to the Refrigerated Food Industries

iif iir

Table 7. *Continued* Comparison of 1,000 kW Heating Capacity Ammonia and CO_2 Heat Pumps to Deliver 68°C and 85°C Hot Water from a Mains Water Temperature of +15C

	PARAMETER	WATER TEMP.			
No.	DESCRIPTION	+68°C		+85°C	
1	Heat pump type	NH_3 (1)	CO_2 (2)	NH_3 (1)	CO_2 (2)
24	Heat from high stage NH_3 compressor, kW	697	796	528	764
25	Hi stage NH_3 compr. power 24 ÷ (20 + 1)	126	97	95	93
26	Total power, 16 + 25	266	263	201	289
27	Credit condenser pump 1 fans	11	13	8	12
28	Total power maximum demand	255	250	193	277
29	Losses from power metering point to high efficiency motor consumers	10	10	10	10
30	Actual MD from refrig. and heat pump	283	278	214	308
31	Add gas heat, kW (see Item 9 above)	-	-	243	-
32	Heater efficiency, %	-	-	80	-
33	Total gas consumed, GJ(1GJ= 277.8 kWhr)	-	-	1.09	-
34	Total power consumption, GJ (30 / 277.8)	1.02	1.0	0.77	1.1
35	Total energy consumed, GJ/h	1.02	1.0	1.86	1.1
36	Hourly emissions				
	.1 Electrical @ 1.2 kg/kWhr	340	334	257	368
	.2 Gas @ 56.3 kg/GJ	-	-	61	-
	.3 Total, kg/hr	340	334	318	368
37	Total heating and cooling				
	.1 Total simult. heating and cooling, kW Item 2 plus Items (24 – 25)	1,571	1,699	1,433	1,671
	.2 Total power consumption, kWhr, 30	283	278	517 (9)	308
	.3 Overall - 37.1/37.2 Actual	5.55	6.11	2.77	5.43
38	Specific emissions kg/kW of heat and cold	0.216	0.197	0.219	0.22

Table 8. Evaluation of Overall Heating and Cooling COP for High Stage Transcritical CO_2 Refrigeration Systems

No	PARAMETER / DESCRIPTION	VALUE	
1	Water temperature, °C	+68	+85
2	Sat. suction temp. CO_2 compressor, °C	–5	–5
3	Compressor discharge pressure, bara	80	100
4	Heat pump capacity, kW	1,000	1,000
5	from Figure 4	3.12	2.54
6	Compressor BkW, 4 ÷ (5 + 1)	243	283
7	Compressor capacity, kW 4 – 6	757	717
8	Total kW heating and cooling	1,757	1,717
9	heating and cooling, BkW	7.23	6.07
10	Transmission losses (semi-hermetic compressors) %	5	5
11	Real based on metered kW	6.87	5.76

IOR ior.org.uk

KAV CONSULTING PTY LTD
Advisers to the Refrigerated Food Industries

Table 9. Summary and Comparison of Various Heat Pumps

Heat pump type. Heating capacity all types 1000 kW	Water temp. °C	Table reference		Total Cap. kW heating and cooling kW	Total power kW MD, kW	Real	Specific emission kg/kW
		Table No.	Item No.				
Two stage NH_3	68	7	37.1-3	1,571	283	5.55	0.216
NH_3 & CO_2	68	7	37.1-3	1,699	278	6.11	0.197
Two stage CO_2	68	8	4, 7-9, 11	1,757	256	6.87	0.175
Two stage NH_3 & gas	85	7	37.1 NH_3 & gas	1,433	214 + 303	2.77	0.219
NH_3 & CO_2	85	7	37.1 NH_3 & CO_2	1,671	308	5.43	0.22
Two stage CO_2	85	8	4, 7-9, 11	1,717	298	5.76	0.208

Conclusions

- Energy Savings of 37 to 40% may be achieved when installing Ammonia and CO_2 to water heat pumps as additional stages to conventional industrial ammonia refrigeration systems.
- High COP's are achieved due to savings in condenser fan pump power and heat recovery from compressor discharges, oil cooling and maximum liquid desuperheating from the heat pump condenser to the liquid receiver of conventional ammonia refrigeration systems.
- Two stage transcritical CO_2 refrigeration plants with heat recovery perform better than three stage ammonia plants, with the third stage acting as a heat pump, as do reverse cascade CO_2 heat pumps. There is an optimisation solution required when high suction pressure transcritical CO_2 compressors become available.
- In this type of application, i.e. Single pass water heating, CO_2 heat pumps produce lower emissions per kW of heat produced.