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CO_2 / NH_3 Cascade Refrigeration Systems

A viable and economical system for tomorrow

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The industrial refrigeration field, like any other field, is becoming more and more competitive. We therefore need to evaluate and carefully check alternative systems before deciding on a particular refrigeration system for a specific application.

For food processing, fisheries, meat packing or any other similar industry, where process temperature requirement is around (–)40°C, generally a two-stage ammonia refrigeration system has been used.

But we need to rethink the economic viability of such two-stage ammonia systems. One good alternative to consider is a cascade refrigeration system of two refrigerants with carbon dioxide on the low temperature side and ammonia on the high temperature side. This article makes a detailed techno-economic analysis of a CO_2 / NH_3 cascade system to check for its advantages and disadvantages in comparison with a conventional two-stage ammonia system.

Before going into the detailed analysis of such a system, let us first understand the basic features of these two types of refrigeration systems. For a two-stage ammonia system, there is a low-stage or booster compressor and a high-stage compressor, both operating on a common refrigerant – ammonia. The vapour compression is carried out in two stages. The booster or low-stage compressor discharge is introduced to the suction of the high-stage compressor via an inter-stage cooler (which cools the booster discharge gas by evaporation of high pressure liquid). A typical simple system with a flash type inter-cooler p - h (pressure - enthalpy) diagram is shown in **Figure 1**.

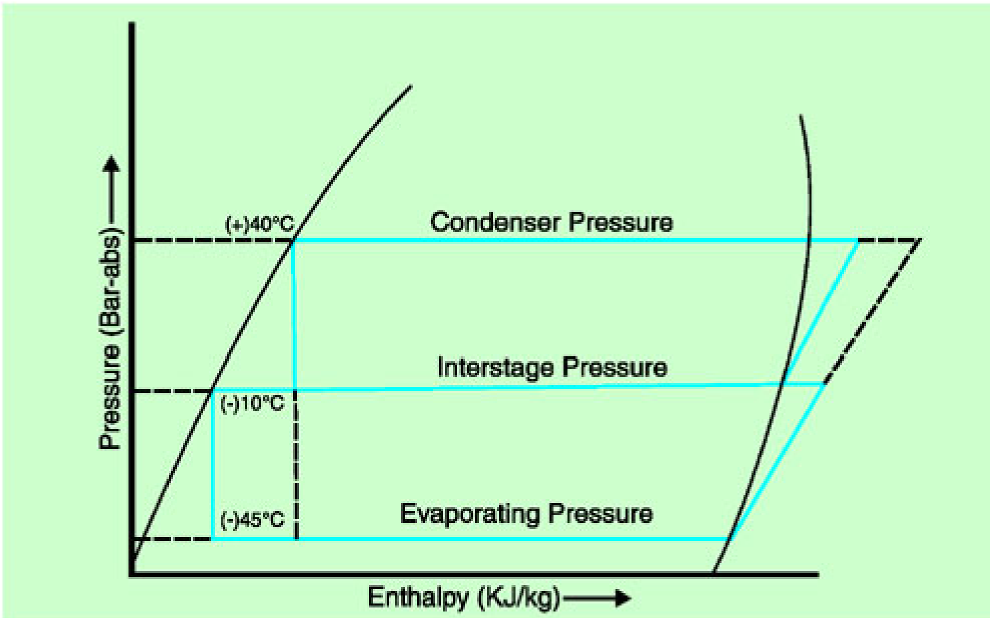

Figure 1 : p–h diagram for two-stage NH_3 system with flash intercooler

In a cascade refrigeration system there can be more than one refrigerant depending on the application or requirement of the plant. In such a cascade system, each refrigerant circuit is separate. For the present application CO_2 will be used as a refrigerant for the low temperature circuit and ammonia will be used for the high temperature circuit.

The condenser of the CO_2 circuit will act as the evaporator of the NH_3 circuit (generally known as cascade cooler or cascade condenser). Thus there will be no inter-stage cooler. For better understanding please refer Figure 2 which shows a schematic arrangement for a CO_2 / NH_3 cascade system.

Now for a detailed techno-economic analysis and comparison, let us consider a typical refrigeration system for food processing or similar application - for which the basic requirements are :

- Process temperature : (–)40 °C
- Evaporating temperature : (–)45 °C (for low-stage or low temperature cycle)
- Condensing temperature : (+)40 °C
- Capacity of plant required : 100 TR (351.63 kW)

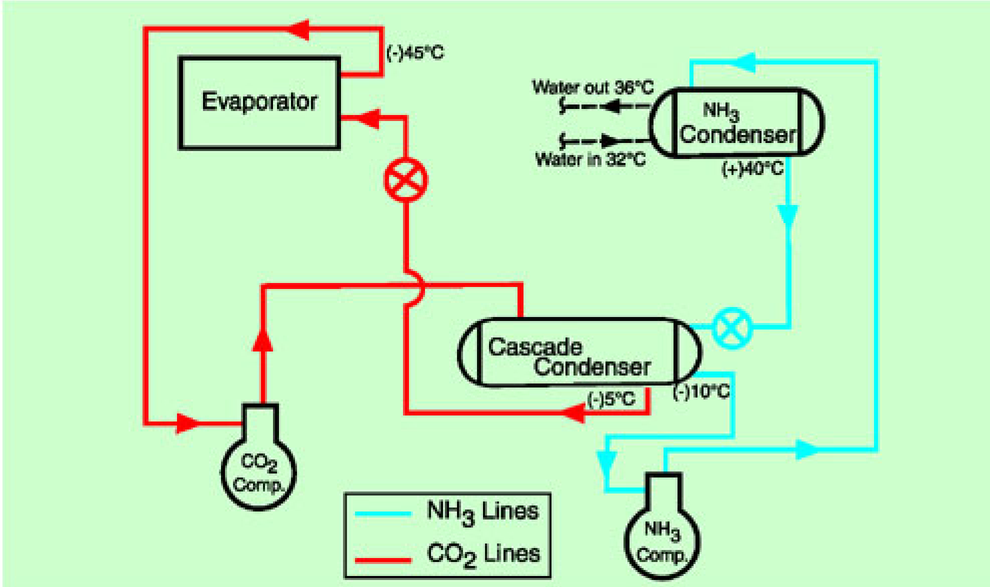

Figure 2 : Schematic arrangement for CO_2 / NH_3 cascade system

[top]

Please note that these parameters form a basis for comparison so that we can make all calculations and evaluate both the systems based on these common system parameters. Similarly for the compressor performance, the same pressure drop or temperature penalty for the suction / discharge line and the same suction gas super heating has been considered for both the systems. Also a specific make of screw or reciprocating compressor has been considered for analysis of operating parameters.

For the two-stage ammonia system we will consider operation of the low-stage compressor at a saturated evaporating temperature (–)45°C and saturated condensing temperature (–)10°C. Whereas, for the highstage compressor, operation has been considered at a saturated evaporating temperature of (–)10°C and saturated condensing temperature of (+)40 °C.

For the CO_2 / NH_3 cascade system we will consider operation of the low temperature circuit CO_2 compressor at a saturated evaporating temperature of (–)45°C and saturated condensing temperature of (–)5°C. Whereas for the high temperature circuit, NH_3 compressor operation will be considered at a saturated evaporating temperature of (–)10°C and saturated condensing temperature of (+)40 °C. This overlap of refrigerant temperatures in the cascade condenser is a “must” for such systems.

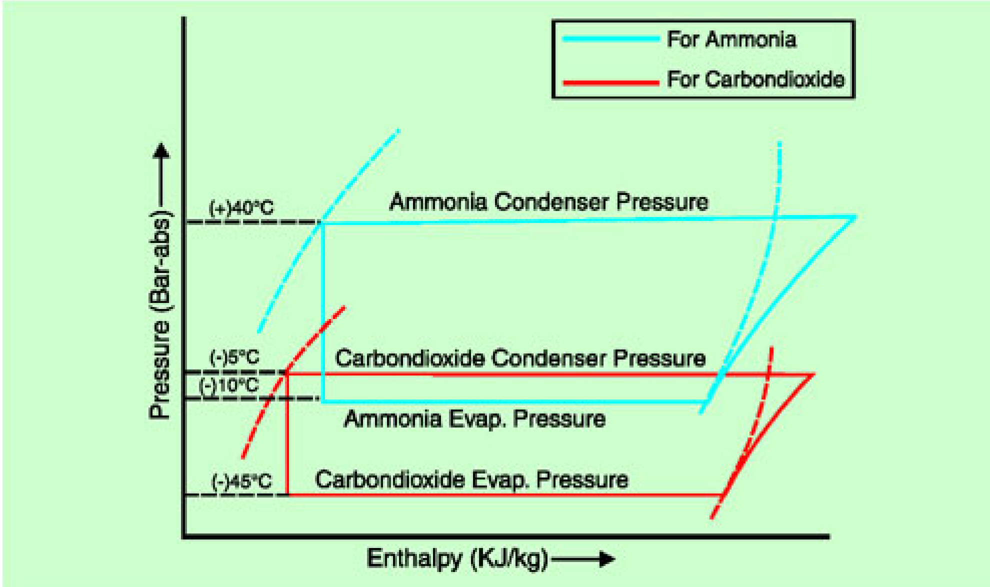

Figure 3 : p–h diagram for NH_3 / CO_2 cascade system

A typical simple CO_2 / NH_3 cascade system p - h (pressure - enthalpy) diagram is shown in **Figure 3**.

With these system parameters, important plant and relevant operating performance parameters are calculated and analysed . The evaluation of these parameters is made for both the options of screw as well as reciprocating compressors. A detailed analysis and comparison of all these basic operating and performance parameters is given in **Table 1** (for Screw Compressors) and in **Table 2** (for Reciprocating Compressors).

Also, for better understanding, the comparison of these performance-related parameters is shown in graphical form in **Figure 4, Figure 5, Figure 6, Figure 7, Figure 8** and **Figure 9**.

Let us now critically examine these operating performance parameters for both the refrigeration systems, for comparison and analysis, keeping **Table 1 & Table 2** as a reference. Columns 3 & 4 show the value of parameters for the low-stage ammonia of the two-stage system and low temperature CO_2 circuit of the cascade system respectively. Similarly columns 6 & 7 show the value of parameters for the high-stage ammonia of the two-stage system and high temperature NH_3 circuit of the cascade system respectively.

For analysis / comparison of these two systems, the following important operating / performance parameters are considered :

- Capacity of compressor required
- Coefficient of performance (COP)
- Compressor shaft power
- Oil cooler load & oil flow (for screw compressor)

- Volumetric efficiency of compressor
- Adiabatic compression efficiency of compressor
- Condenser capacity & water flow rate required
- Discharge vapour temperature
- Compression ratio
- Suction mass & volume flow rate required
- Compressor swept volume required
- Number of compressors required
- Total number of compressors required (for low + high stage)
- Compressor head / side cover cooling medium required (for recip compressor)

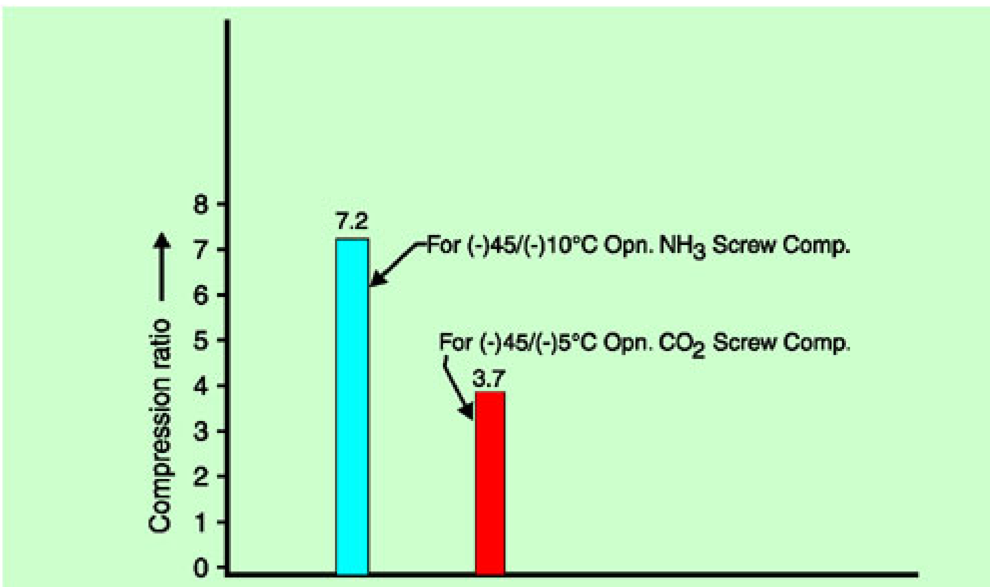

Figure 4 : Comparison of compression ratio

From a study of **Table 1** and **Table 2** we can conclude the following advantages / benefits of the CO_2 / NH_3 cascade system over a two-stage ammonia system:

1. Compressor size (or compressor swept volume) required for the CO_2 low-stage side is appreciably smaller as compared to the low-stage ammonia.

CO_2 has a much lower vapour specific volume at low temperatures compared to NH_3 . This is approximately 97% less at a saturated vapour of (–)45°C. Basically, compressors are selected based on volume flow rate requirement of a particular plant. Greater the vapour volume flow rate requirement - larger the compressor that is required. Hence with this advantage the compressor size for the low-stage is drastically reduced. This effect will have an added advantage when considering superheated suction vapour, as the difference of suction vapour specific volume (for CO_2 & NH_3) will be more for superheated vapour than saturated vapour.

As per **Table 1**, we require only one CO_2 low-stage screw compressor against nine similar capacity NH_3 lowstage screw compressors. Similarly, from **Table 2** we require only one CO_2 low-stage reciprocating compressor against eleven similar capacity NH_3 low-stage reciprocating compressors.

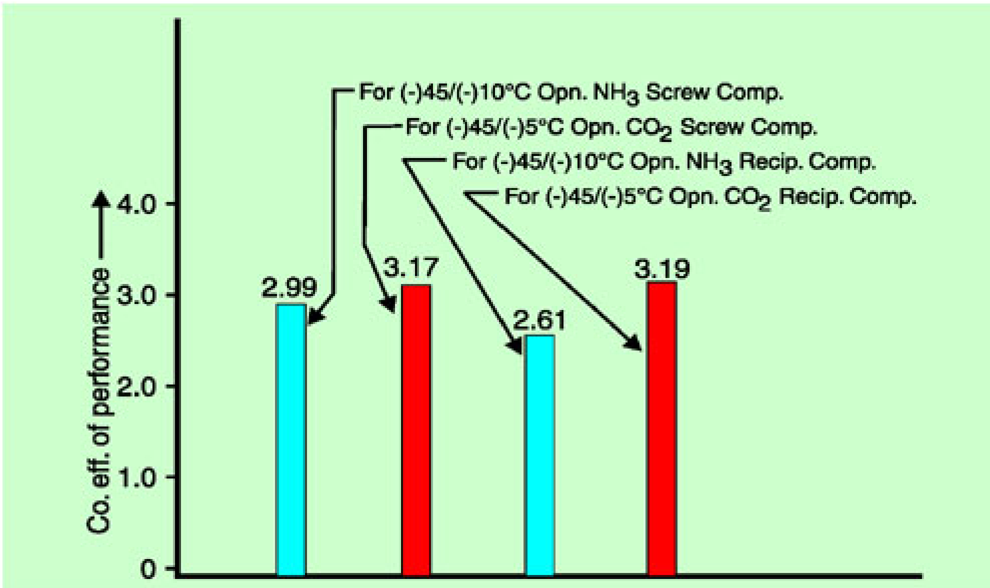

Figure 5 : Comparison of COP

The major contributing factor for the initial cost of a refrigeration plant is the compressor (approximately 15 to 25%) and thus the CO_2 low-stage system will appreciably reduce the initial plant cost . Each screw compressor is to be taken as a module consisting of compressor and its independent items such as motor, oil cooler, oil separator, suction / discharge valves, suction strainer, coupling, capacity control arrangement, interconnected piping, instruments & controls, cabling, base frame and structural items. Thus when the number of screw compressors is reduced from nine to one, there will be a huge reduction in cost of all such related items.

A related saving is the smaller plant room required and the lower cost of installation.

With the CO_2 low-stage system requirement of only 302.79 m^3/h compressor swept volume we can easily consider the option of adopting a reciprocating compressor; which in case of ammonia may not be a viable option-as the swept volume required is very high (3420.32 cu.m/hr.). A refrigeration plant with reciprocating compressors will be much cheaper (approximately 10 to 15%) as compared to a plant with screw compressors. Thus we can clearly conclude that with the option of reciprocating compressor, instead of screw compressor, there will be an appreciable saving in initial plant cost.

2. The compression ratio required for the low-stage is much lower for CO_2 . It is approximately 44 to 49% less compared to the ammonia booster stage.

The advantages of a lower compression ratio are better volumetric efficiency, lower discharge gas temperature and higher adiabatic compression efficiency. All these advantages of a lower compression ratio will have a greater effect on a reciprocating compressor compared to a screw compressor and this is clear from **Table 1** and **Table 2**.

As the discharge gas temperature is much lower for the low side CO_2 compressor, the chances of oil decomposition and its related operating problems are absent. Because of this lower discharge gas temperature and appreciably lower compression ratio, we have the option to adopt a reciprocating compressor for the lowstage CO_2 compressor. In the case of ammonia, it is almost impossible to consider a reciprocating compressor for such a high compression ratio and discharge gas temperature.

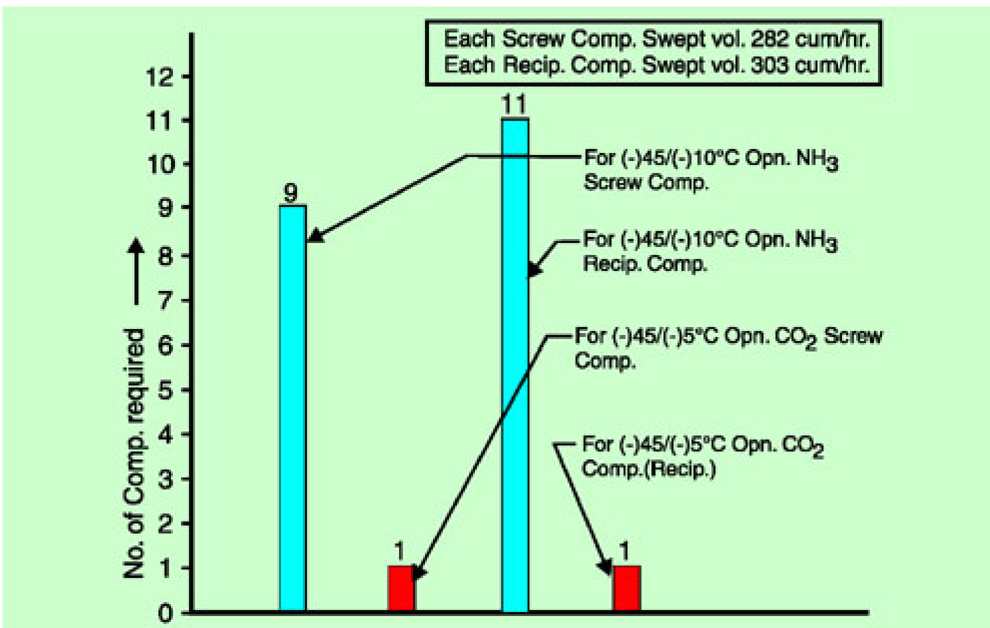

Figure 6 : Comparison of number of compressors required

As the compressor discharge gas temperature is appreciably lower for the CO_2 low-stage screw compressor (59°C as compared to 71.50°C for ammonia) the oil cooler load will also be less for CO_2 low-stage screw compressor (can be seen in Table 1). Thus the size of the oil cooler will be smaller, oil circulation rate will be lower, total oil required for the compressor will be less and the oil pump capacity and its power consumption will also be reduced. All these will result in reduction of initial plant cost and operating cost for the CO_2 lowstage side of a cascade system.

Similarly, because of low discharge gas temperature (62.40°C as compared to 112.90°C for ammonia) no external water head and side cover cooling is required for a CO_2 low-stage reciprocating compressor. In the case of ammonia low-stage reciprocating compressor, a water head / side cover cooling is a "must" under these operating conditions. Thus no water piping with valves, fittings and supports is required for the CO_2 low stage reciprocating compressor and this will reduce the cooling water pump power consumption. All of which would result in a reduction of initial as well as operating cost.

With a low discharge gas temperature there is less chance of oil decomposition with its related problems and failure of the discharge valve plate of the compressor. Thus, less service and maintenance is required for such plants with CO_2 .

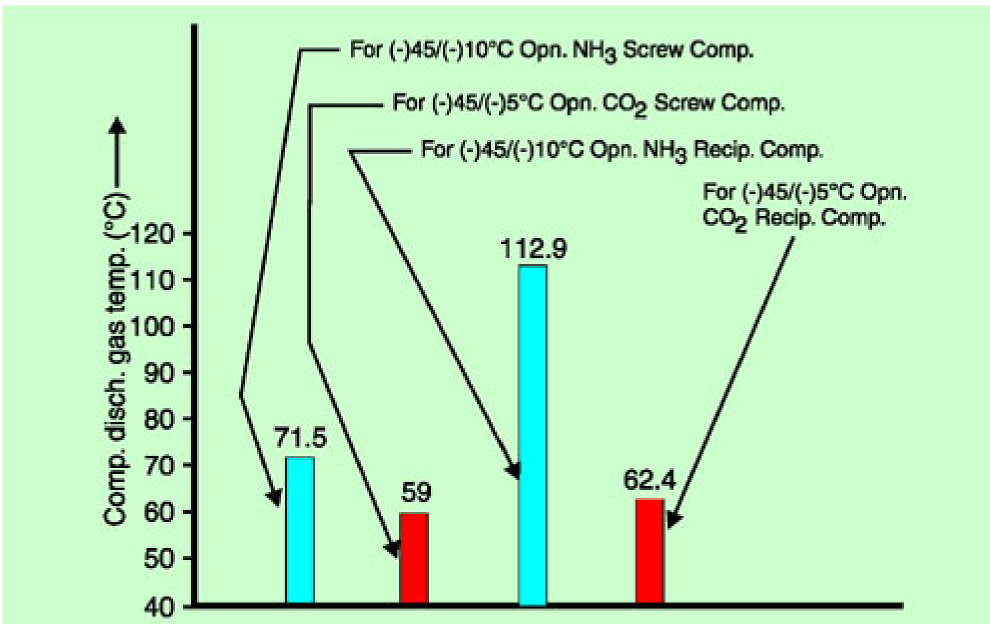

Figure 7 : Comparison of discharge gas temperature

Table 1 : Comparison of operating parameters between two-stage NH_3 and CO_2 / NH_3 cascade system for Screw compressors

Sr. No.	Parameter	Low stage of 2-stage system	Low temp. circuit of cascade	Remarks	High stage of 2-stage system	High temp. circuit of cascade
1	Refrigerant	Ammonia	Carbon dioxide		Ammonia	Ammonia
2	Refrigerant designation	R 717	R 744		R 717	R 717
3	Sat. evap. / cond. temp. in °C.	(-)45 / (-) 10	(-)45 / (-) 5		(-)10 / (+) 40	(-)10 / (+) 40
4	Type of compressor	Screw	Screw		Screw	Screw
5	Suction pressure in bar abs.	0.50	8.30	For R717 less than atm. pressure	2.90	2.90

6	Discharge pressure in bar abs.	3.60	30.5	87.05% less for R717	15.70	15.70
7	Capacity of comp. reqd. in TR	100	100		133.45	131.55
8	Capacity of comp. reqd. in kW	351.63	351.63		469.23	462.55
9	COP (comp. cap. / power)	2.99	3.17	6.02% more for R744	3.31	3.31
10	Comp. shaft power in kW	117.60	110.92	5.68% less for R744	141.76	139.74
11	Oil cooler load in kW	53.32	5.13	90.38% less for R744	74.62	73.56
12	Oil flow reqd. in LPM	104.15	36.35	65.09% less for R744	88.29	87.04
13	Volumetric effy. of comp. in %	88.80	88.50	Nearly same since screw comp.	91.40	91.40
14	Adiabatic (compression) effy. in %	65.80	78.50	19.30 % more for R744	80.30	80.30
15	Condenser capacity reqd. in kW	N.A.	N.A.		610.99	602.30
16	Condenser water flow rate in LPM	N.A.	N.A.		2189.39	2158.24
17	Discharge vapour temp. °C	71.50	59	12.50°C less for R744	82.30	82.30
18	Compression ratio	7.2	3.67	49.03% less for R744	5.41	5.41
19	Suction mass flow in kg/ hr.	1026.49	5145.41	80.05 % more for R744	1588.68	1566.07
20	Suction vol. flow rate cu.m./ hr.	2166.58	249.09	88.50% less for R744	687.25	677.47
21	Suction line size in mm NB	150	65	Appreciable lower size for R744	100	100
22	Suctn. line thermal insulation thk. in mm	150	125	Less insultn. reqd. for R744	75	75
23	Wet return line size reqd. in mm NB	200	80	Appreciable lower size for R744	N.A.	N.A.
24	Wet return line insulation thk. in mm	200	125	Less insultn. reqd. for R744	N.A.	N.A.
25	Discharge line size reqd. in mm NB	100	50	Appreciable lower size for R744	65	65
26	Comp. swept vol. reqd. in cu.m./hr.	2439.84	281.46	88.46% less for R744	751.91	741.21

27	No. of comp. (@282 cu.m/hr. each) reqd.	9	1	8 nos. additional comp. reqd. for R717	3	3
28	Total power for comps. (low+high) in kW			250.66 kW for cascade system		
29	Total no. of comps. reqd. (low+high)			4 nos. for cascade system		

3. The COP (coefficient of performance) for the CO_2 low stage compressor is much higher compared to the ammonia compressor for the required operating conditions.

Thus, there is a reduction in compressor power consumption, both for the screw as well as the reciprocating compressor (5.68% less for screw compressor and 18.18% for reciprocating compressor). Based on the total plant capacity we will require a lower kW rating motor for CO_2 low-stage compressor (screw or reciprocating). This advantage of lower power consumption has an effect on the entire plant life operating cost. We are all aware of the present-day crisis of electric power and its ever-increasing price all over the world. Therefore, the lower power requirement of a CO_2 low-stage compressor for such a cascade system has high potential in reducing operating cost for end users in future refrigeration plants.

The high-side ammonia compressor capacity required will be lower for a cascade system (as compared to the high stage of a conventional two-stage ammonia system). This is because of lower low-stage compressor power for CO_2 . From **Table 1 & Table 2** this is 1.42% less for a screw compressor and 5.03% less for a reciprocating compressor.

Similarly, the power consumption of the high-stage compressor will be less (1.42% for a screw compressor and 5.03% for a reciprocating compressor) for a cascade system compared to a two-stage ammonia system.

Thus the total power consumption of compressors (low-stage + high-stage) for cascade system is less (3.35% for screw and 11.13% for reciprocating) for a CO_2 / NH_3 cascade system compared to a two-stage ammonia system.

We can also conclude that the condenser capacity required is lower (1.42 % for screw and 5.03% for reciprocating) for a CO_2 / NH_3 cascade system compared to a two-stage ammonia system. Thus the condenser size will be smaller, water flow rate across the condenser will be less, pipeline size and valves etc. shall be smaller, cooling water pump capacity and power consumption for such a pump will be less, cooling tower capacity required also will be less, cooling tower fan capacity and power consumption by the fan motor will also be marginally less. All these will result in a further reduction in initial as the well as operating cost of plant.

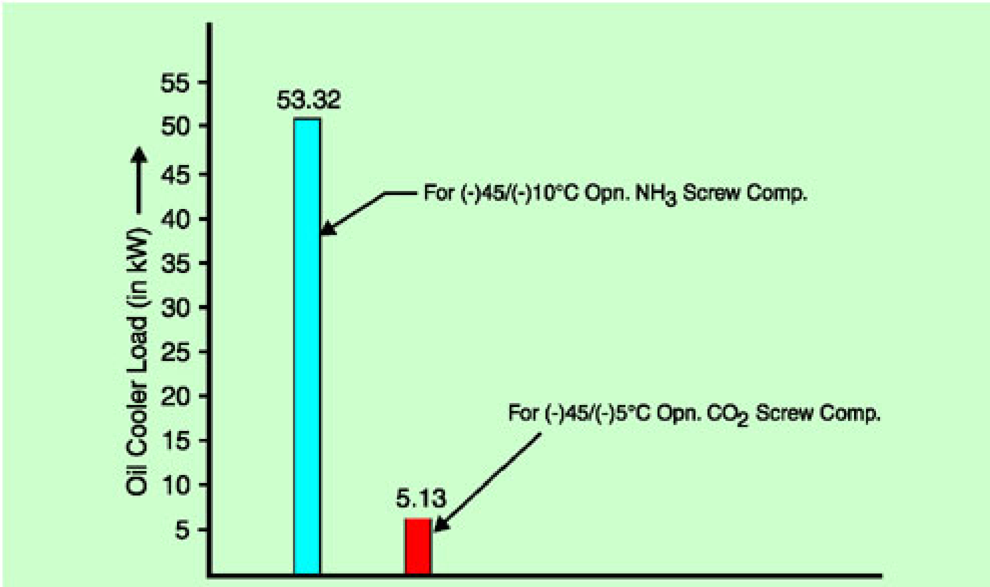

Figure 8 : Comparison of oil cooler load

Table 2 : Comparison of operating parameters between two-stage cascade system for Reciprocating compressors

Sr. No.	Parameter	Low stage of 2-stage system	Low temp. circuit of cascade	Remarks	High stage of 2-stage system	High temp. circuit of cascade
1	Refrigerant	Ammonia	Carbon dioxide		Ammonia	Ammonia
2	Refrigerant designation	R 717	R 744		R 717	R 717
3	Sat. evap. / cond. temp. in °C.	(-)45 / (-) 10	(-)45 / (-) 5		(-)10 / (+) 40	(-)10 / (+) 40
4	Type of compressor	Reciprocating	Reciprocating		Reciprocating	Reciprocating
5	Suction pressure in bar abs.	0.53	8.16	For R717 less than atm. pressure	2.85	2.85
6	Discharge pressure in bar abs.	3.60	30.84	83.33% less for R717	15.77	15.77
7	Capacity of comp. reqd. in TR	100	100		133.31	131.35
8	Capacity of comp.	351.63	351.63		486.35	461.86

	reqd. in kW					
9	COP (comp. cap. / power)	2.61	3.19	18.18% more for R744	3.13	3.13
10	Comp. shaft power in kW	134.72	110.23	18.18% less for R744	155.38	147.56
11	Comp. head / side cover cooling	both water	both water	90.38% less for R744	both water	both water
12	Volumetric effy. of comp. in %	63	82		68	68
13	Condenser capacity reqd. in kW	N.A.	N.A.		641.74	609.42
14	Condenser water flow rate in LPM	N.A.	N.A.		2299.56	2183.75
15	Discharge vapour temp. °C	112.90	62.40	50.50°C less for R744	137.20	137.20
16	Compression ratio	6.79	3.78	44.30% less for R744	5.53	5.53
17	Suction mass flow in kg/ hr.	1022.57	5134.13	80.08 % more for R744	1651.00	1567.87
18	Suction vol. flow rate cu.m./ hr.	2154.8	248.29	88.48% less for R744	719.84	683.60
19	Suction line size in mm NB	150	65	Appreciable lower size for R744	100	100
20	Suctn. line thermal insulation thk. in mm	150	125	Less insultn. reqd. for R744	75	75
21	Wet return line size reqd. in mm NB	200	80	Appreciable lower size for R744	N.A.	N.A.
22	Wet return line insulation thk. in mm	200	125	Less insultn. reqd. for R744	N.A.	N.A.
23	Discharge line size reqd. in mm NB	100	50	Appreciable lower size for R744	65	65
24	Comp. swept vol. reqd. in cu.m./hr.	3420.32	302.79	91.15% less for R744	1058.59	1005.29
25	No. of comp. (@282 cu.m/hr. each) reqd.	11	1	10 nos. additional comp. reqd. for R717	3	3

26	Total power for comps. (low+high) in kW	257.80 kW for cascade system
27	Total no. of comps. reqd. (low+high)	4 nos. for cascade system

4. The low-stage compressor suction pressure is higher for CO_2 , higher than atmospheric pressure; thus there is no chance of entry of air from a low side leakage and its related operating problems. In the case of an ammonia plant this is a common problem in low temperature applications. Hence, for a two-stage ammonia system, a costly automatic air purger with its controls and piping is always used to get rid of this problem of entry of non-condensable air in the system from the low side.

So a costly automatic air purger with its controls, instruments, valves, piping, and thermal insulation, can be totally eliminated for the CO_2 plant. This will have an appreciable effect on reducing the initial cost of the plant. Also there is no chance of accumulation of noncondensable air in the system causing high condensing pressure which increases compressor power requirement for the compressor.

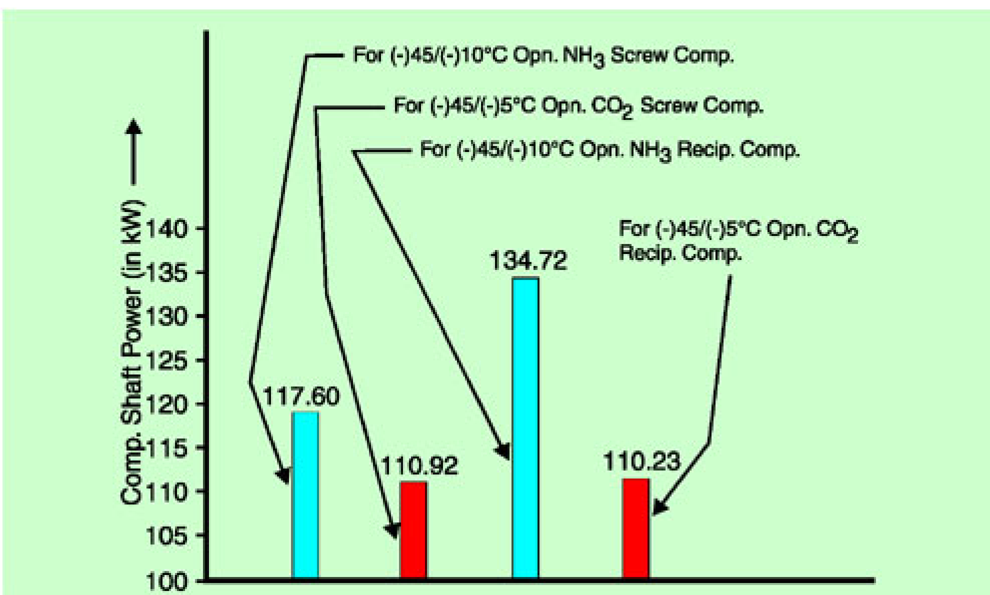

Figure 9 : Comparison of compressor shaft power

5. CO_2 suction vapour specific volume is much lower compared to ammonia ; hence for a similar capacity plant the suction line size will be smaller.

From Table 1 and Table 2 we find that for 100 TR (351.63 kW) plant with (–)45 °C evaporation temperature the suction line size will be 65 mm NB for carbon dioxide as compared to 150 mm NB for ammonia. Since the suction line size is smaller the thermal insulation requirement will be also less (insulation thickness with EPS 125 mm for CO_2 as compared to 150 mm for NH_3).

As the suction line size is smaller for CO_2 , hence suction valves, strainer, fittings etc. will also be of smaller size. All these items for such low temperature application require low temperature carbon steel (LTCS) or suitable grade Stainless Steel (S.S.) material, which are extremely costly compared to general carbon steel materials. Thus with CO_2 refrigerant in the low temperature side of a cascade system there is a significant reduction of initial plant cost and installation cost.

6. The vapour volume flow rate for CO_2 at suction temperature is appreciably lower compared to NH_3 for the same capacity and temperature. Hence the accumulator / liquid separator used for separating the suction vapour from the liquid to avoid liquid carry over to the compressors can be much smaller. This vessel also calls for LTCS or special grade S.S. material; hence the advantage of a smaller size accumulator will also result in an appreciable reduction in initial plant cost.

The thermal insulation of the accumulator will also be reduced compared to a similar capacity ammonia accumulator. This will result in further reduction in initial cost of plant as well as installation cost.

With a similar logic for pumped re-circulation system the wet return line size and its thermal insulation requirement will also be less compared to ammonia.

7. The discharge condition CO_2 vapour has lower specific volume compared to ammonia. Hence the discharge line size for a CO_2 plant will be smaller compared to similar capacity ammonia. This will also result in advantages of lower piping, fittings and smaller size valves resulting in a further reduction in the overall plant cost.

8. Because of lower suction / wet return lines, lower size discharge line and a smaller accumulator, the total first charge of refrigerant for such a CO_2 / NH_3 cascade system will be smaller than a conventional two-stage NH_3 system.

The estimated total initial refrigerant charge requirement will be 60 to 70% less as compared to a two-stage ammonia plant.

CO_2 is approximately 37% cheaper than ammonia. Thus there will be an additional benefit in future cost saving while replenishing the refrigerant.

9. CO_2 gas is non-toxic and non-flammable. Hence carbon dioxide can be used in direct contact with food items.

CO_2 is also odourless and it is a better and a safer refrigerant for food processing or other industries. Also, it is environment-friendly and not lethal like ammonia for human inhaling. Hence in food processing industries, where customers object to ammonia because of possible leakage in the food processing area, they can safely decide to go for carbon dioxide, by adopting the CO_2 / NH_3 cascade system.

10. CO_2 compressors require special synthetic lubricating oil with food grade quality and this is 80% more costly compared to standard lubricating oil required for ammonia compressor. But the requirement of such compressor oil for CO_2 is lower because of less number of compressors or smaller compressors and smaller oil cooler. In the case of a two-stage ammonia system, for both the stages (booster & high stage) we need to use a better quality oil suitable for low temperature ammonia service, as both the stages are interconnected . Whereas standard oil for ammonia for (–)10°C temperature can be used for the cascade system ammonia side (since both circuits are separate and independent).

Table3 : Comparison of important properties

Sr. No.	Parameter	Ammonia	Carbon dioxide
1	Chemical formula	NH_3	CO_2
2	Molecular weight	17	44
3	Refrigerant designation	R 717	R 744
4	Critical temp. °C	133	31.06
5	Critical pressure Bar abs.	113	73.84
6	Type	Inorganic Compound	
7	Boiling point °C at std. atm. pressure(NBP)	(-) 33.30	(-)78.30
8	Safety group	B2 (evidence of toxicity identified, lower flammability limit)	A1 (toxicity not identified, No Flame propagation)
9	Sp. Heat at const. press.(Cp) kJ / kg .K	2.1269	0.8709
10	Sp. Heat at const. vol.(Cv) kJ / kg .K	1.6705	0.6783
11	Ratio of Cp / Cv	1.2732	1.2839
12	Gas constant (R) J / kg .K	487	189
13	Flammability	Flammable with 16 to 25% by vol. In air	Not flammable in air
14	Health hazard	Injurious / lethal for 0.5 to1% conc. for 0.5 Hr. exposure	Not injurious or lethal
15	ODP factor (ozone depletion potential)	Nil	Nil
16	Sat. press. at (-)45°C sat temp. bar abs.	0.545	8.336

17	Sat. press. at (-)5°C sat temp. bar abs.	3.548	30.47
18	Sp. vol. sat. vap.at (-)45°C temp. cu.m / kg	2.00458	0.0459
19	Sp. vol. sat. liq..at (-)5°C L / kg	1.5495	1.0447
20	Consideration for food contact	Direct contact with food not permitted	Can have direct contact with food
21	Odour	Pungent smell	Odourless

Thus the overall cost of the first charge of compressor oil (low temperature side CO_2 compressor oil and high temperature side ammonia compressor standard oil) will be less as compared to a two-stage ammonia plant.

Please also refer to Table 3 for a comparison between CO_2 and NH_3 as refrigerants for various important properties and parameters; this shows that as a refrigerant, carbon dioxide can be considered a better refrigerant compared to ammonia. In fact, it was being used long before we became familiar with CFC, HFC, ammonia or Hydro carbons as refrigerants.

But CO_2 cannot be used on the high-stage side of the plant, as condensing pressure at 40 °C temperature will be much higher than ammonia. This calls for a condenser design pressure which is extremely high and not economically viable. Hence it is used only in the low temperature side. Whereas ammonia is used on the high temperature side of the cycle, with its benefit of a lower condensing pressure. Thus by having these two refrigerants in a cascade refrigeration system we can make the plant design most cost-effective and optimum, taking advantage of the properties of both the refrigerants, CO_2 & NH_3 .

However, like any other system, the CO_2 / NH_3 cascade system has some disadvantages as compared to a two-stage ammonia refrigeration system. The major disadvantages of such a cascade refrigeration system are:

1. For carbon dioxide the saturated pressure is much higher (more than 75 bar) when liquid refrigerant is warmed to ambient temperature (say 40°C). This condition would require that all the components in the low temperature circuit be suitable for such high pressure, which is economically not viable.

   To make the plant viable a suitable volume fade-out vessel is provided on the CO_2 circuit (in between the condenser and the chiller) to permit the liquid refrigerant to be warmed to room temperature. When the plant is shut down for a long period, such a situation may occur. A fade-out vessel is simply an empty vessel that is open to the cascade refrigerant CO_2 . This is designed with suitable volume so that when the system is shut down and temperature rises the liquid can expand to vapour without exceeding a reasonable limiting pressure. Lower the limiting pressure, larger is the volume required of the fade-out vessel. Thus we can have, say 40°C equalising temperature which has enough room to expand to vapour at a pressure not higher than 32 bar absolute. This is additional equipment required for cascade systems

2. In the case of liquid overfeed refrigeration system, the CO_2 liquid pump capacity required is 2.5 to 3.5 times higher than an NH_3 pump for similar operating parameters. Thus, liquid line sizes for such a pump suction and discharge will be higher compared to ammonia.
3. The CO_2 side vessel and exchanger design pressure is higher compared to the booster ammonia side vessel and heat exchanger.

In spite of the above mentioned disadvantages the CO_2 / NH_3 cascade system can be considered a better and more cost-effective proposal for a system requiring less than (–)40 °C evaporation.

Conclusion

Since compressors and lubricating oils suitable for CO_2 are already available in the market and since a CO_2 / NH_3 combination in a cascade system performs better and at a lower cost, both initial and operating, than the conventional two-stage NH_3 system there is every possibility of such systems becoming the standard for all food processing and industrial applications in the future.