Technical and energetic appraisal of ammonia refrigerating systems for industrial use

0. General

The refrigerant ammonia (NH_3) is the definitive operating fluid for industrial use. Throughout its period of use as a refrigerant, NH_3 has proven to be ideally suited to this purpose. Large-scale refrigeration plants, e.g. for the food product, beverages and chemicals industry, have been and are being operated successfully with NH_3.

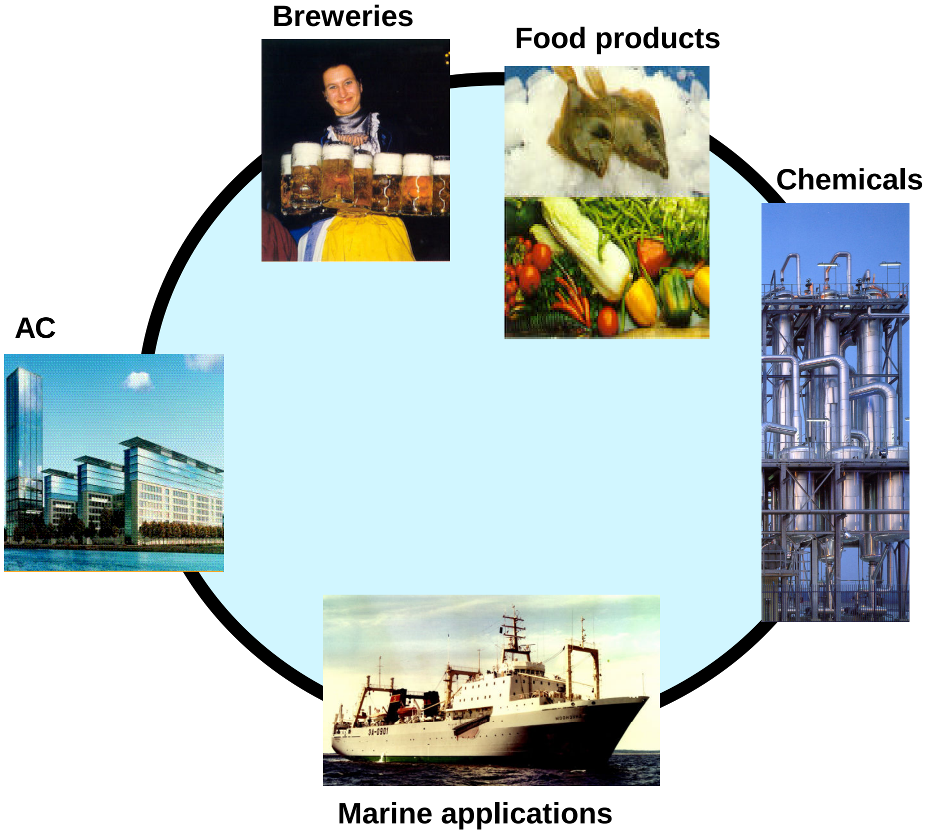


Fig. 1: Refrigeration applications with NH_3

These systems mostly used in dairies, breweries, abattoirs and large refrigeration plants, and often filled with several tons of refrigerant, were installed for a large number of operators, ran for decades and were then dismantled again and disposed of at the end of their service lives. NH_3 thus has the unmistakable advantage that many years of extensive experience and know-how is available for dealing with this natural refrigerant, gathered regularly from the above mentioned areas, but also in applications previously deemed to be sensitive to NH_3 (e.g. human air-conditioning systems).

Another important reason for the undisputed use of NH_3 for decades in many areas of industrial refrigeration is the economic efficiency resulting from its outstanding thermodynamic properties. The efficiency, expressed in total costs, is one of the key criteria for deciding for or against an NH_3 system. Higher procurement costs resulting from the more complicated technical work aspects of its production are offset by a lower refrigerant price and less energy costs to operate the refrigerating system, so that the overall costs for an NH_3-refrigerating system are extremely favourable. The ratio of refrigerating capacity to required power input (COP, Coefficient of Performance) for an NH_3 system is often much higher than that for traditional systems operating with synthetic refrigerants. This can offer a significant reduction in the electrical energy costs, which will often pay back the additional capital cost in a relatively short time, i.e. 1 to 3 years.

The number of annual operating hours of large-scale refrigeration plants used in the above areas and in particular in the food product industry is very high. Priority must therefore always be given to economic use of energy in fulfilling the refrigerating demands. Special attention should be paid to fluctuations in the outside air temperatures ($t_A \approx$ -15 to +35 °C) and to the possibility of using such fluctuations to save energy in operating the refrigeration plant. This is illustrated by the cyclic process for a refrigeration plant shown in Fig. 2:

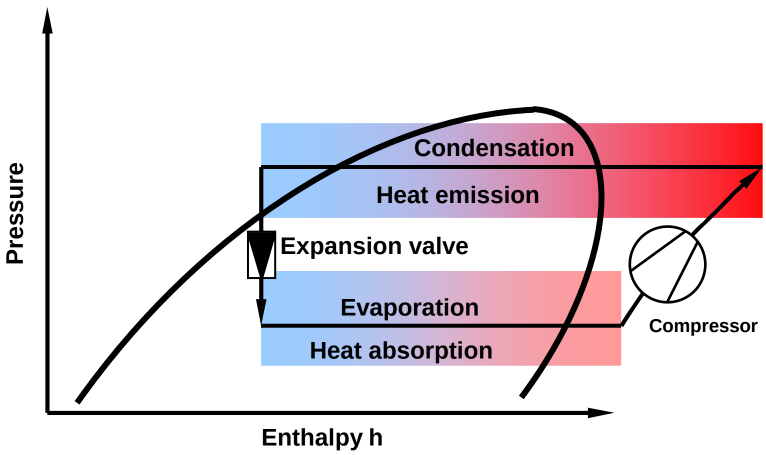


Fig. 2: Cyclic process of a refrigeration plant in the lg p, h-diagram

<u>Explanations:</u>

The refrigeration plant transports heat from a low temperature to a higher temperature. The compressor output required for this purpose depends on the heat quantity per time unit and on the difference in temperature. This results in the following starting points for rational use of energy:

- The room being cooled should have a minimum thermal load (refrigerating demand from external heat, transmission, packaging, ventilator heat and similar)
- The temperatures in the room being cooled should only be as low as necessary (regular controls, service cycles)
- Dissipation of the condensation heat must be brought to a low level with the available media (air/water), paying attention to seasonal fluctuations in temperature.

Note:

The lower the temperature for heat absorption and the higher the temperature for heat emissions, the more power is required.

1. Plant concept

Given the extensive range of applications for NH_3 refrigeration plants in industrial refrigeration, the evaporation temperature range extends from approx. -50 ℃ to +5 ℃ (freeze-drying of coffee, through processing room refrigeration in meat and sausage production to building air-conditioning application). NH_3 refrigeration plants are designed in one and two stages. The screw compressor with all its advantages has become the most common solution in industrial refrigeration applications. It has a major advantage over the reciprocating compressor of a wider single stage operational envelope. The reciprocating compressor is not allowed to exceed a pressure ratio corresponding to -10 ℃/+40 ℃ (+45 ℃ for water-cooled cylinders) because of the high discharge temperatures occurring here, particularly with NH_3. The resulting plant concepts are shown in table 1:

Refrigeration plant	**Direct cooling system**		**Indirect cooling system**	
	DX [1])	flooded [2])	DX	flooded
1-stage	X	X	X	X
2-stage	X	X	X	X
HP stage in cascade NH_3/CO_2	X	X	–	–

[1]) Direct expansion
[2]) Pump forced circulation/gravity circulation

Table 1: Plant concepts for NH_3 refrigeration plants

The plant concept defined in the planning phase with the corresponding operating parameters essentially stipulates the economic efficiency of the future refrigeration plant's operation (COP, see section 0). Together with efficient rating of the compressors, the heat exchangers used on both the heat absorption side (evaporator) and the heat emission side (condenser) play a major role in the economic efficiency of the refrigeration plant. The following Figs. 3 to 6 show diagrams of the various plant concepts.

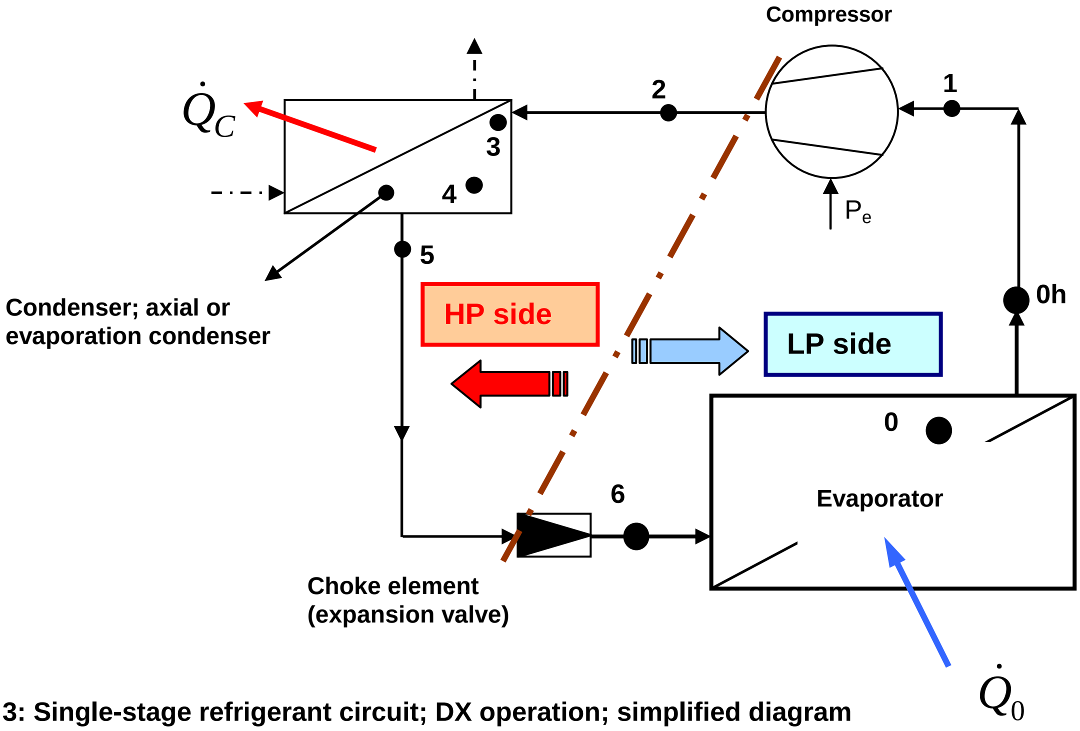


Fig. 3: Single-stage refrigerant circuit; DX operation; simplified diagram

Legend:

1	Compressor inlet
2	Compressor outlet / Condenser inlet
3	Condensation begins
4	Condensation status
5	Condenser outlet (undercooled refrigerant)
6	Evaporator inlet (relaxed refrigerant)
0	Saturation state (completely evaporated refrigerant)
0h	Evaporator outlet (evaporated overheated refrigerant)

A single-stage refrigeration plant with screw compressors can be fitted with an economizer (operation with supercharging, Fig. 4) to enhance its capacity Q_0 with a slight increase in the required power input of the compressor motor P_e, e.g. ΔQ_0 = +13 % at ΔP_e = +8 %.

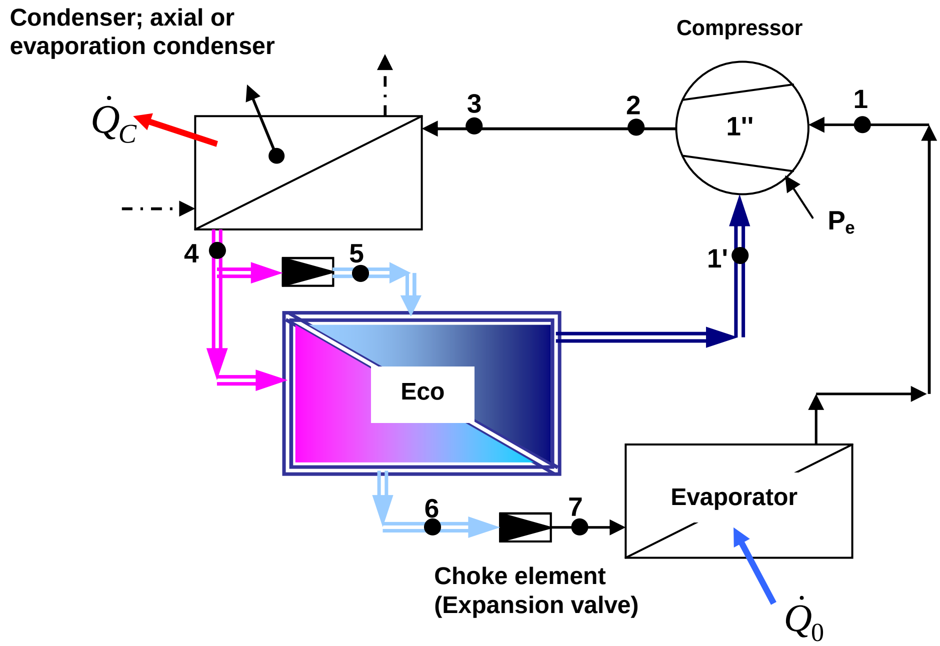


Fig. 4: Single-stage refrigerant circuit with economizer operation; simplified diagram

<u>Legend:</u>

1	Compressor inlet – evaporator side
1'	Compressor inlet – economizer side
1''	Condition of the compressed refrigerant vapour in the compressor
2	Compressor outlet
3	Condenser inlet
4	Condenser outlet
5	Economizer inlet – supercharging partial flow
6	Economizer outlet – evaporator side
7	Evaporator inlet (relaxed refrigerant)

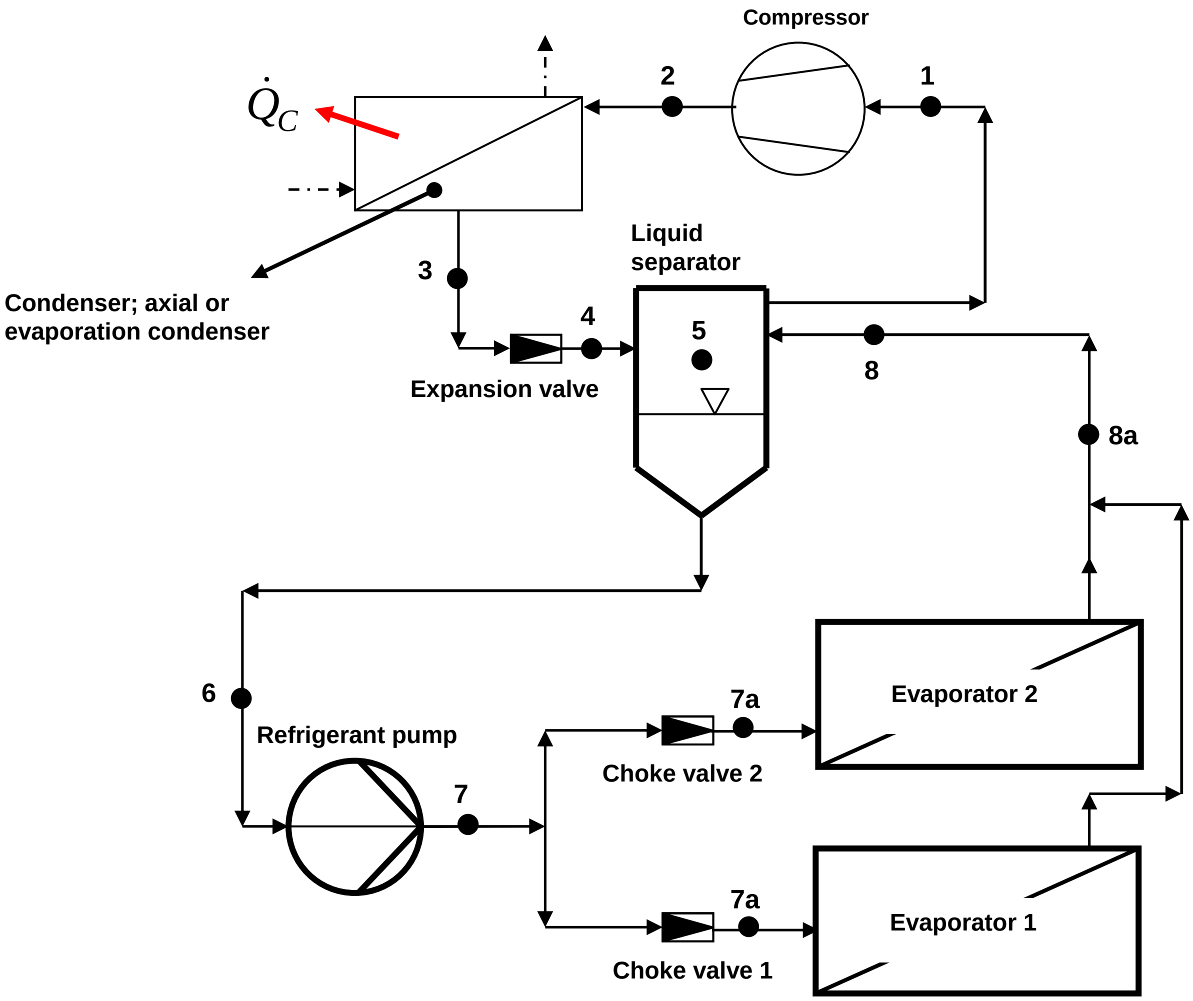


Fig. 5: Pump circuit, simplified diagram

<u>Legend:</u>

1 – 2	Compression
2 – 3	Condensation
3 – 4	Restriction down to separation pressure
5	Status in separator
5 – 6	Static delivery head of the liquid refrigerant
6 – 7	Delivery height of the pump
7 – 7a	Restriction in the evaporator control valve
7a – 8a	Evaporation to x = 1/n
8a – 8	Pressure loss in the return pipe

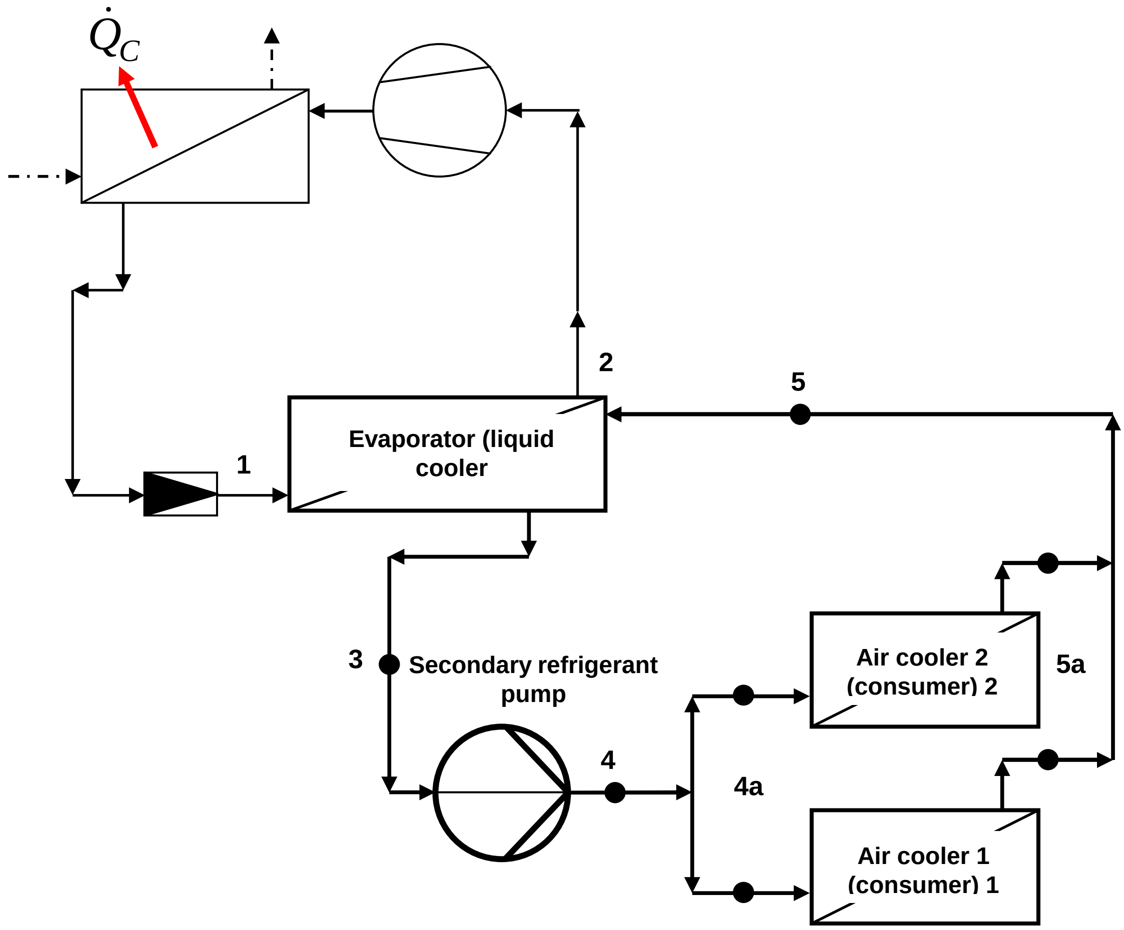


Fig. 6: Indirect cooling system, simplified diagram

Legend:

1	Evaporator inlet
2	Evaporator outlet
3	Liquid cooler outlet, secondary refrigerant pump inlet
4	Secondary refrigerant pump outlet
4a	Consumer (air cooler) inlet
5a	Consumer (air cooler) outlet
5	Liquid cooler inlet

2. Refrigeration plant / high-pressure side (heat emission side)

The energy demand and thus the economic efficiency of a refrigeration plant depends essentially on effective dissipation of the condensation heat. Heat dissipation takes place with air (condenser; axial), with air/water (evaporation condenser) or with water (pipe bundle or plate heat exchanger). Heat dissipation with water (surface water, river or seawater) is only rarely used in Europe for land refrigeration plants, particularly in food product refrigeration and storage. The chemicals industry mainly uses water from rivers and wells for cooling. In the case of marine refrigeration systems, generally it is normal to use seawater for heat dissipation. Land refrigeration plants make equal use of dry (axial condenser) or wet systems (evaporation condenser). Various different factors (e.g. use of night operation, installation requirements, erection weight, plant size, possibility of storing cold water, water costs) affect the choice of the specific configuration. But the possibility of combining dry and wet systems is also used in practice.

The choice of condenser design should certainly give due consideration to fluctuations in the outside air temperature t_A and thus to the possibility of always condensing as close as possible to the minimum permissible condensation temperature t_{Cmin}. Selection of the condenser design along these lines will result in minimum operating costs for energy and water. The following diagram (Fig. 7) clearly shows how energy and water consumption in refrigeration plants can be influenced by keeping close to the minimum permissible condensation temperature t_{Cmin}.

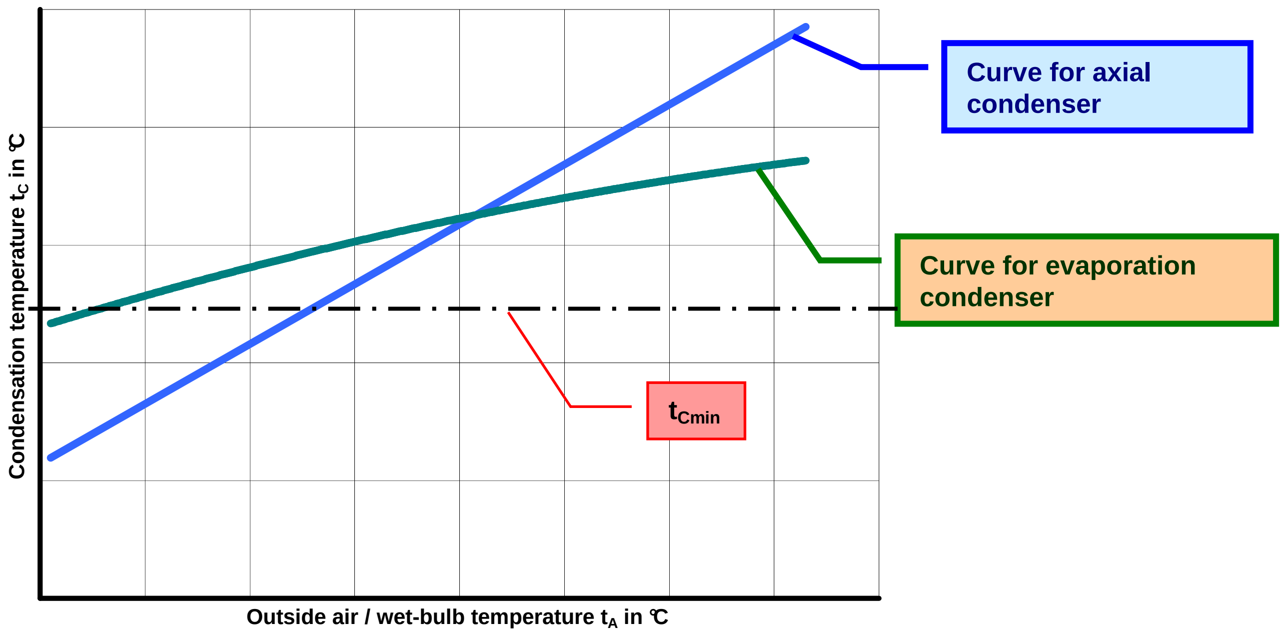


Fig. 7: Condensation temperature t_C (range +20 to +50 ℃) over outside air temperature t_A (-15 to +35 ℃) and wet bulb temperature t_F (0 to +23 ℃)

The use of screw compressors with their integrated oil circuits permits discharge pressures of up to the equivalent of +50 ℃ (compared to reci procating compressors with max. +40 ℃). The heat generated during compression is dissipated partly by the oil cooler in the oil circuit, thus relieving the condenser. The dissipated oil cooler heat can be used for thermal recovery without special apparatus. The high temperature level of this procedure (up to approx. +90 ℃/+65 ℃ oil temperature) results in a large appli cation area for this waste heat.

3. Refrigeration plant / low-pressure side (heat absorption side)

On the low-pressure side of the refrigeration system, heat is absorbed from the room being cooled or from the product in it via the evaporator. The evaporator can be part of the following cooling systems:

Cooling system	
Direct cooling system	Indirect cooling system
Function: The refrigerant in a closed circuit exchanges heat directly with the air being cooled (single separation).	*Function:* The refrigerant in a closed circuit exchanges heat directly with a secondary refrigerant in a closed circuit, which in turn exchanges heat directly with the air being cooled (double separation).
Operating modes: • Dry evaporation (DX mode) • Flooded operation o Pump forced circulation o Gravity circulation	

Table 2: Cooling systems

In selecting the operating mode of the refrigeration plant, it must be borne in mind that the COP and thus the economic efficiency of the refrigeration plant is influenced to a certain extent by every heat exchanger contained in the plant i.e. also the evaporator. In terms of saving energy, the aim must be to select the smallest possible difference in temperature between the evaporating refrigerant and the air being cooled.

<u>Dry evaporation</u> (DX mode) with thermostatic expansion always demands an overheating section in the evaporator so that the thermostatic expansion valve can work correctly. The low mass flow density of the refrigerant NH_3 (the density of NH_3 is only about half that of conventional HFC refrigerants) means that rating the evaporators is not without problems

and demands plenty of experience. Consideration of the following special aspects of refrigerant NH_3 compared to HFCs

- high evaporation heat, e.g. compared to R404A 1.328/181.5 kJ/kg at -20 °C
- low expansion vapour share
- lower refrigerant mass flow, e.g. compared to R404A ≈ 1/4

and the structural design of the evaporator including the chosen expansion permit such low differences in temperature between the evaporating refrigerant and the air being cooled as can be virtually achieved with evaporators in flooded mode. The advantages of the DX mode consist in a lower quantity of refrigerant required to fill the refrigeration plant, thus saving on refrigerant (environment and safety aspects).

Industrial applications, which are the main use for NH_3 refrigeration plants, normally use the <u>flooded mode</u> for medium-sized and large capacities. Refrigeration plants with evaporators working with flooded evaporation (see section 1, Fig. 5) must be provided with a liquid separator. The liquid separator sends liquid refrigerant to the evaporators which in this case work in flooded state. The size of the liquid separator is to be rated on the one hand to prevent any intake of liquid refrigerant into the compressor, and on the other hand to ensure that the evaporator is supplied with liquid refrigerant. In industrial refrigeration plants, refrigerant pumps are used for supplying refrigerant to the evaporators in large distributed systems, such as food factories. Packaged chillers for process and air-conditioning applications operate without pumps, usually using gravity fed, i.e. thermosyphon, refrigerant. There are also examples of pumpless refrigeration systems supplying refrigerant to evaporators in cold and chill store applications.

The functional principle for evaporators with <u>pump forced circulation</u> is necessary in particular

- if many consumers have to be supplied with refrigerant which are possibly far apart,
- if there are large flow resistances through the evaporators including delivery and feed pipes, and
- if particularly constant evaporation is required (same flow form and thus same heat transmission coefficients in the two-phase flow occurring in the pipe taking the flow, during evaporation), particularly during part load operation or with several rows of pipes in the depth.

This warrants very reliable refrigerant supply to the evaporators; slight differences in temperature can also be expected between the evaporating refrigerant and the air being cooled (approx. 3 K). It is thus possible to increase the evaporation temperature of the compressor and thus improve the COP and the energy efficiency of the refrigeration plant (see section 0, Fig. 2).

In gravity circulation systems, the refrigerant flows from the liquid separator to the evaporator through the difference in density in the liquid separator and evaporator and as a result of the inlet height. This requires a precise arrangement of liquid separator and evaporator. The height of the liquid separator must be stipulated so as to overcome the pressure resistances in the pipe to the evaporator and in the evaporator itself. However, if the liquid separator is positioned too high, the liquid column in the inlet pipe results in inadmissible increases in pressure with superheating in the evaporator.

Together with the energy savings from increasing the evaporation temperature, the choice of evaporator must also look at its functions in the cooling system. These include:

- Adapted air volume of energetically optimised ventilators (efficiency ventilator/motor, size of the dynamic pressure share)
- Compliance with low temperature differences between evaporating refrigerant and the air being cooled, with the following advantages:
    - Minimum icing
    - Longer defrosting intervals
    - Less energy required for defrosting
- Adapted relative humidity of the air being cooled to preserve the quality of the products being cooled
- Optimum air control in deep-freeze plants, making use of natural thermals according to the cold air lake principle

4. Refrigeration plant with indirect cooling system

Refrigeration plants with an indirect cooling system (see section 1, Fig. 6) are used where a direct cooling system is not suitable, for safety reasons, on account of demands to save refrigerant, or for various requests expressed by the operator. In other words, in non-traditional NH_3 application areas where parts conveying refrigerant must not come into contact with the substance being cooled, possibilities for using NH_3 are created by indirect cooling systems with double separation between refrigerant and the air being cooled. Indirect cooling systems with NH_3 as refrigerant are used both in industry and for air-conditioning systems. The main areas of application here include:

- Industrial and human air-conditioning
- Food product industry
- Chemicals industry
- Automotive industry

NH_3 air-conditioning systems in particular result in refrigerant charges of less than 0.1kg/kW for the production of cold water (see *eurammon*-information No. 9). As well as fulfilling safety requirements, industrial applications in particular offer significant refrigerant savings compared to refrigeration plants with a direct cooling system, as the NH_3 refrigeration system is usually accommodated centrally in a special machine room. Processing rooms in particular are mainly equipped with air coolers using secondary refrigerant (corresponding to Fig. 6).

The secondary refrigerants mainly consist of blends of ethylene glycol or propylene glycol (for food product applications) with water in various ratios and with a wide range of different trade names. Another frequently used secondary refrigerant is Pekasol 2000, a combination of organic salts which can be used for cooling down to -70 ℃ with still acceptable viscosities. Brine as the traditional secondary refrigerant of former times is only rarely used today (note the use of materials here). Brine consists of salt-and-water solutions with sodium chloride, (NaCl), magnesium chloride (MgCl) or calcium chloride (CaCl).

A highly favourable secondary refrigerant in the temperature range below +15 ℃ is carbon dioxide (CO_2, freezing point -56.7 ℃). In particular the possi bility offered by CO_2 of working with phase transformation brings significant improvements compared to conventional secondary refrigerants in the rating parameters for refrigeration systems with an indirect cooling system (see table 3).

Secondary refrigerant	**Ethylene glycol 40 %**	**Pekasol 2000**	**CO_2**
Phase transformation	no	no	yes
Refrigerating capacity in kW	50	50	50
Secondary refrigerant temperature in ℃ inlet outlet	 -25 -20	 -25 -20	–
Evaporation temperature in ℃	–	–	-22
Pumping rate	–	–	2.5 (2–3)

Mass flow in kg/h	10,537	12,732	1,573
Density in kg/m³ Liquid Steam	 1,083 –	 1,228 –	 1,040 48.4
Volume flow in m³/h inlet outlet	9.73	10.37	1.51 (liquid) 12.95 (vapour)
Connections in mm / secondary refrigerant velocity in m/s inlet outlet	DN 50 / 1.3	DN 50 / 1.47	DN 20 / 1.33 DN 32 / 4.5
Viscosity; liquid in Pa s	$2.45*10^{-2}$	$1.06*10^{-2}$	$1.4*10^{-4}$

Table 3: Comparison of secondary refrigerants with and without phase transformation

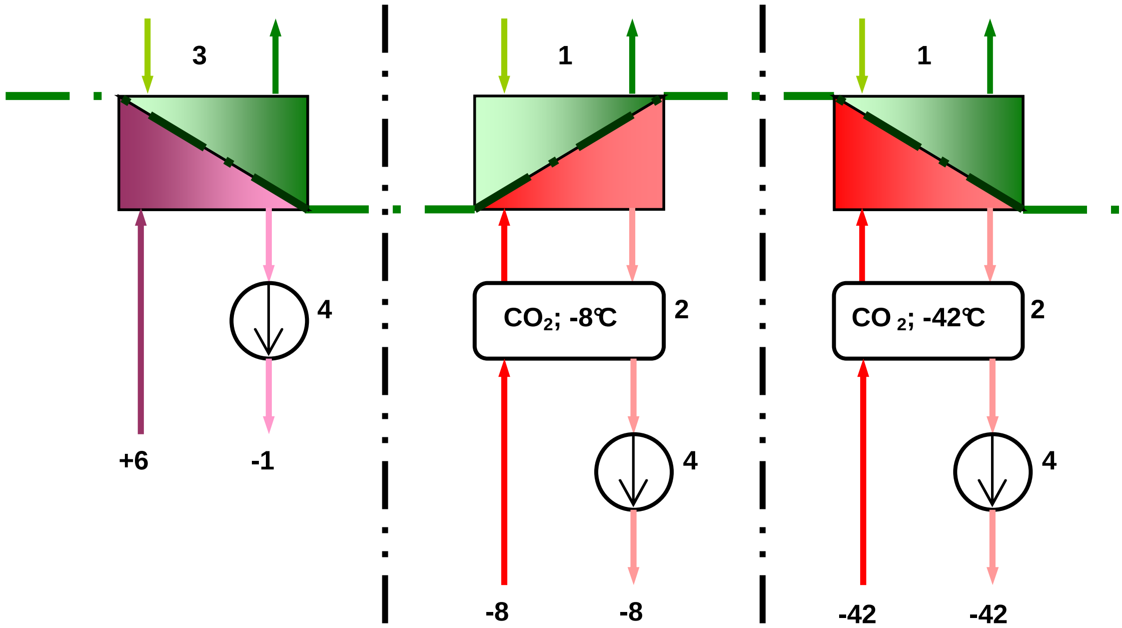
When using the secondary refrigerant CO_2 with phase transformation, savings are possible in the following areas:

- Pipe dimensions: reduction by approx. two to three nominal widths
- Pumping capacity: volume flow is decreased approx. 5.5 fold, more favourable viscosity values by approx. two to the power of ten
- The evaporation temperature in the refrigeration plant can be increased by approx. 3 K (corresponding to -25 °C to -22 °C)

One reference project for this kind of system is Europe's most advanced fish processing plant in Sassnitz on the island of Rügen, Germany. Here the secondary refrigerant CO_2 is in the secondary circuit of a cascade refrigerating system, with a two-stage NH_3 refrigeration plant as primary circuit (Fig. 8). The refrigeration plant is installed centrally in a refrigeration machine room. In contrast to conventional secondary refrigerant circuits, the CO_2 undergoes phase transformation on absorbing heat in the air cooler: it boils into a gas. The CO_2 gas then enters the NH_3/CO_2 cascade heat exchanger where it condenses. The individual sections of the overall plant are equipped with different secondary refrigerant circuits, as shown in Fig. 8.

The use of the propylene glycol/water mixture as secondary refrigerant in the circuit for the processing rooms results from the high pressure level (particularly for rating pipes and fittings) which would occur when using CO_2 under these conditions.

Two-stage NH_3 compression refrigeration plant



Secondary refrigerant circuit propylene glycol/water	Secondary refrigerant circuit CO_2	Secondary refrigerant circuit CO_2
Secondary refrigerant temperature -1 / +6 °C	**Secondary refrigerant temperature -8 °C**	**Secondary refrigerant temperature -42 °C**
Refrigerating capacity 2,000 kW	**Refrigerating capacity 1,300 kW**	**Refrigerating capacity 1,500 kW**

Fig. 8: Simplified diagram of the secondary refrigerant circuit for fish processing in Sassnitz, Germany

Legend:

1 Cascade heat exchanger NH_3/CO_2

2 CO_2 liquid separator

3 Liquid cooler for secondary refrigerant propylene glycol

4 Liquid pump for secondary refrigerant (propylene glycol resp. CO_2)

Alongside the advantages stated above (safety and environment aspects, refrigerant savings), the refrigeration plant with an indirect cooling system also has drawbacks resulting from the need to install an additional heat exchanger. This heat exchanger requires a driving difference in temperature, which in turn has a negative effect on the evaporation temperature (has to be reduced). Plate heat exchangers with their possibility of high heat flow densities (22 to 28 kW/m²) allow the use of compact units with differences in temperature between evaporating refrigerant NH_3 and the secondary refrigerant within very low limits of up to 4 K. At the reference project fish processing in Sassnitz described above, it was possible to reduce this difference in temperature to 2 – 3 K thanks to phase transformation (evaporation) of the secondary refrigerant.

5. Summary

The technical and energetic explanations provided above show that the many advantages of the natural refrigerant NH_3 can be used for all plant concepts with both direct and also indirect cooling systems, achieving a high rate of energetic efficiency. It is important that the requirement for systems using NH_3 is properly evaluated at the planning phase and that a clear technical specification detailing these requirements be prepared for issue to suppliers and contractors.

Rating the high-pressure side of the refrigeration plant (heat emission, condensation) depends to a great extent on the meteorological conditions (temperature and relative humidity of the outside air, frequent distribution of the outside air temperature, erection height a.s.l. and similar). The choice of condenser is also influenced by the attributes of operating the refrigeration plant (use of night operation, combined operation, simultaneity factor etc.) and consideration of the minimum permissible condensing temperature. Rating the low-pressure side (heat absorption, evaporation) is defined almost exclusively by operating temperature required by the users (cooling, freezing, storing, defrosting), together with air volumes and air control as the air-side parameters. For indirect cooling systems, operation with CO_2 as secondary refrigerant with phase transformation offers significant advantages (refrigerant savings, reduced pipe diameters, increased evaporation temperature).

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