Efficiency comparison of refrigeration technologies for ultra-low temperature (ULT) applications between -40 °C and -110 °C

Abstract

Climate change resulted in a phasedown of fluorinated refrigerant gases, driven by the EU F-gas regulation, in 2020. This is forcing the market to develop and apply new technologies to replace the high Global Warming Potential (GWP) refrigerants (Average GWP by 2030 < 500) currently used within the market. There are already sustainable and environmentally friendly solutions available for heating and cooling applications such as CO_2 ($GWP_{100} = 1$) heat pumps for domestic water heating or as booster systems for commercial refrigeration, propane ($GWP_{100} = 3$) water chillers and ammonia ($GWP_{100} = 0$) for industrial applications. For ultra-low temperature applications, the availability of refrigerants is very limited. Currently, there is an exception for refrigerants with high GWP values for refrigeration at temperatures below −50 °C, these applications are referred to as Ultra-Low Temperature (ULT). The cost of suitable fluorinated refrigerants are rising, and the availability shrinking. Furthermore, the exception for these refrigerants are under discussion since solutions are available in the market that cover ultra-low temperature applications with sustainable refrigerants. In the following document an efficiency comparison is presented for a compressor cascade system, liquid nitrogen, and the state of the art Mirai Intex air cycle refrigeration machines for ultra-low temperature applications.

1. Current availability of refrigerants

The most common solutions for temperatures below −50 °C are vapour compression cascade systems (and with some exceptions two-stage R410A ($GWP_{100} = 2088$) vapour compression systems), liquid nitrogen (LN_2) systems and air cycle refrigeration machines. All mentioned systems have different working principles, resulting in a different performance at lower temperatures. The working principle of a vapour compression system is based on the Carnot cycle, while the air cycle machine uses the Joule cycle. The direct LN_2 systems use liquefied nitrogen which is stored at −196 °C and vaporized in a heat exchanger for cooling demands.

The current ULT cascade system technology is limited by the availability of suitable refrigerants. The operation range of a refrigerant is determined by the saturation vapour pressure curve. Saturation pressure curves of common refrigerants are illustrated in Figure 4 under the Appendix. Refrigerants for temperatures from 20 °C down to −50 °C are broadly available. Usually the smaller the molecules of refrigerants the lower the minimum evaporating temperature of the refrigerant. Due to this fact there are only few refrigerants applicable to work below −50 °C. One of these refrigerants is R23 with a remarkably high GWP of 14900 the other is R469A, a blend with a high GWP of 1357. Natural refrigerants used in ULT applications are for example methane, ethane, and ethylene, these alternative refrigerants are however either flammable or have a challenging temperature glide.

2. Efficiency in ULT storage applications

In general, the lower the temperature the higher is the effort to achieve it. When it comes to the efficiency of low temperature storage applications it is most important to find the balance between necessary storage temperatures, the appropriate insulation and the efficient load and unloading procedure.

Ultra-low temperature or cryogenic storage requires temperatures from −30 °C down to −160 °C. The three most common technologies for ULT-refrigeration are compared in Figure 1, where the grey area represents the Coefficient Of Performance (COP) of cascade systems, the orange area is the COP of liquid nitrogen and the red area is the COP of the air cycle refrigeration system from MIRAI Intex. The COP values are nominated at a heat sink of 30 °C ambient temperature.

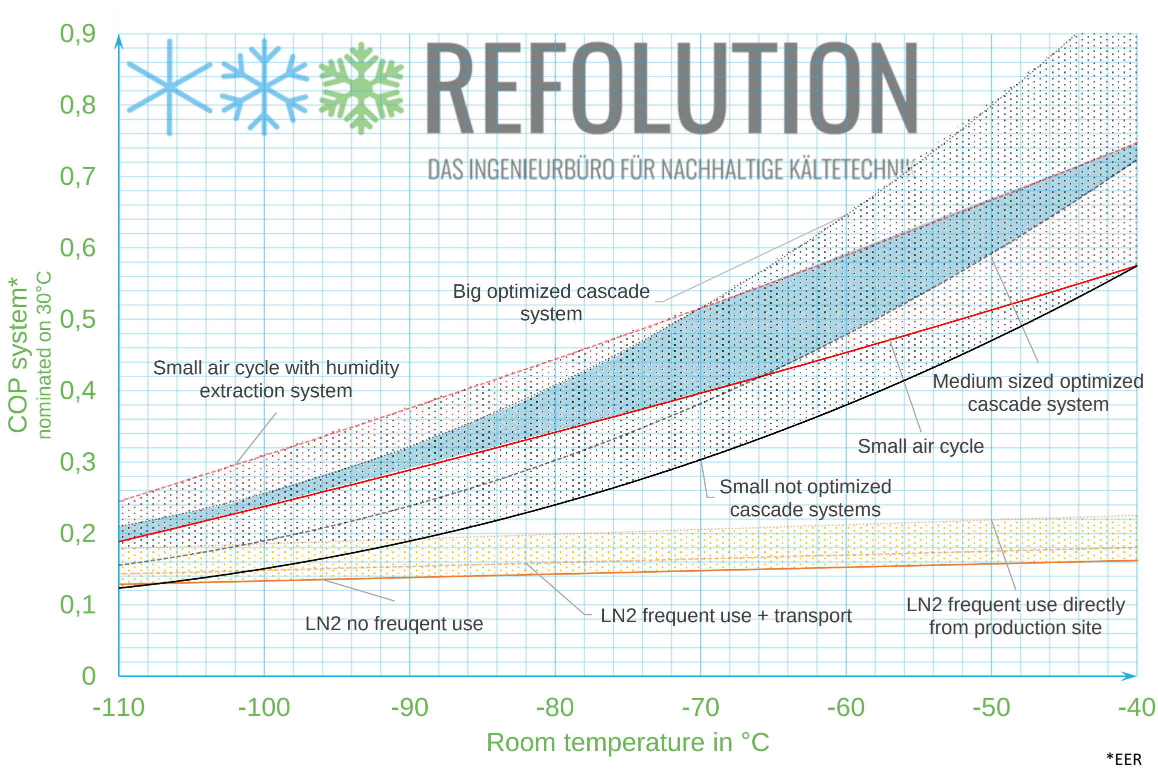

Figure 1: Full load efficiency comparison of liquid nitrogen, cascade system and air cycle refrigeration for storage

The closer the system is operating to ambient temperature the more efficient are cascade system based on the Carnot-cycle and have smaller additional heat emission to the cold room by an evaporator with fans and defroster heaters. Due to this fact much lower cooling capacities of the open air-cycle machine are required because no evaporator is needed as well as, no fans and therefore heat created by these components do not consume any cooling capacity. During the operation of an evaporator at temperature below 0 °C, humidity agglomerates in form of ice on the surface and reduces the heat transfer. Additional energy is needed due to the reduced suction pressure and therefore the compression ratio is increasing. Reaching a critical point for the heat transfer, the ice must be removed by melting the ice with thermal energy and transporting the water out of the refrigerated room.

About only 30 % of the energy for defrosting at -20 °C is used to melt the ice, the remaining energy is emitted to the cold room or stored in the mass of the evaporator (Pradeep Bansal et al., 2010). When using Mirai air cycle technology there is no need for fans inside the cold room because the open air-cycle machine operates with air from the cold room, circulating it between the oil-free refrigeration machine and the cold room. Furthermore, there is no additional temperature difference needed for heat transfer in the heat exchanger. Regarding the lower cooling demand, the air-cycle machine can already be more efficient at temperatures $< -40\ °\mathrm{C}$ depending on the application. The standard MIRAI air-cycle machine compared to liquid nitrogen is more efficient at temperatures $> \sim -130\ °\mathrm{C}$. Besides the higher efficiency of the air cycle, the system offers benefits such as low dew-point temperatures resulting in less ice on the refrigerated products, fail-safe operation due to advanced compressor technology and temperature flexibility (no additional refrigeration system needed for higher or lower temperatures). Last but not least, there are no special machine room requirements and no leakage monitoring required. The Mirai air-cycle machine has no need for defrosting due to the advanced humidity extraction device shown in Figure 2 which allows a temperature stability with a deviation of 0.5 K, ensuring the product does not go outside of its temperature specification.

Usually bigger refrigeration machines are more efficient due to smaller tolerances, thermal conductivity, and other effects. This is considered in the diagrams Figure 1and Figure 3. The used scale: small means below 5 kW and big means above 100 kW of cooling capacity.

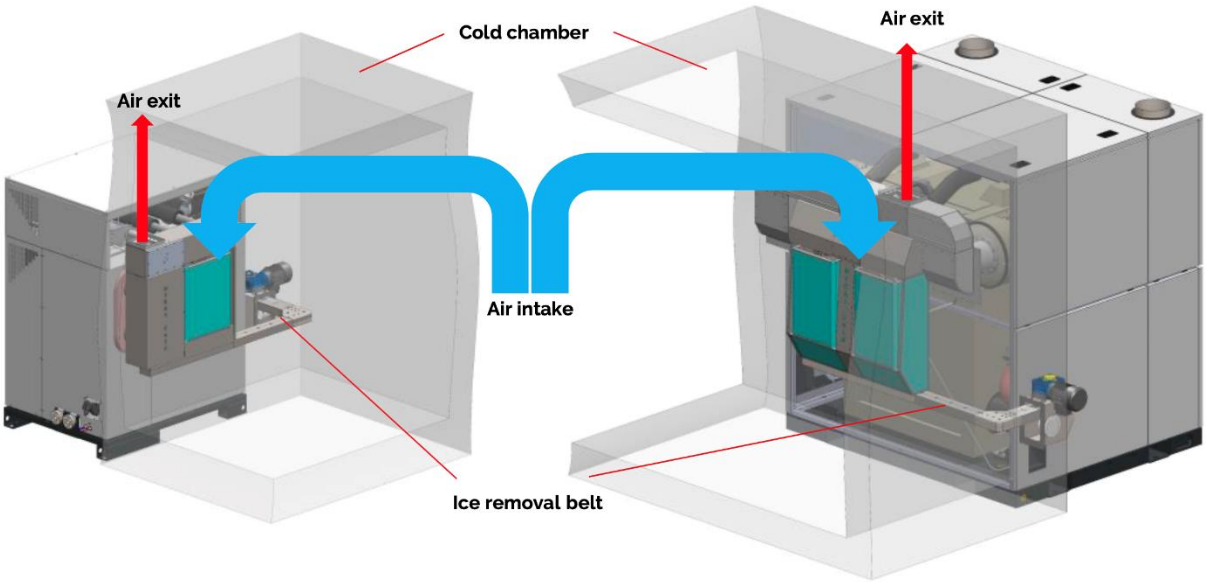

Figure 2 – Dehumidification System of Mirai Intex

3. Efficiency of ULT process or secondary fluid cooling

In general, the lower the temperature the higher is the effort to achieve it. When it comes to the efficiency of process cooling it is important to find the balance between the, necessary process temperature and the implementation of heat recovery systems.

Many applications require heat exchangers for cooling processed gas or other types of fluids. The closed air cycle machine still operates with air as a refrigerant but operates in a closed cycle with a heat exchanger and loses its advantage over the other systems with the reduced cooling capacity for the process. In Figure 3 the three technologies are compared for cooling a secondary fluid.

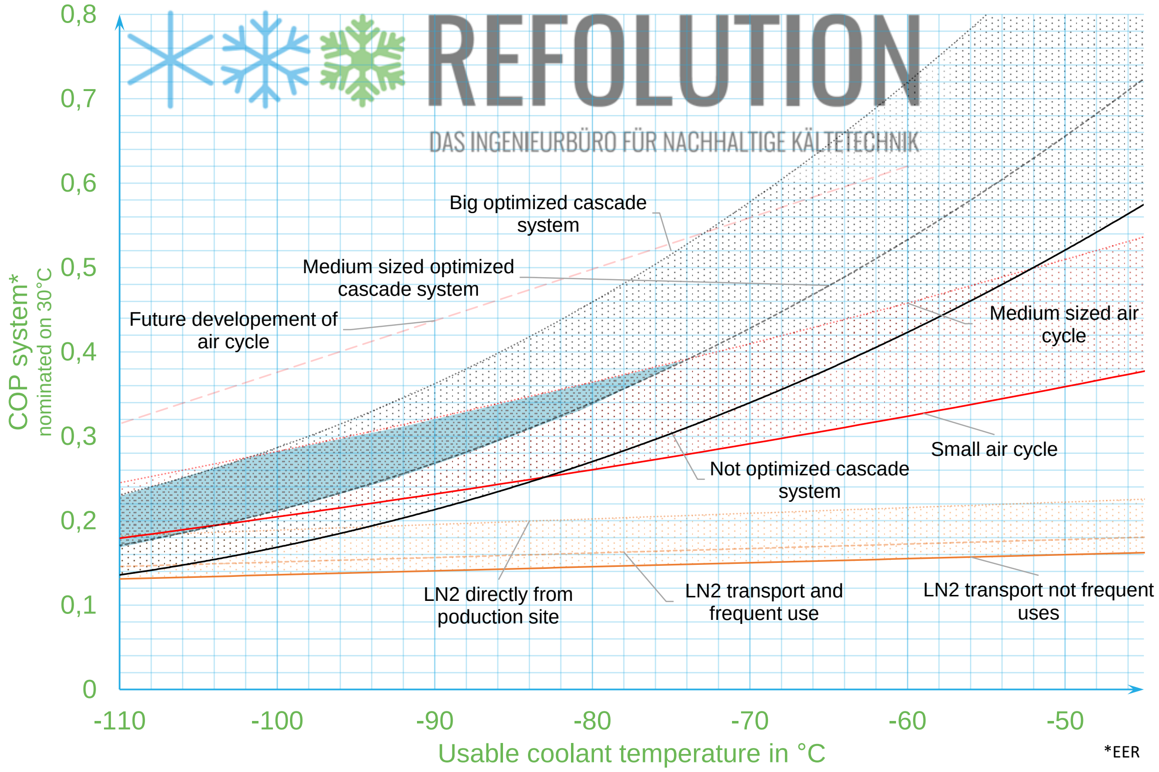

Figure 3: Full load efficiency comparison of liquid nitrogen, cascade system and air cycle refrigeration for secondary fluid

For applications where there is a serious risk of chemical reactions in case of a heat exchanger breach, the air cycle machine can be operated with nitrogen. Vapour compression systems are designed to operate within a certain envelope and are optimized for these specific conditions inside the operating envelope and therefore are not flexible and have inefficient part load behaviour. The MIRAI air-cycle machine can perform efficiently at every temperature and can adapt to change in process parameters with a more efficient operation at partial loads than conventional vapour compression systems due to a single speed-controlled compressor. This is very convenient for processes with rapidly varying cooling loads over time. The commissioning of the air cycle machine is easy, due to its plug & play design and is suitable to be used for retrofitting existing systems to replace high GWP refrigerants. A general comparison of the refrigeration technologies can be found in Table 1.

Table 1: General comparison of the refrigeration technologies

#	Category	Air cycle machine	Vapour compression	Liquid nitrogen
1	Future proof	Air with 1 to 10 barg pressure	Critical with synthetic refrigerants natural refrigerants influenced by safety regulations	Transport and storage regulations
2	Reliability	Air-bearing compressors - no wear during normal operation	Wear on compressor - Damage by liquid refrigerant or failure of oil management	No rotating parts high - thermal stress
3	Safety / Machinery-room	No special needs. Low pressures with air and no vibrations	gas sensors, ventilation, vibration damping floor, Ex ventilation for respective refrigerants	gas sensors, ventilation
4	Maintenance	standard is only filter exchange of the electrical box	oil and refrigerant management, safety valves check, trained personal is necessary, regular leakage control	periodically refill of LN2- tank, control of valve function, control of safety valve (every 5 years)
5	Part load	Speed controlled compressors	Depending on the control strategy - most of the time on start / stop or hot gas bypass	Dosage based
6	Investment	New technology with high costs per machine, fix cost for every temperature	Standard components but 2 to 3 stages of equipment	Mostly rental models for tanks
7	Lifecycle cost	Almost no maintenance required No refrigerant purchase	Refrigerant leak checks Refrigerant prices Maintenance intensive	High running costs in a long term LN2 transport to the site

4. Conclusion

With having a lot of advantages on air refrigeration, like future proof, long live time, reliability, safe for humans and environment and many more it can be seen that also when it comes to full load efficiency it can already be competitive below -40°C on the storage application and below -60°C on process cooling. Getting even more efficient to lower temperatures it is hard to beat below -80°C.

Due to the fact LN_2 is produced on -196°C even with the most efficient production and transport system it is not efficient on temperatures above -110°C and should only be considered in this temperatures ranges when there is a specific project need.

The new generation of air refrigeration systems from Mirai Intex is the most environmentally friendly solutions for ULT applications in the certain operation areas described in this report.

Appendix

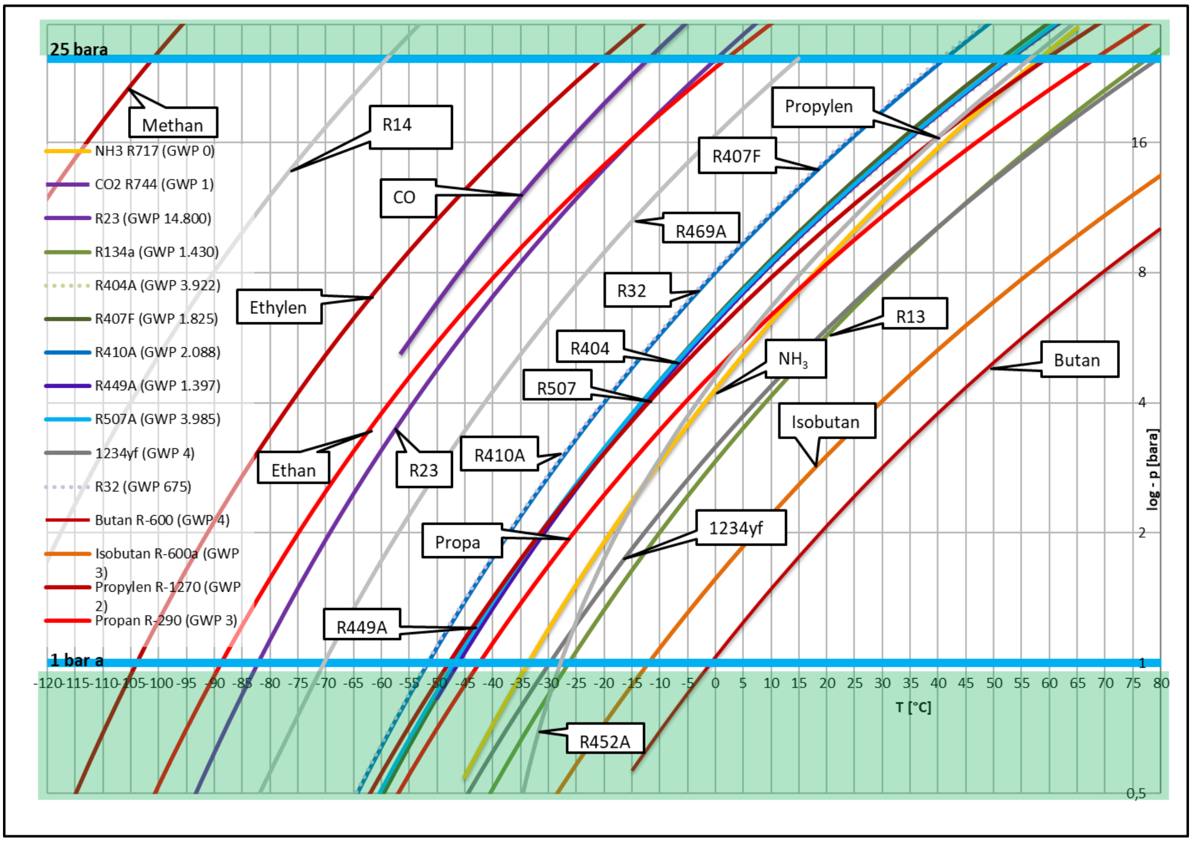

Figure 4: Overview of the most used refrigerants

5. Literature

Pradeep Bansal, David Fothergill & Ryan Fernandes (2010). Thermal analysis of the defrost cycle in a domestic freezer. *International Journal of Refrigeration*, *33*(3), 589–599. https://doi.org/10.1016/j.ijrefrig.2009.11.012

Umweltbundesamt. (2000). *Prozessdetails: Xtra-generischN2 (flüssig)* [Press release]. https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id=%7B0E0B2E00-9043-11D3-B2C8-0080C8941B49%7D

Assumptions for calculations:

Liquid nitrogen:

- Specific liquefaction work for nitrogen $e_{l,real}$ = 1568 kJ/kg (from 30 °C to -196 °C; efficiency of liquefier 50 % (0,55 kWh/m³ (Umweltbundesamt, 2000))
- Boil-off for storage 1%$_{Vol.}$/d
- Only 5/6 of produced volume is delivered to the customer
- 5 % transfer loss in a batch process with liquid nitrogen

Mirai air-cycle:

- Up to 30 % higher efficiency due to humidity extraction system (open system)
- Capacity and electric power of data sheets (closed: MC10 C/W/T, MC23 C/W/T, MC80 C/W/T; open: MC15 O/A
- Data from own measurements
- ΔT heat exchanger to process 5 K

Cascade system:

- Efficient cascade system with low pressure drop (0,06 bar on suction - industrial standard)
- Minimum suction gas temperature of -50 °C (Materials for low temperatures)
- ΔT cascade heat exchanger of 5 K
- ΔT heat exchanger ambient 8 K
- ΔT heat exchanger cold room 10 K
- ΔT heat exchanger to process 5 K
- Not optimized curve is based on measurements