Air – A Natural Refrigerant

Environmentally friendly

Air refrigeration systems use ambient air as the refrigerant, offering a natural and environmentally friendly cooling solution. With growing environmental awareness and regulations such as the EU F-Gas Regulation, air cycle refrigeration technology is gaining increasing relevance. Air neither depletes the ozone layer nor contributes to global warming, making it a future-proof alternative to conventional refrigerants. An additional advantage is its unlimited availability.

Characteristics

Air as refrigerant has no ozone depletion potential (ODP=0) and no global warming potential (GWP=0). It is non-toxic and non-flammable. Air is also appropriate for Ultra-Low Temperatures.

Air cycle machines present an effective solution for ultra-low-temperature applications from −40 °C to −160 °C. The machines, characterized by their efficient and wear-free turbo technology, demonstrate notable advantages in terms of energy efficiency, reliability, future viability, and safety.

Practical applications include freeze-drying processes, which have demonstrated potential energy savings of up to 19% compared to traditional refrigerants like R404A. Air cycle refrigeration has also been successfully employed in cold room applications, providing efficient cooling without moisture-related problems due to innovative dehumidification systems.

Air refrigeration systems thus offer considerable environmental, operational, and economic benefits for industries requiring low-temperature refrigeration.

Working Principle of Air Cycle Refrigeration

As shown in figure 1 air cycle refrigeration operates by compressing ambient air (1->2), cooling it through a heat exchanger (2->3), then expanding it through a turbine (3->4), significantly lowering its temperature. This cooled air absorbs heat (4->1) from the target environment or process, becoming warmer before returning to the compressor, thus completing the cycle.

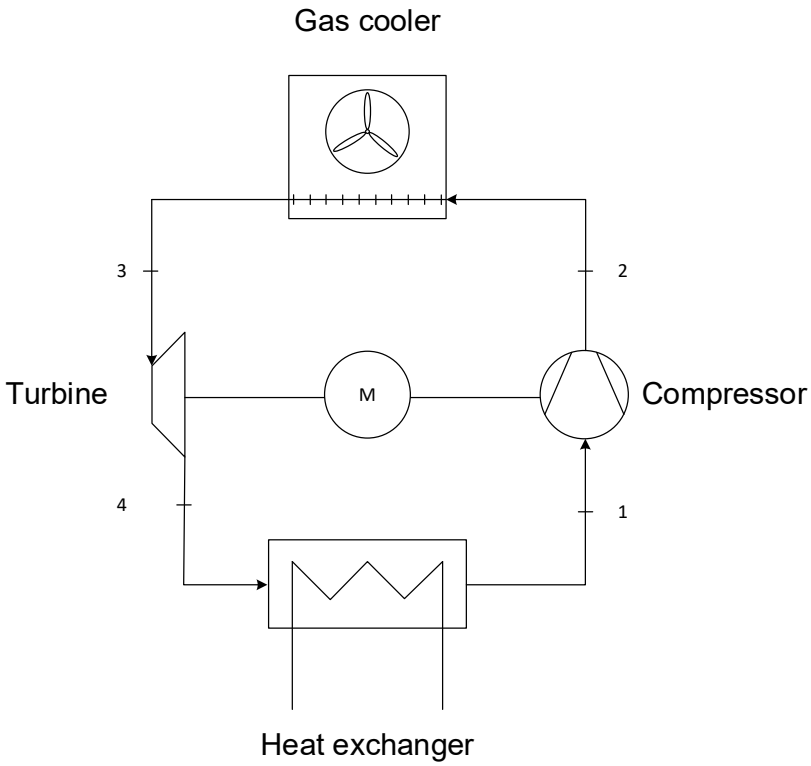

Figure 1: Air cycle refrigeration

The primary advantage of air cycle refrigeration lies in its simplicity and environmental friendliness. However, the efficiency largely depends on the isentropic efficiencies of the compressor and expander, which significantly influence the net refrigeration capacity and the overall energy efficiency.

Variations of Air Cycle Processes

Closed Air Cycle with Internal Heat Exchanger

In a closed air cycle with an internal heat exchanger, air is compressed, then cooled first in an external cooler and subsequently further cooled by an internal heat exchanger. The cooled, compressed air then expands through a turbine, dropping significantly in temperature, enabling it to absorb heat from the refrigerated space or process.

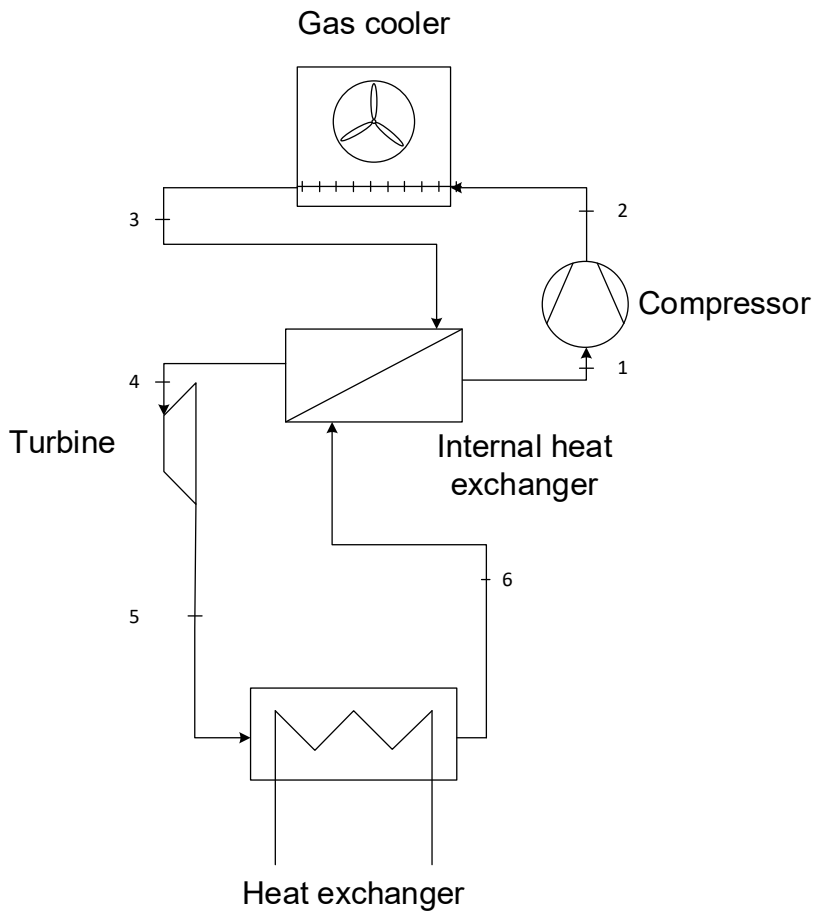

Figure 2: Closed air cycle with internal heat exchanger

The internal heat exchanger improves cycle efficiency by pre-cooling air entering the expander and pre-heating air entering the compressor, thus reducing the required compression energy and enhancing the overall cycle performance.

Open Air Cycle

The open air cycle eliminates the heat exchanger on the low temperature side. This reduces heat transfer losses and increases the systems efficiency. The air inside of the chamber is directly compressed, cooled, and expanded and fed back into the room at lower temperature.

Due to the circulation of the air via the air cycle machine, no additional installation of fans inside of a cooling room is required. This reduces the installed cooling capacity and increases the overall efficiency of the system. In some cases the netto cooling load can be reduced up to 40 % by eliminating heat from fans, heaters and defrost cycles.

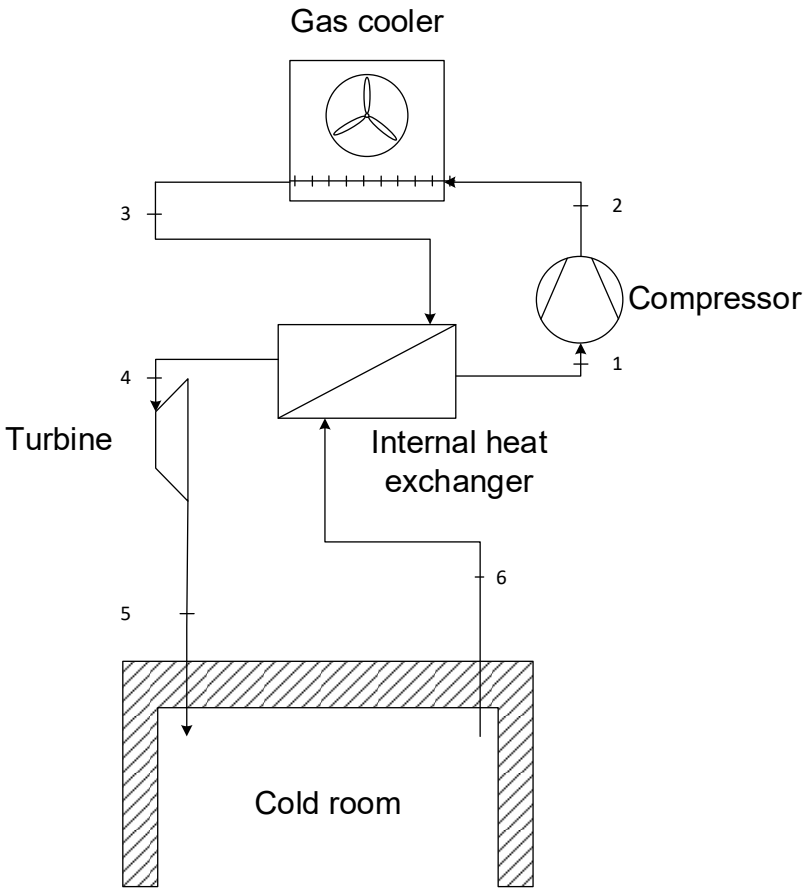

Figure 3: Open air cycle

Applications of Air Cycle Refrigeration

Air refrigeration technology is effectively used in various industrial and medical applications including:

- Freeze-drying (Lyophilization)
- Cryotherapy chambers
- Biological and medical storage
- Cryopreservation of biological materials
- Gas traps
- Cryogenic deburring of plastics
- Cryogenic grinding
- Cryogenic hardening of metals

The versatility of air refrigeration provides advantages such as high operational safety, environmental friendliness, and cost efficiency, particularly in highly regulated environments.

Energy Efficiency Comparison

When evaluating refrigeration systems, energy efficiency plays a key role in both operational cost and environmental impact.

Air cycle systems typically demonstrate lower Coefficient of Performance (COP) at higher temperatures due to losses from non-ideal compression and expansion. However, as temperatures decrease, particularly below −60 °C, the efficiency of vapor-compression systems drops significantly, especially when multiple cascade stages are required.

At this low-temperature, air cycle systems become energetically competitive. Compared to cascade vapor-compression systems using flammable refrigerants (e.g., R290/R170), air systems eliminate the need for intermediate heat exchangers and complex safety precautions, improving simplicity.

When compared to liquid nitrogen cooling, air cycle systems provide a higher energy efficiency at temperatures above -130 °C. Although liquid nitrogen offers very low temperatures, it must be produced through an energy-intensive process and transported in a cryogenic state, incurring high operating costs.

Thus, for temperature ranges from −40 °C to −160 °C, air refrigeration represents a compelling, energy-efficient alternative, particularly when future-proofing and sustainability are critical design goals.

Outlook

The usage of air as a refrigerant for low temperature applications is expected to expand further due to its environmental advantages, regulatory compliance, and increasing energy efficiency advancements. The ongoing development in air cycle technology will likely broaden its application spectrum, particularly in sectors emphasizing sustainability and reduced ecological footprints.

Further information:

Eckert, M., Kauffeld, M., & Siegismund, V. (Hrsg.). (2022). *Natural Refrigerants: Applications and Practical Guidelines*. VDE Verlag. ISBN 978-3-8007-5330-7

Maurer, T. (2021). *Kältetechnik für Ingenieure* (2. aufl.). VDE-Verlag. ISBN 978-3-8007-5240-9.

Refolution Industriekälte GmbH. (2020). *Energievergleich – ULT-Report*. Refolution. Abgerufen am 21. Januar 2026, von https://www.refolution.de/de/kaeltetechnik/energievergleich-ult-report/

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