Celeroton

White Paper – Centrifugal compressors for refrigerants

1 Heating and cooling with refrigerant circuits

The macro trend of attaining sustainable, secure and competitive energy generation and use while combating climate change drives many micro trends in heating and cooling applications, such as:

- Replace fossil fuel based heating equipment with heat pumps
- In thermal management of buildings the focus is shifting from heating towards cooling/climate control, which usually requires refrigerant circuits
- For already existing heat pump and cooling applications based on refrigerant circuits, the trend is towards lower temperature lifts, e.g. by using geothermal sources and low temperature floor heating
- Replace heating with resistors by heat pumps in hybrid/electric vehicles to extend range and combine the heating and cooling
- Cooling with refrigeration cycles in future more/all electric aircrafts like planes, air taxis, UAVs, helicopters
- Cooling of electronics in confined spaces in spacecraft, satellites, UAVs, drones, etc.
- Trends to lower global warming potential (GWP) refrigerants and ban of ozone depletion potential (ODP) refrigerants

In short: The future in heating and cooling is based on a refrigerant circuit driven by an electrical compressor. Such a refrigerant circuit is depicted in Figure 1.

Most current refrigerant circuits for heating and cooling utilize displacement compressor such as scroll compressors. The compressor choice depends on the refrigerant choice itself, but also the operating requirements such as temperature levels, thermal power, required coefficient of performance (COP), size and weight restrictions, lifetime, maintenance, vibration and noise limits, manufacturing quantities, cost, etc. For many of these requirements, the centrifugal compressor, also called radial turbo compressor, has advantages.

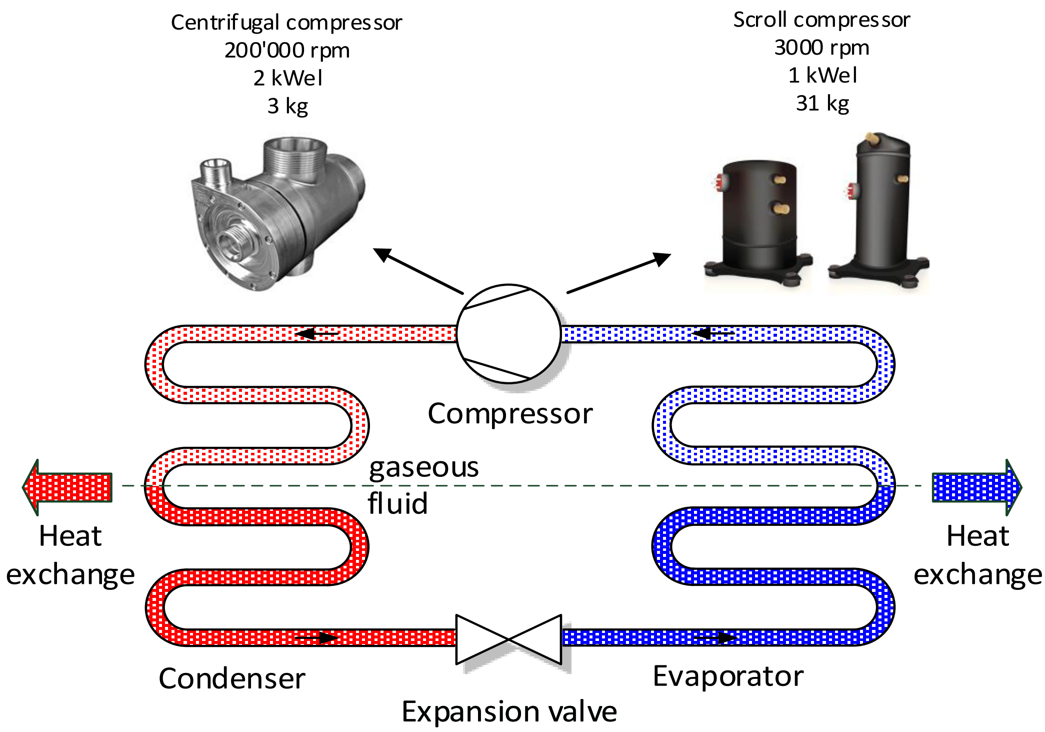

Figure 1: Refrigerant circuits for heating and cooling are driven by a compressor, which can be a state-of-the-art scroll or other displacement compressor or a centrifugal compressor.

The choice of the refrigerant is a key decision in refrigerant circuit design. An overview of the different refrigerants, which can be compressed by centrifugal compressors, is given hereafter:

- Standard refrigerants:
  - R134a
  - R470
  - R410
- Low GWP refrigerants, e.g. Hydro-fluoro-olefins (HFO):
  - 1-Chloro-3,3,3-trifluoropropene (R1233zd)
  - 2,3,3,3-Tetrafluoropropene (R1234yf)
  - 1,3,3,3-Tetrafluoropropene (R1234ze)
- Hydrocarbon natural refrigerants
  - Butane (R600)
  - Isobutane (R600a)
  - Isopentane (R601a)
  - Propane (R290)
- Other natural refrigerants:
  - Carbon dioxide (R744)
  - Argon (R740) or other noble gases, specifically for ultra-low temperature / cryogenic applications
  - Air (R729)
  - Nitrogen (R728)
  - Steam (R718)
  - Ammonia (R717)

However, watch out: the centrifugal compressor is not the ideal solution everywhere. This article shall be a guideline to determine if your application can profit from centrifugal compressor technology or not.

2 Application examples

2.1 Rocket science

Celeroton has been granted ESA funding to develop a breadboard model of a turbo compressor for satellite thermal control based on a heat pump system. More information can be found here. For spacecraft thermal control, ammonia is the refrigerant of choice, due to its superior thermal behavior and resulting low piping and heat exchanger dimensions. According to the technical insights provided in the following, the high absolute pressure and other gas parameters of ammonia pose a high challenge to the centrifugal compressor design. Despite this very challenging refrigerant choice, the centrifugal compressor is selected due to:

- Low micro vibration emission. This is key in future satellites due to vibration sensitive transmission equipment. In applications on earth, the benefit of low vibration emission is usually low noise.
- Low weight and size – directly translating to reduced launch cost for satellites
- No wear, long lifetime and no maintenance – a must for space applications
- Oil-free
- High efficiency

2.2 Down to earth

Beside spacecraft thermal management, more down-to-earth applications like low temperature lift heat pumps where centrifugal compressors can make the difference, e.g. if the following requirements are present:

- Low temperature lift heating and cooling
- Oil-free operation
- No, low maintenance
- Low noise
- Confined space requirements
- High efficiency
- Power adjustment by speed control

An example of an isobutane compressor for low temperature lift heating and cooling is shown in Figure 2.

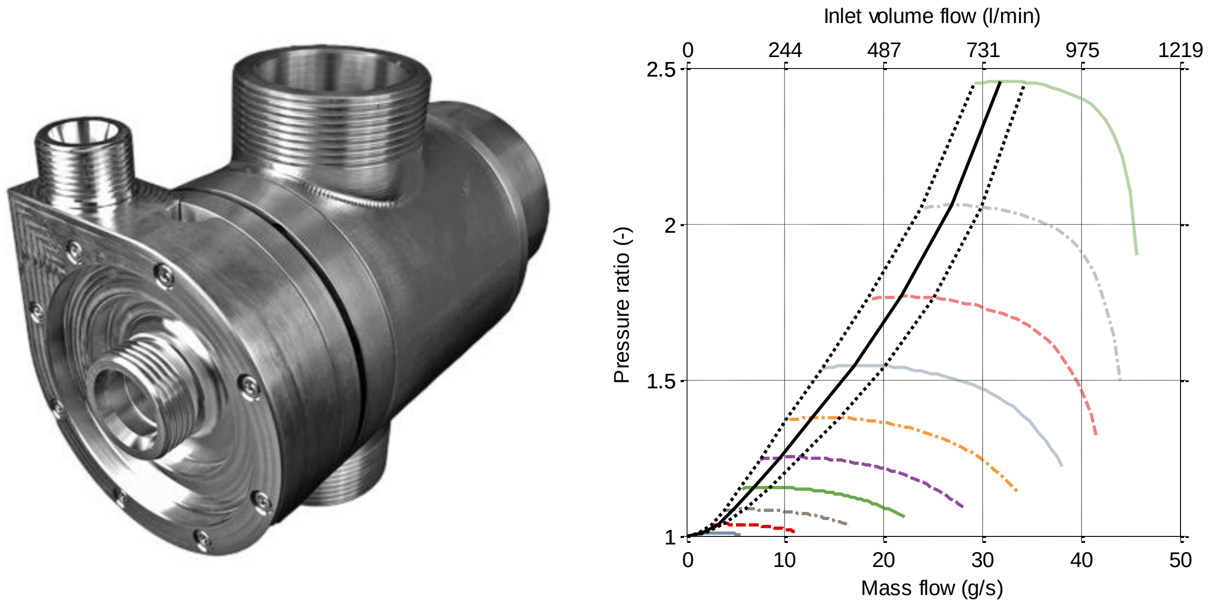

Figure 2: Picture of the realized low temperature lift heat pump compressor (left side) and according compressor map for isobutane at 9 °C inlet temperature and 1.24 bara inlet pressure (right side).

3 Centrifugal compressors for refrigerant circuits

3.1 Centrifugal vs. displacement compressors

In contrary to displacement compressors, centrifugal compressors compress gas by dynamic principles. Mechanical (shaft) power is transferred to the fluid by the blades of an impeller. The flow than is decelerated resulting in a significant pressure increase. More information can be found here. This compressor type requires only one moving part, the rotor, which can run on contact free gas bearings, and can be driven directly with a high-speed electrical motor. This results in several advantages compared to displacement compressors for compressing refrigerants:

- Oil-free operation due to gas bearings, which utilize the refrigerant itself as lubricant. Oil-free operation is preferred in refrigerant cycles to avoid foaming of the refrigerant.
- No rotating (or moving) seal
- Compact and lightweight due to high-speed
- Low noise
- High efficiency (especially/also at low temperature lifts)

However, there are also drawbacks of centrifugal compressors compared to other compressor types such as displacement compressors:

- The dynamic working principle results in restrictions in the operating range (keywords: surge line/choke line), which limits the operating envelope in the condensing (T_C) over evaporating (T_E) temperature diagram
- The stationary continuous flow limits the pressure rise (and therefore the temperature lift) per compressor stage. For high temperature lifts (resulting in higher pressure ratios) multi-stage compressors are required
- The small size, mentioned as an advantage above, results in high power density and a challenging thermal and compressor cooling design
- The small size furthermore results in tight manufacturing tolerances

A comparison of various compressor technologies is available here.

3.2 When is a centrifugal compressor the best choice for a heating or cooling application?

The refrigerant choice significantly influences the applicability of a centrifugal compressor. Gas bearing centrifugal compressors operate best with refrigerants with low absolute pressures such as butane or R1233zd. Gas bearing turbo compressors have low performance with high pressure refrigerants such as carbon dioxide and ammonia, although you have read in an application example above that for such refrigerants the centrifugal compressor can be the right choice if other requirements such as low emission of vibrations, oil-free operation and reliability call for a centrifugal compressor.

Therefore, the answer to above question is not only defined by the refrigerant, but by all technical requirements of the refrigerant circuit, and moreover also by the business case. Clearly, the centrifugal compressor is a preferred choice if technical requirements cannot be fulfilled by displacement compressors, such as:

- Oil-free operation
- Top level target/goal of low size and/or weight
- Low noise/low micro vibration emission
- High efficiency at low temperature lifts
- High volume flow requirements (e.g. such as for high thermal power, low temperature lift heating and cooling, for certain refrigerants, or in steam/air cycles)

However, a centrifugal compressor is usually not the right choice if it is a direct replacement for an existing scroll or other displacement compressor. The reason being that a centrifugal gas bearing compressor is a high-tech solution requiring for high manufacturing precision, and therefore cannot compete in price if an existing scroll/displacement compressor is fulfilling the requirements.

3.3 Insight into centrifugal compressor design for refrigerants

Centrifugal gas bearing compressor for refrigerant circuits are usually custom designed for specific technical requirements. Celeroton offers such customized designs and has all the capabilities and know-how to cover customer needs with optimal solutions. More information on custom developments can be found here.

Designing a centrifugal compressor for refrigerants has many technical challenges and versatile, interdisciplinary know-how is required:

- Refrigerant trade-offs including compressor feasibility and performance, but also heat exchanger, piping and expansion valve sizing, performance and availability of existing components.
- Compressor efficiency and resulting heating or cooling COP calculation for different operating points early in design.
- Compressor concepts with several compressor stages in parallel or series (stage stacking) to cover high thermal power and/or high temperature lift applications. Compressor maps for multi-stage compressor systems. Control strategy of multi-stage compressor systems.

- Integration of compressor cooling into thermal management system (suction gas cooling, liquid (refrigerant) cooling, water cooling, forced air cooling).

A refrigerant circuit specific know-how required is the conversion of the compressor map, which is the standard performance visualization in centrifugal compressor design, into the operating envelope in the T_C-T_E diagram, which is the standard performance visualization in refrigerant circuits:

- The compressor map is usually defined for fixed compressor inlet conditions (inlet temperature and pressure), e.g. a fixed evaporating temperature. The pressure ratio and mass/volumetric flow range defines the temperature lift and thermal power range at these inlet conditions.
- On the other side, customers planning a refrigerant circuit require to know the performance limits at different evaporating temperatures.
- Different compressor inlet, i.e. evaporating temperatures results in different pressure ratio and mass flow limitations within the different compressor maps, which have to be converted into the T_C-T_E diagram.

Figure 3 depicts the two different diagrams and the conversion in between, which can be provided by Celeroton.

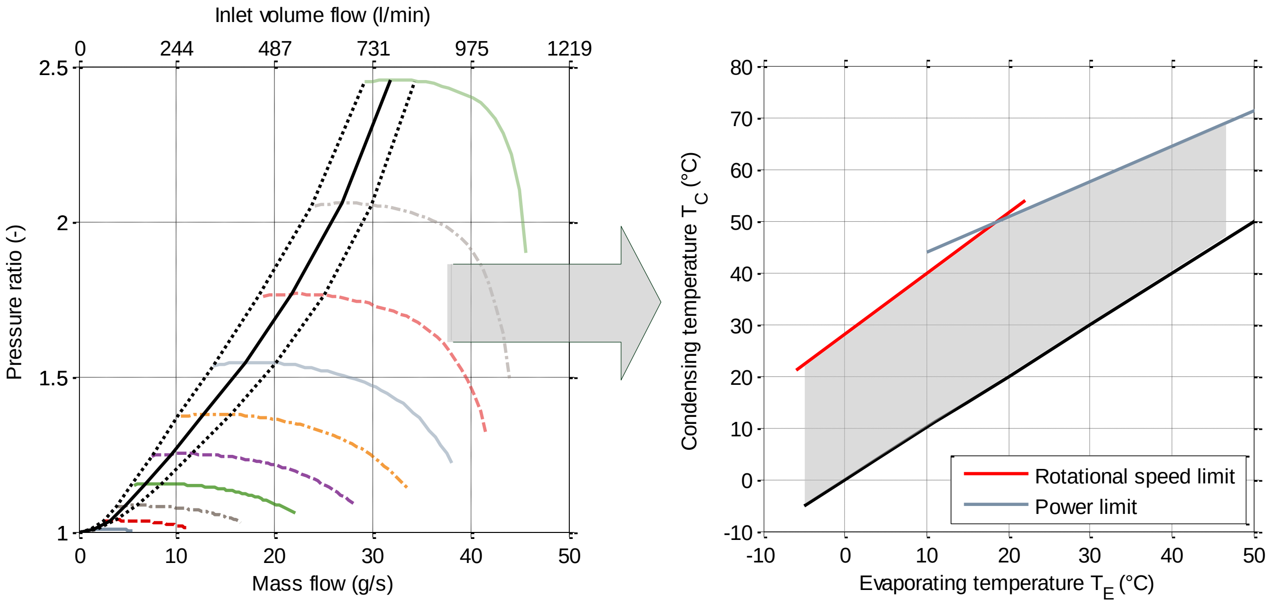

Figure 3: Compressor map with pressure ratio over mass flow for different speed lines on the left side and resulting T_C-T_E diagram with condensing vs. evaporating temperature on the right side.

4 Your refrigerant circuit inquiry

Celeroton combines know-how in centrifugal compressor design and customer needs in refrigerant based heat pump and cooling applications and is therefore as your ideal partner to:

- Check the feasibility of centrifugal compressors for your heating or cooling application
- Develop your custom specific centrifugal compressor for your refrigerant circuit
- Test of your centrifugal compressors in refrigerants at Celeroton, also see here
- Supply centrifugal compressor prototypes for testing in your application
- Plan the series production: From design for manufacturing, to production by Celeroton, up to license models for mass manufacturing quantities

We are looking forward to receiving your refrigeration cycle compressor challenge!