WORLD GUIDE TO TRANSCRITICAL CO_2 REFRIGERATION

Part 1

World Guide to
Transcritical CO_2 Refrigeration

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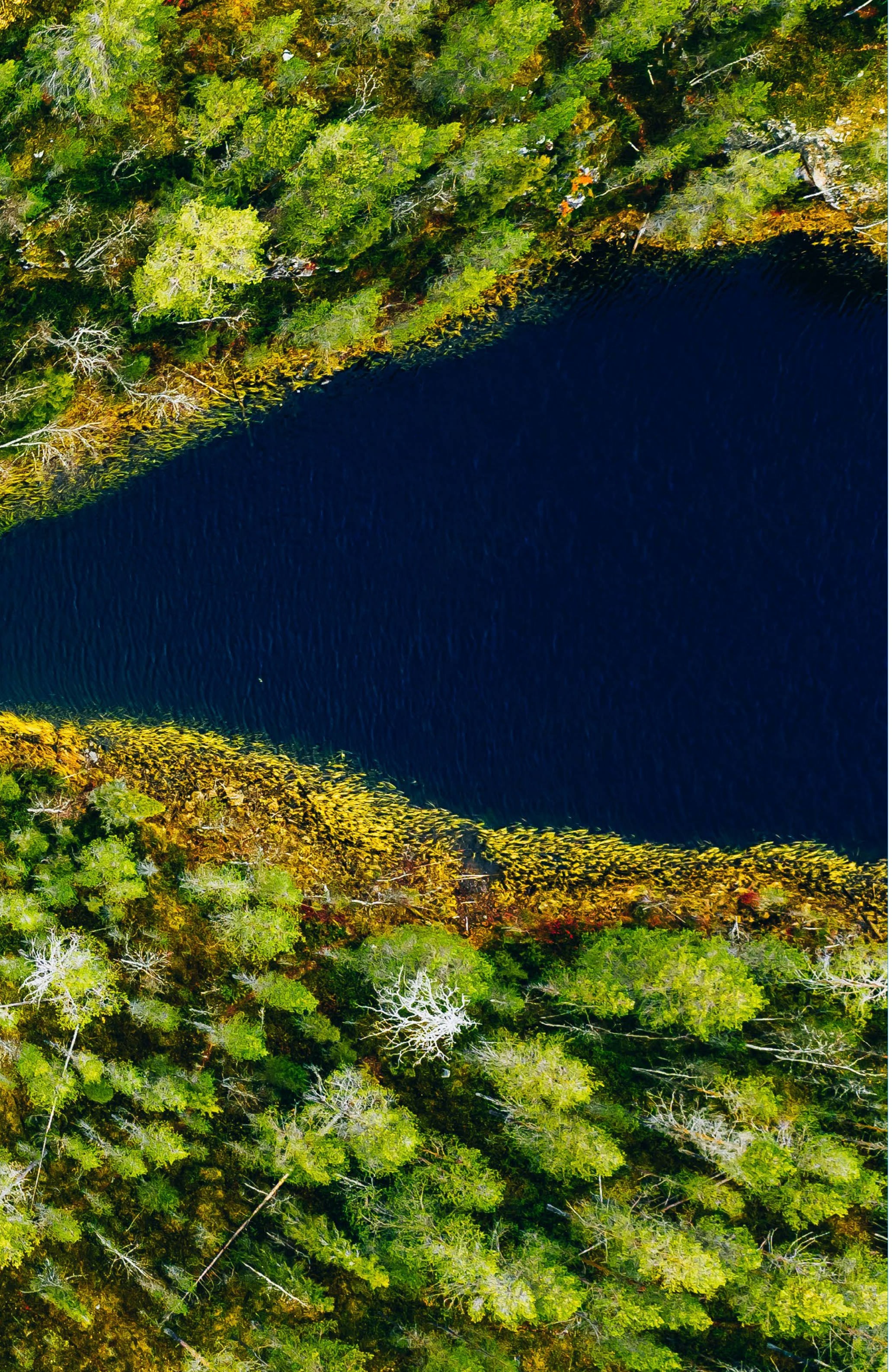
ABOUT THIS GUIDE



Introduction

The use of CO_2 as a refrigerant began in early industrial times and has been revived in the past few decades. Just like other natural refrigerants (ammonia, propane, isobutane etc), it neither contributes to ozone depletion nor to global warming, making it a preferred choice in terms of climate friendly cooling technologies.

CO_2 is often preferred over other natural alternatives as it has no flammability risk and no toxicity issues. This has allowed it to thrive without fear of policy or standard interventions that so often stifle the growth of alternatives such as ammonia and/or propane. The only potential concern is the high operating pressures of a CO_2 system, but much research and development has gone into designing the modern systems of today to ensure that this can easily be accommodated.

It's clear that CO_2 is the rising star of the commercial food retail industry – particularly since the refinement of transcritical systems. In Europe especially it's become almost a "no brainer" to select transcritical CO_2 systems for any commercial retail project – new or retrofit. Not only does this ensure the installation is future proof and protected from inevitable synthetic refrigerant phase downs, but it usually also offers impressive energy savings over other refrigerants – curbing indirect greenhouse gas GHG emissions as well as direct ones.

However, CO_2 is no longer confined to just commercial installations. Even smaller convenience store end users are seeing the benefit of going the transcritical CO_2 route and despite a widespread belief that industrial systems are more the domain of ammonia; there is a clear rise in industrial CO_2 applications around the world.

The global HVAC&R market is changing, and it is crucial to keep with the latest industry trends and technologies. As such, this guide will specifically look at the potential of transcritical CO_2 – today and in the future. By sharing case study examples, technical information, policy updates, challenges, opportunities, and even actual figures on the amount of installations completed globally, the aim is to help accelerate the uptake of this climate-neutral, sustainable refrigeration technology around the world.

A SHORT OVERVIEW

CHAPTER 1
Introduction to CO_2 as a refrigerant

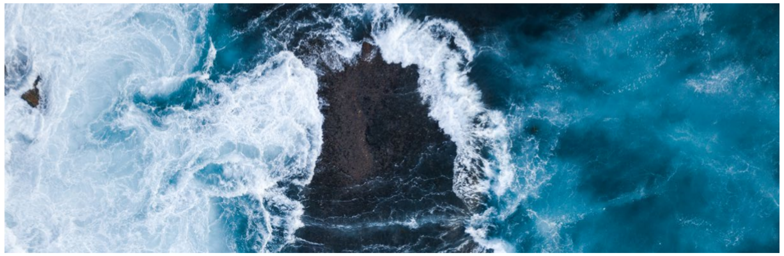
This chapter takes a look at the history of the use of CO_2 as refrigerant. It describes the key characteristics of CO_2, the types of available systems and the technical function of various components.

CHAPTER 2
Applications of transcritical CO_2

This chapter shows examples of applications of transcritical CO_2 around the world, from its beginnings in commercial supermarkets to new convenience store and industrial applications as well.

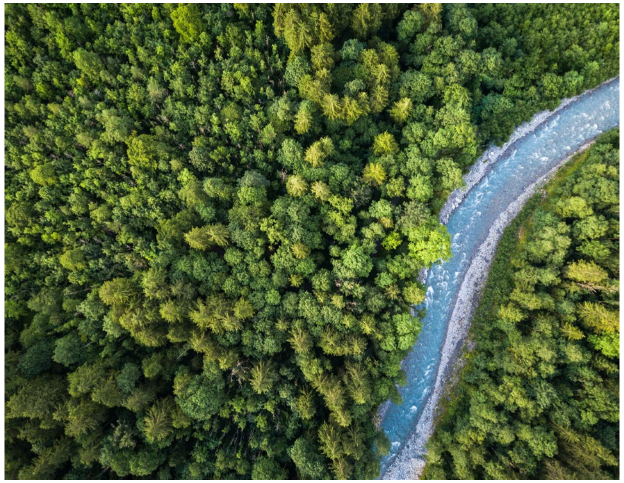
CHAPTER 3
Transcritical CO_2 today

This chapter will give an introduction to our market research results and offer insight into the global transcritical CO_2 market today. It will look at the number of global installations and share general comments from our in-depth industry survey. It will also give an overview of policy and standards affecting the use of CO_2 as a refrigerant.



CHAPTER 4
Convenience store (small) applications

This chapter takes a closer look at the market for transcritical CO_2 in convenience stores today, including global market trends, partner case studies, and survey results. What is the potential of this technology for smaller systems?



CHAPTER 5
Commercial/supermarket applications

What does the market for transcritical CO_2 in supermarkets and commercial installations look like today? We take a look at global market trends, partner case studies and share survey results to get a better picture of this.

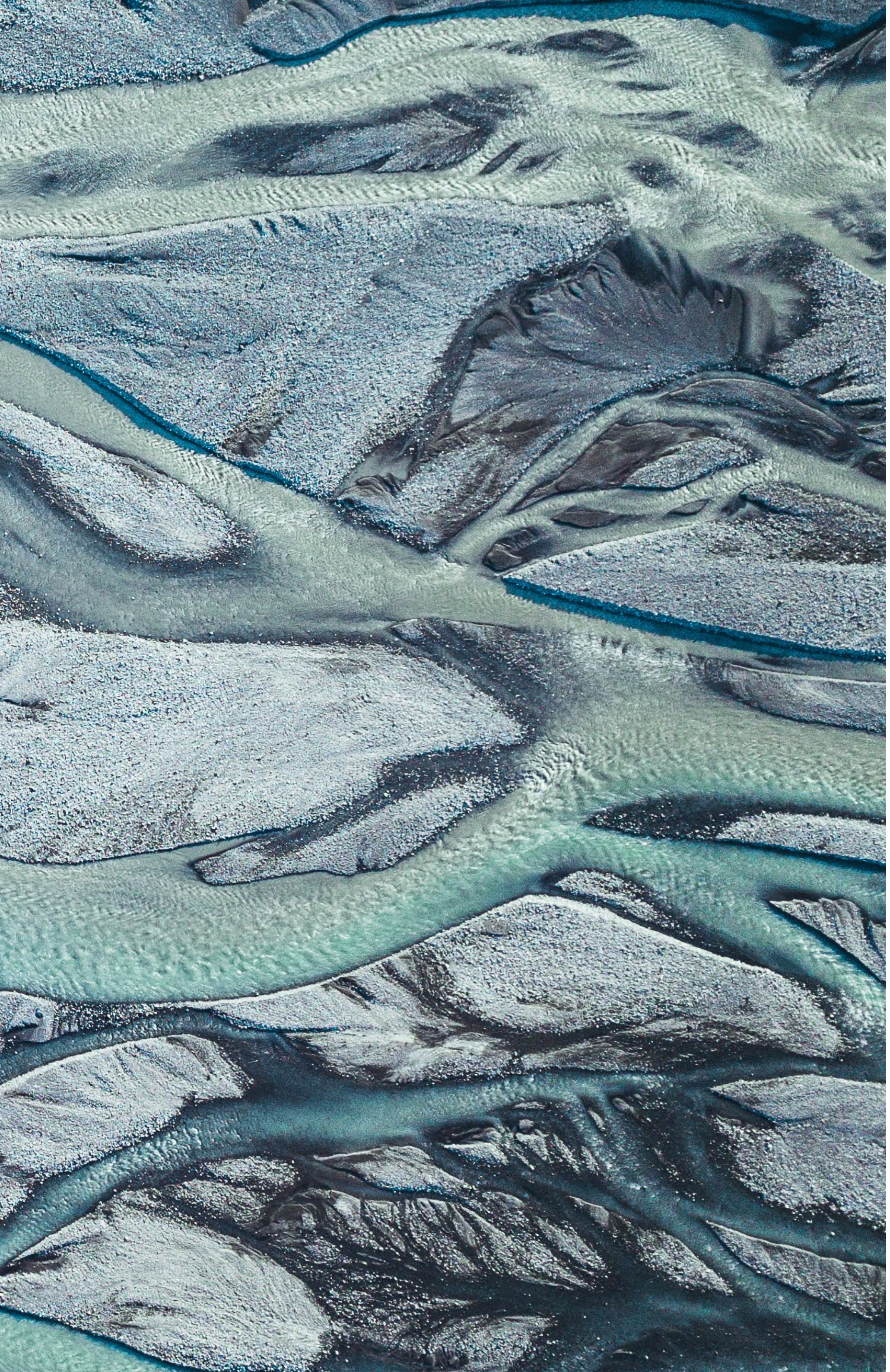
CHAPTER 6
Industrial applications

This chapter investigates the current market for transcritical CO_2 in industrial applications specifically with a look into global market trends, partner case studies and survey results relating to this.

CHAPTER 7
The future of transcritical CO_2 refrigeration

Based on interviews, market research, and survey results, this chapter anticipates the global market potential for transcritical CO_2 technology, looking at its future uses and projected growth. It will also cover drivers and barriers for the uptake of this technology and include partner interviews on the topic.

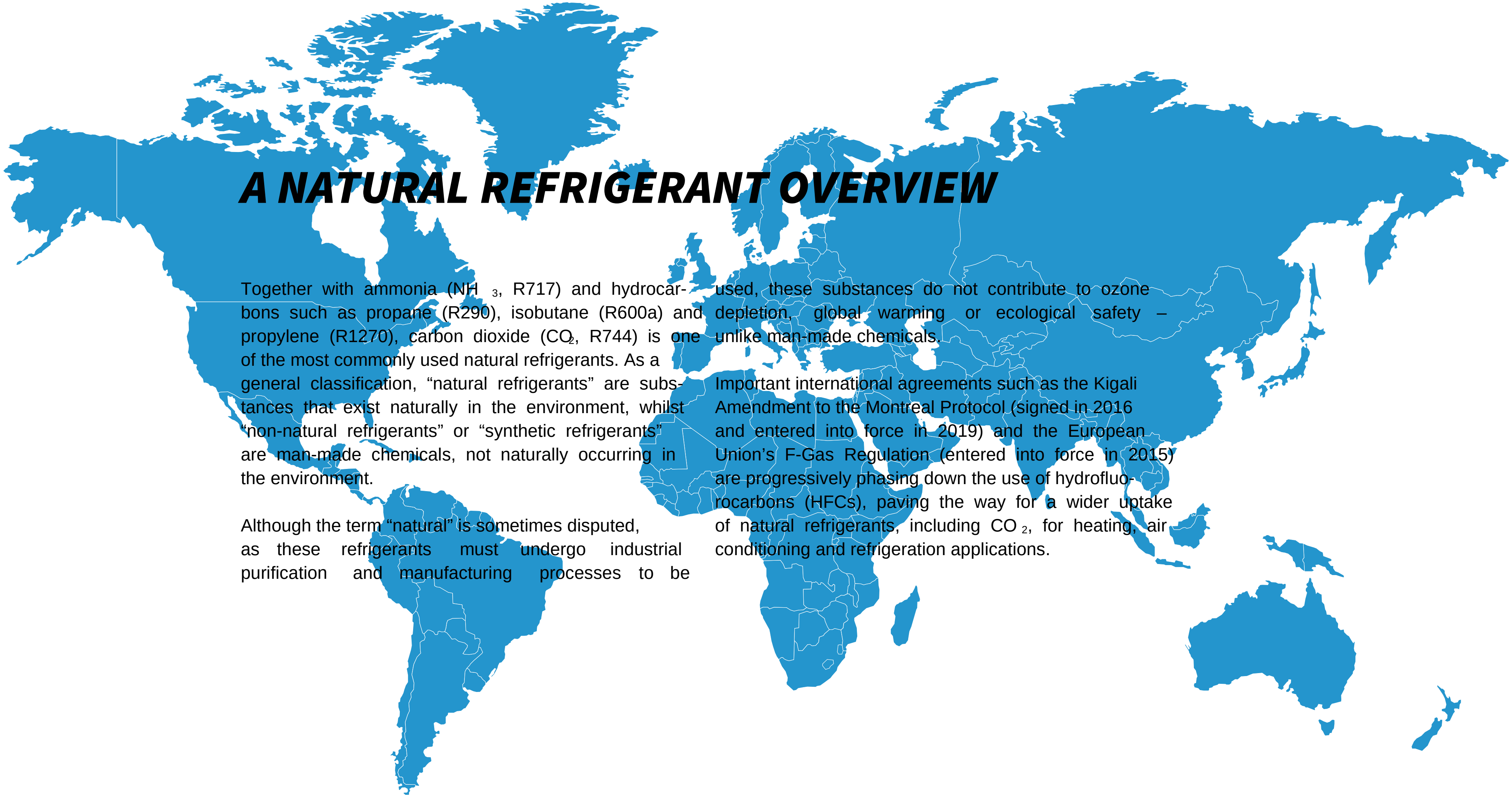
INTRODUCTION TO CO_2 AS REFRIGERANT



An overview

The first chapter of the guide seeks to provide the background needed to understand the transcritical CO_2 market today. By looking at natural refrigerants and particularly CO_2 as refrigerant, it is easy to understand what sets this gas apart from all other alternatives.

This chapter also includes a brief history on using CO_2 in HVAC&R, coupled with a rough timeline showing just how quickly this technology has developed over recent years. This section will also delve further into types of CO_2 systems (transcritical systems and others) and the function of key components, giving a basic understanding without getting too technical.



A NATURAL REFRIGERANT OVERVIEW

Together with ammonia (NH_3, R717) and hydrocarbons such as propane (R290), isobutane (R600a) and propylene (R1270), carbon dioxide (CO_2, R744) is one of the most commonly used natural refrigerants. As a general classification, “natural refrigerants” are substances that exist naturally in the environment, whilst “non-natural refrigerants” or “synthetic refrigerants” are man-made chemicals, not naturally occurring in the environment.

Although the term “natural” is sometimes disputed, as these refrigerants must undergo industrial purification and manufacturing processes to be used, these substances do not contribute to ozone depletion, global warming or ecological safety – unlike man-made chemicals.

Important international agreements such as the Kigali Amendment to the Montreal Protocol (signed in 2016 and entered into force in 2019) and the European Union’s F-Gas Regulation (entered into force in 2015) are progressively phasing down the use of hydrofluorocarbons (HFCs), paving the way for a wider uptake of natural refrigerants, including CO_2, for heating, air conditioning and refrigeration applications.

SHORT HISTORY OF CO_2 AS REFRIGERANT

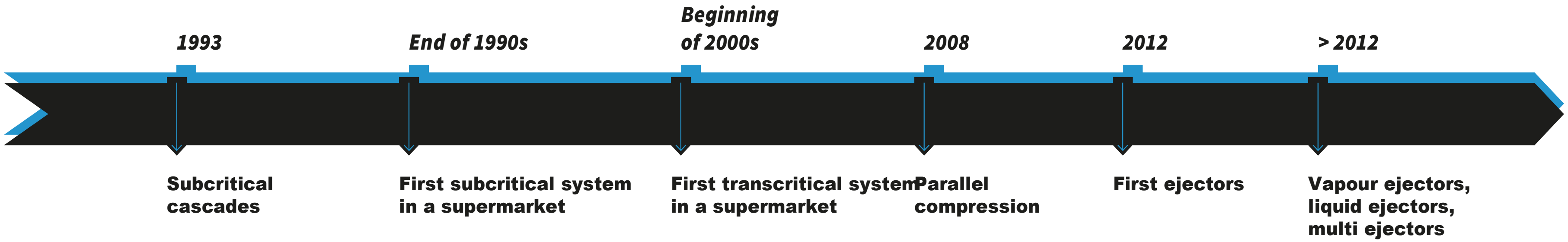
The use of CO_2 as a refrigerant dates back to the early industrial times. In 1850, Alexander Twining obtained a British patent for his “refrigeration machine” and proposed to use CO_2 as a refrigerant.[1] In 1860, S.C. Lowe built a CO_2 refrigeration system. In the years following 1860, CO_2 became more widely used. The peak in the use of CO_2 refrigeration systems occurred in the 1920s. In the 1950s, the last CO_2 systems were installed in marine applications, before CO_2 was replaced by synthetic refrigerants.[2] Unlike ammonia, it did not survive the introduction of CFC and HCFC refrigerants[3].

With the Montreal Protocol phasing out the use of ozone-depleting substances, CO_2 was rediscovered as an alternative[3]. The revival of CO_2 refrigeration technology happened in 1993 with the first subcritical systems being installed again.[2]

At the end of the 1990s, the first subcritical system was installed in a supermarket. At the beginning of the 2000s, it was the first transcritical system in a supermarket. Starting from around 2008, the introduction of parallel compression and subsequently ejectors led to a much higher adaptability of transcritical CO_2 in regions with high ambient temperatures.[4][5]

Infographic timeline of key milestones in the global expansion of CO_2 use

INFOGRAPHIC TIMELINE OF KEY MILESTONES IN THE GLOBAL EXPANSION OF CO_2 USE



KEY CHARACTERISTICS OF CO_2 AS REFRIGERANT

Carbon dioxide (CO_2) is naturally occurring; and a colorless gas (or a solid) at atmospheric pressure, which makes up 0.04% of the Earth's atmosphere [6].

It is a crucial part of life on Earth, as it is the main product of respiration and the main carbon source for plants during photosynthesis. CO_2 is non-flammable and non-toxic. However, a large leak in a confined space can displace available oxygen for breathing [7].

Emissions of CO_2 from the combustion of fossil fuels lead to the greenhouse effect that is warming up the global climate. However, CO_2 is not the only, and certainly not the most potent, greenhouse gas. Moreover, CO_2 is used as a reference when determining the Global Warming potential (GWP) of other gases. Hence, CO_2 has a GWP of 1.

Another measurement of the environmental impact of substances such as refrigerants is the Ozone Depletion Potential (ODP). Synthetic refrigerants with chlorine compounds were found to contribute to the depletion of the ozone layer [8]. CO_2 does not have ozone-depleting characteristics and therefore has an ODP of 0.

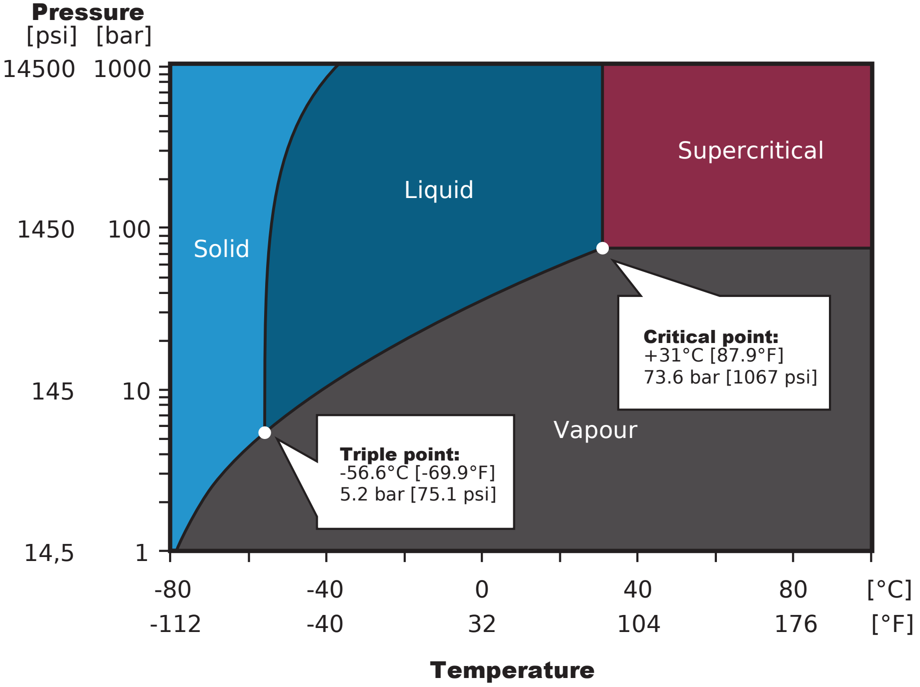
CO_2 is classified as an A1 refrigerant, with low toxicity and low flammability [7].

The phase diagram of CO_2 shows that at atmospheric pressure, CO_2 can only exist as a vapor, or as a solid at extremely low temperatures.

For any type of CO_2 (refrigeration) system, both the triple point and the critical point must be considered. The triple point is at 5.2bar [75.1psi] and at -56.6°C [-69.9°F] and this is where all three phases exist simultaneously in equilibrium. CO_2 can be employed as a refrigerant in a number of different systems including subcritical and transcritical configurations. A classical refrigeration system is subcritical, meaning between triple point and critical point. [9]

CO_2 reaches its critical point at 73.6bar [1,067psi] and at 31.1°C [88°F], a relatively low temperature compared to other refrigerants. Beyond this point, it is in the "supercritical" phase, meaning that there is no clear distinction between the liquid and the gas phase. In refrigeration systems operating in ambient temperatures higher than 31.1°C [88°F], CO_2 is present as a supercritical fluid and is not able to condense. [9]

CO_2 PHASE DIAGRAM



Critical point:
+31°C [87.9°F]
73.6 bar [1067 psi]

Triple point:
-56.6°C [-69.9°F]
5.2 bar [75.1 psi]

Adapted from Danfoss Handbook on Food Retail CO_2 Refrigeration Systems [8]

The p-h diagram of any substance, such as CO_2, shows the phase of a substance at a specific pressure and enthalpy. Generally speaking, the more to the left in the diagram, the more of the refrigerant is in the liquid state. The isothermals show the corresponding temperature. Typically, enthalpy is in units of kJ/kg or BTU/lb.

An example of CO_2 in a subcritical process is shown in the following. In this case, the refrigeration cycle will not take place at temperatures higher than -5.5°C [22°F].

Operating pressures of subcritical systems are between 5.7bar and 73.6bar [82.7psi and 1,067psi], corresponding to a temperature of -55°C to 31.1°C [-67°F to 88°F] (all in vapor state). A single stage subcritical system has some disadvantages, for example limited temperature range and high pressure. [9]

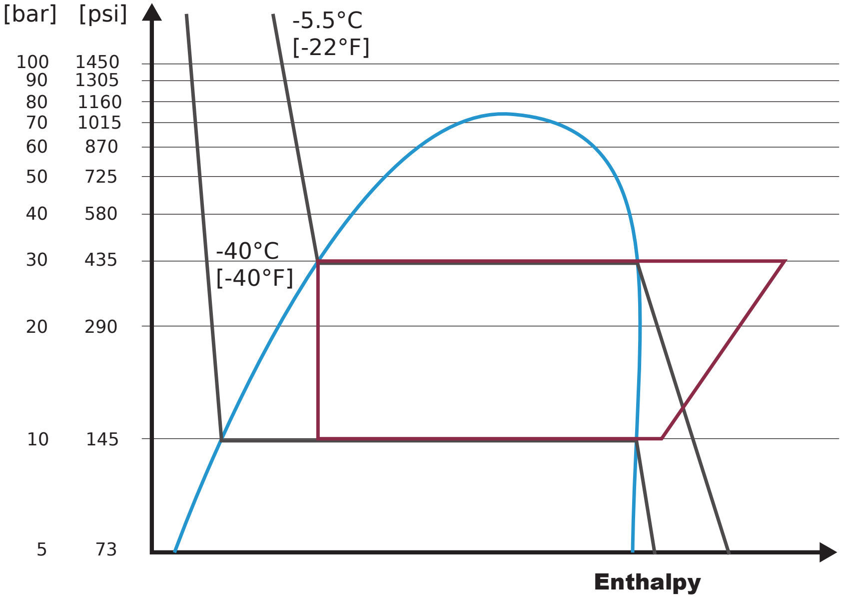
The pressure can be limited to such an extent that commercially available components like valves, compressors and controls can be used. [9]

The p-h diagram of CO_2 in a transcritical system shows that part of the process takes place in the transcritical mode. That is where gas cooling is used.

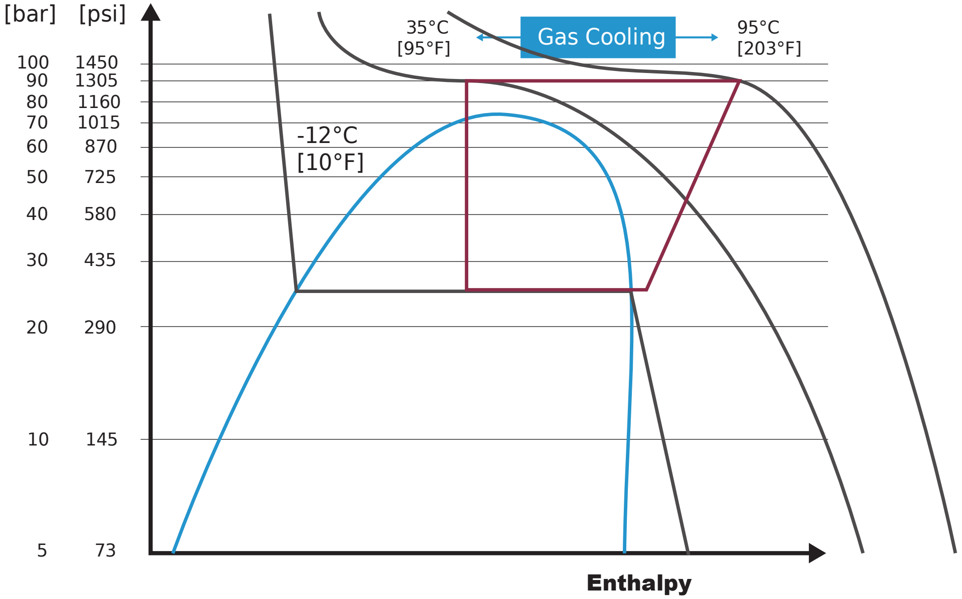
The process of heat rejection differs between a system that operates in subcritical conditions compared to one in a transcritical condition. In transcritical conditions, the gas cannot condense, as there is no correlation between pressure and temperature, in contrast to a subcritical system. The function of the gas cooler is to reject heat just like a condenser. But it does so by decreasing the temperature of the gas, and not like in condensation, by phase changing (without changing temperature). [10]

Any direct CO_2 system can operate in subcritical and transcritical modes, depending on the ambient temperature. There is the possibility to force a system to operate in transcritical mode by design, but this is only desirable for heating applications, as shown in the following: [10]

SUBCRITICAL REFRIGERATION PROCESS

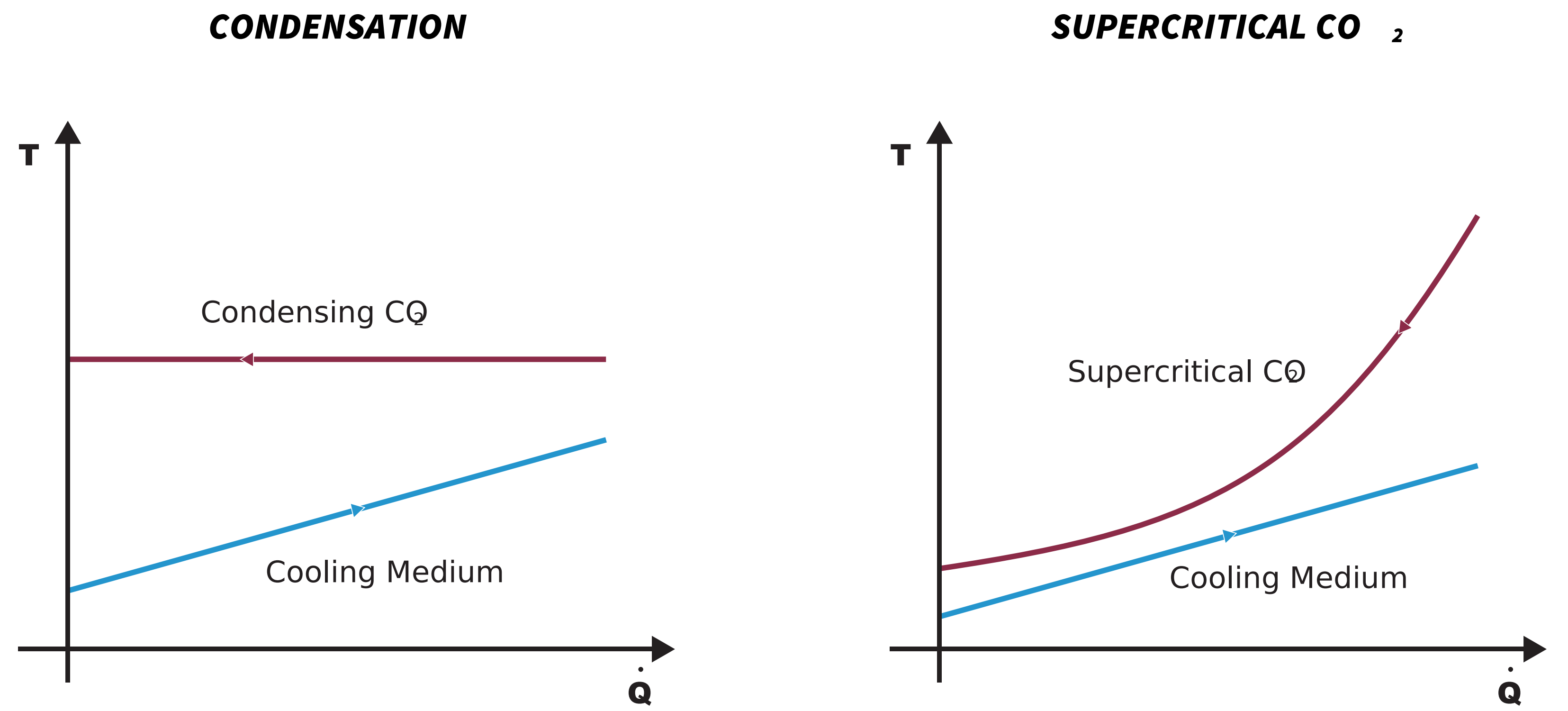


TRANSCRITICAL REFRIGERATION PROCESS



Adapted from Danfoss Handbook on Food Retail CO_2 Refrigeration Systems

Using CO_2 is advantageous because of its heat transfer properties.[11] In a supercritical fluid, pressure and temperature are no longer dependent on each other during the heat rejection process[9]. During a phase change, such as condensation, the temperature stays constant. In transcritical CO_2 systems, however, the temperature continuously decreases when CO_2 passes through the gas cooler[9]. The heat transfer between CO_2 and the cooling medium (water or air) works differently in subcritical and transcritical systems. In a subcritical system with a counter-flow heat exchanger, the temperature difference between CO_2 and the cooling medium is the lowest at the outlet of the cooling medium (meaning inlet of CO_2). In a transcritical system, the pinch point, meaning the closest approach in temperatures between CO_2 and the cooling medium, is at the inlet of the cooling medium or between the inlet and outlet of the gas cooler (in the middle of the gas cooler).[9] Therefore, it is possible to achieve very high temperatures using CO_2 for heating applications, with a cooling medium such as air or more commonly water.[10] This relationship can be seen in the following figure(s), which shows temperature over heat flow during condensation and during gas cooling. The actual temperatures and pressures are dependent on the specific application. For the transcritical CO_2 curve, they might, for example, be between 35°C and 95°C [95°F and 201°F] (for the transcritical process shown in the p-h diagram).



Adapted from Santini, L. et al.[12]

During condensation, the temperature difference between the cooling medium and the condensing steam (here CO_2) is decreasing with increasing heat flow (of the CO_2 and cooling medium). This means that the temperatures approach each other with increasing quantity of heat over time. For transcritical CO_2, this is different – the temperatures approach each other the most between the inlet and the outlet of the gas cooler. With transcritical CO_2, relatively high temperatures can be reached in the refrigeration cycle, which can be used for heating applications, such as heating water or air.

However, the temperature at the gas cooler outlet mainly depends on the ambient temperature. The optimum pressure is not constant but depends on the temperature at the gas outlet. [13]

High ambient temperatures increase the temperature at the gas outlet and increase the pressure ratio to be overcome by the compressor, between suction and discharge pressure. This is the case for any refrigeration system. [10]

The additional problem for CO_2 is the flash gas generated. Flash gas is refrigerant in gas form produced spontaneously when liquid is subjected to boiling. Flash gas is generated in any refrigeration system during a pressure drop into the two-phase region. It does not contribute to refrigeration but still needs to be compressed. A pressure drop occurs at the expansion valve into the evaporator; and, in CO_2 systems, at the high-pressure valve into the receiver. However, systems using refrigerants other than CO_2 do not have a high-pressure valve (see Section "Types of CO_2 systems and function of key components"). [10]

Thus, flash gas is generated in CO_2 systems that are running in subcritical mode; but to a higher extent in systems in transcritical mode because of the higher quality of the CO_2 (high percentage of vapor) due to the higher gas cooler outlet temperatures. That is why it is desirable to go more into the liquid phase ("to the left in the p-h diagram"). [10]

Yet, there are many solutions available today in order to efficiently use transcritical CO_2 in regions with high ambient temperatures (see Section "Key components in a transcritical CO_2 refrigeration system").

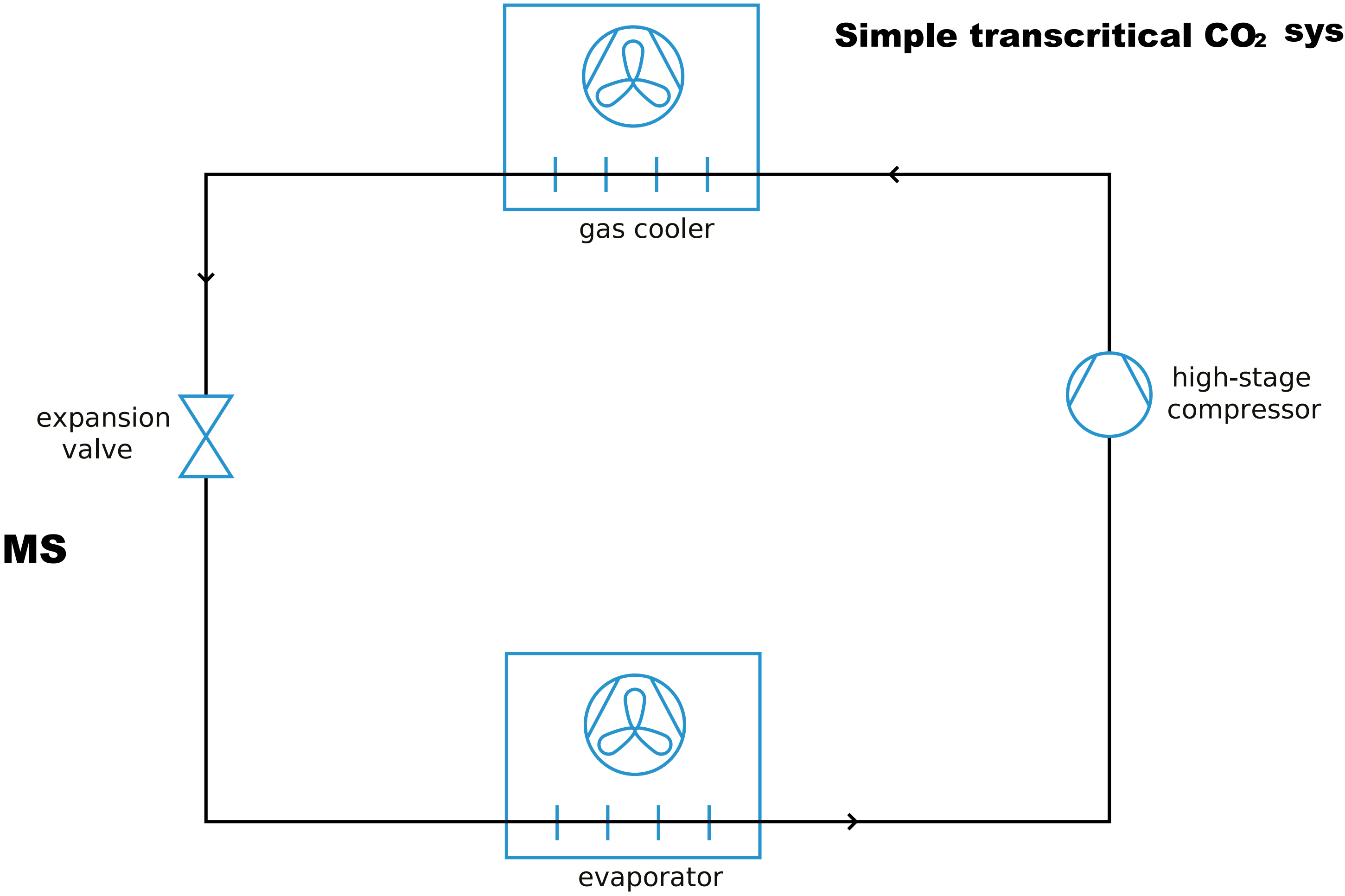
TYPES OF CO$_2$ SYSTEMS AND FUNCTION OF KEY COMPONENTS

In the following, different types of CO$_2$ systems are briefly described. They are the simple transcritical CO$_2$ system, single-stage system, simple booster system, cascade system and secondary/ indirect system. The following CO$_2$ systems are able to operate in trans-critical mode: a simple transcritical CO$_2$ system, a single-stage system, and a simple booster system. The cascade system uses CO$_2$ in transcritical mode only in rare instances and the secondary/indirect system only uses CO$_2$ in subcritical mode.

TYPES OF CO$_2$ SYSTEMS

Simple transcritical CO$_2$ system

A simple transcritical CO$_2$ system is like a subcritical refrigeration system, only with a gas cooler in the place of a condenser. It is not being used, but for explanation, a schematic sketch is shown in the next figure.



Simple transcritical CO$_2$ system

Adapted from Guide by Emerson on Commercial CO$_2$ Refrigeration Systems[14]

Single stage system

A simple single stage system is shown in the next figure (typically a CO_2 system doing MT refrigeration). [10]

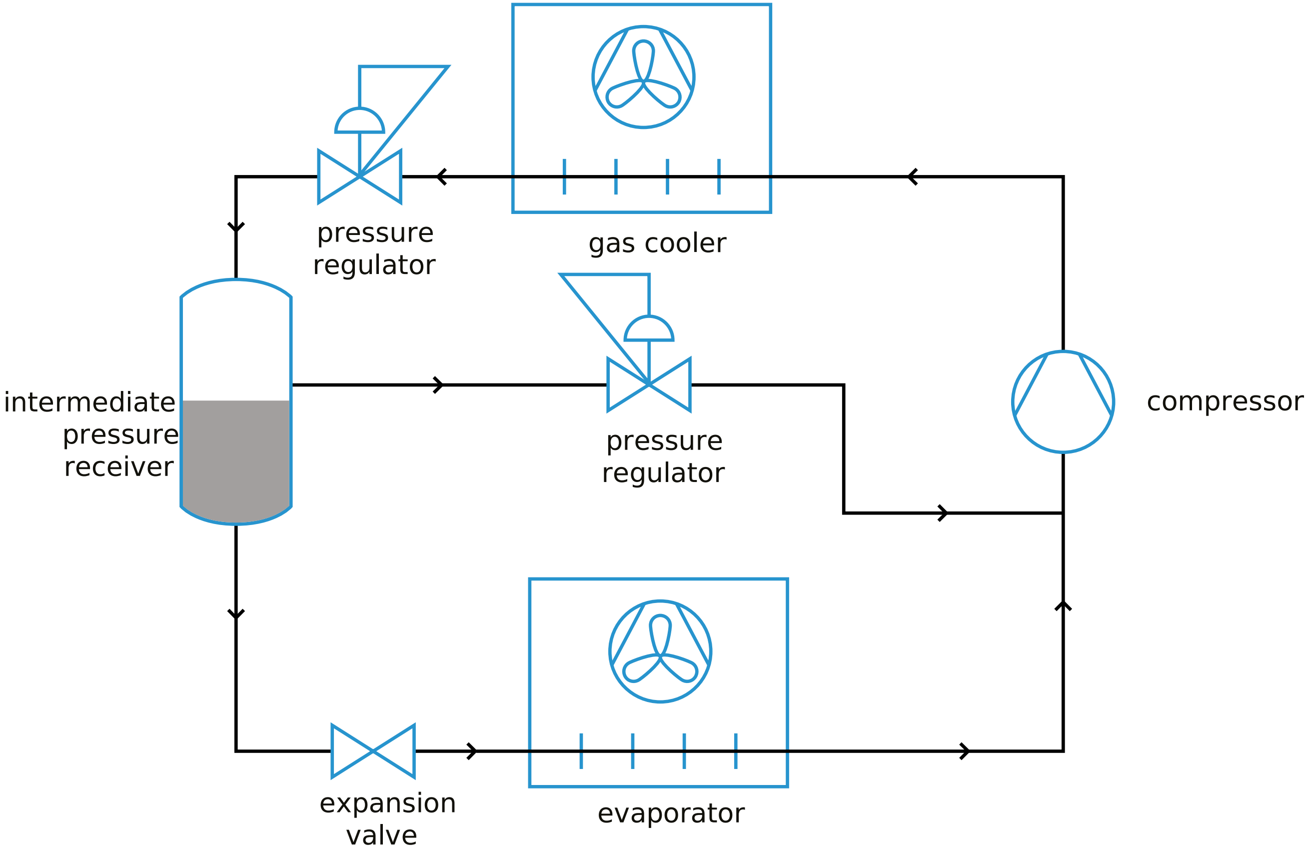
In a single stage transcritical system, the gas cooler pressure is controlled to provide either optimum capacity or optimum efficiency while maintaining the pressure below the maximum allowed at all times. The simple diagram shows how this pressure is controlled in a typical system with single stage compression. [14]

In a single stage transcritical system, there are two additional valves compared to a simple system. They control the gas cooler and the intermediate pressure receiver. The gas cooler pressure valve (also called the high-pressure regulating valve) controls the pressure in the gas cooler. It is a pressure-reducing valve, controlled by measuring two parameters — CO_2 pressure in the gas cooler and its exit temperature (exit/outlet of the gas cooler). [14]

The receiver pressure valve (also called the medium pressure regulating valve or the **flash gas valve**) controls the pressure of the refrigerant in the receiver and associated liquid distribution pipe work. It is controlled by one parameter, the pressure in the receiver. The receiver is also called a **flash tank**.[14] Flash gas is generated when high pressure CO_2 undergoes a pressure drop into the receiver. [10]

The receiver separates the liquid phase from the vapor phase – the liquid is sent back to the evaporator and the vapor is sent back to the compressor.

Simple single stage system

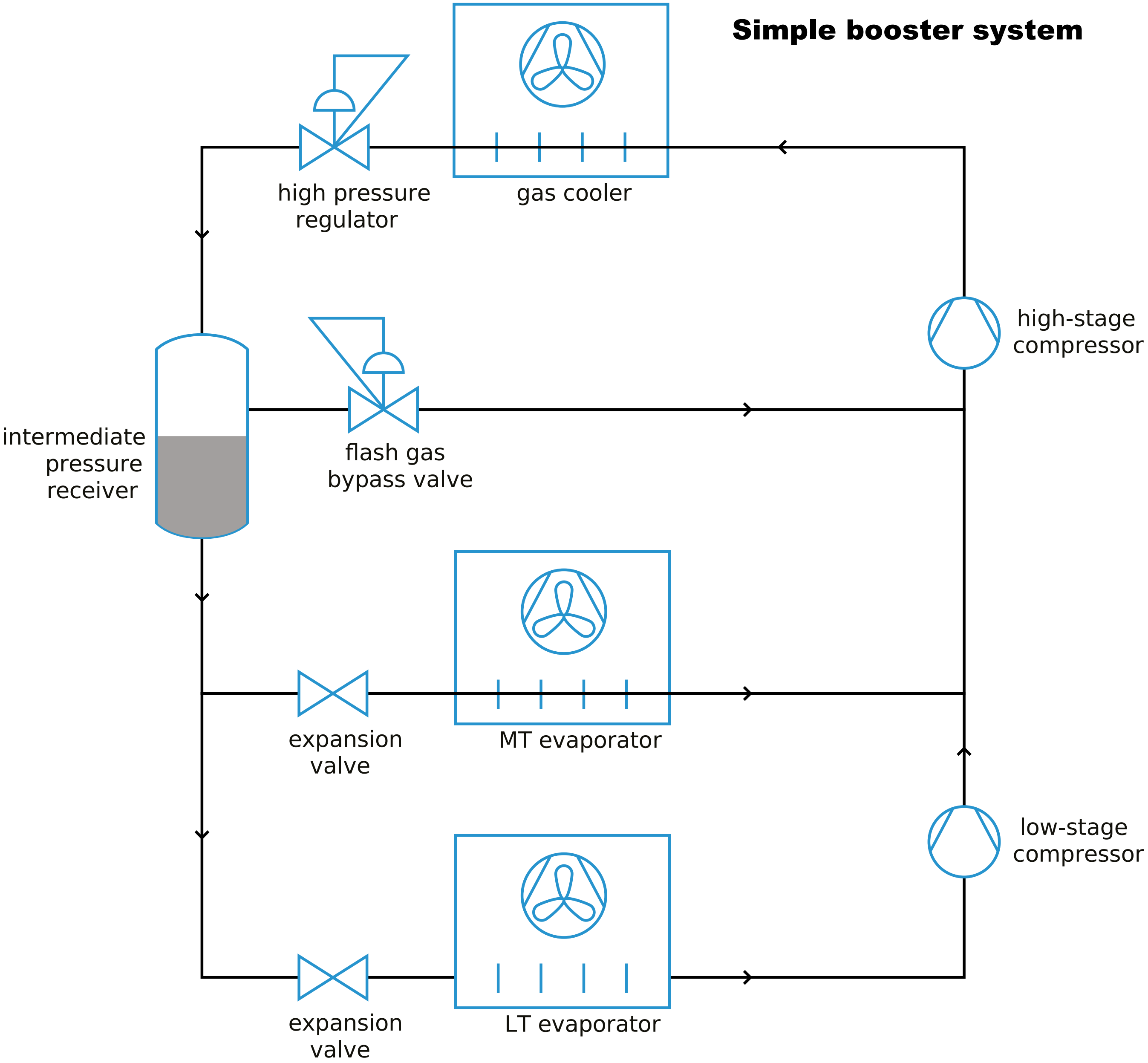


Adapted from Guide by Emerson on Commercial CO_2 Refrigeration Systems[14]

Simple booster system

Compared to single-stage retail systems, booster systems are quite commonly used, namely for MT and LT together. A booster system uses two-stage evaporation, for low temperature and medium temperature. Similarly, it uses two-stage compression, with low-stage and medium-stage compressors. [14] [10]

The two pressure regulating valves here are the same as in the simple single stage system; first the high pressure regulating valve ("high pressure regulator") regulating the gas cooler pressure, and then the flash gas bypass valve controlling the receiver pressure (receiver pressure valve).



Adapted from Guide by Emerson on Commercial CO_2 Refrigeration Systems[14]

Cascade systems

A cascade system uses a combination of two centralized refrigeration systems. The high temperature refrigeration system (ammonia, HFC, HC) cools the lower-temperature refrigeration system (usually subcritical CO_2).[15] [16] This means that the heat rejected by the condensing CO_2 is absorbed by the evaporating high-stage refrigerant [14]. The evaporator for the high-stage system is also the condenser for the low-stage system[16]. At the low-stage, CO_2 will always be in a subcritical state because the temperature and the pressure of the low-stage is controlled by the high-stage refrigerant [15].

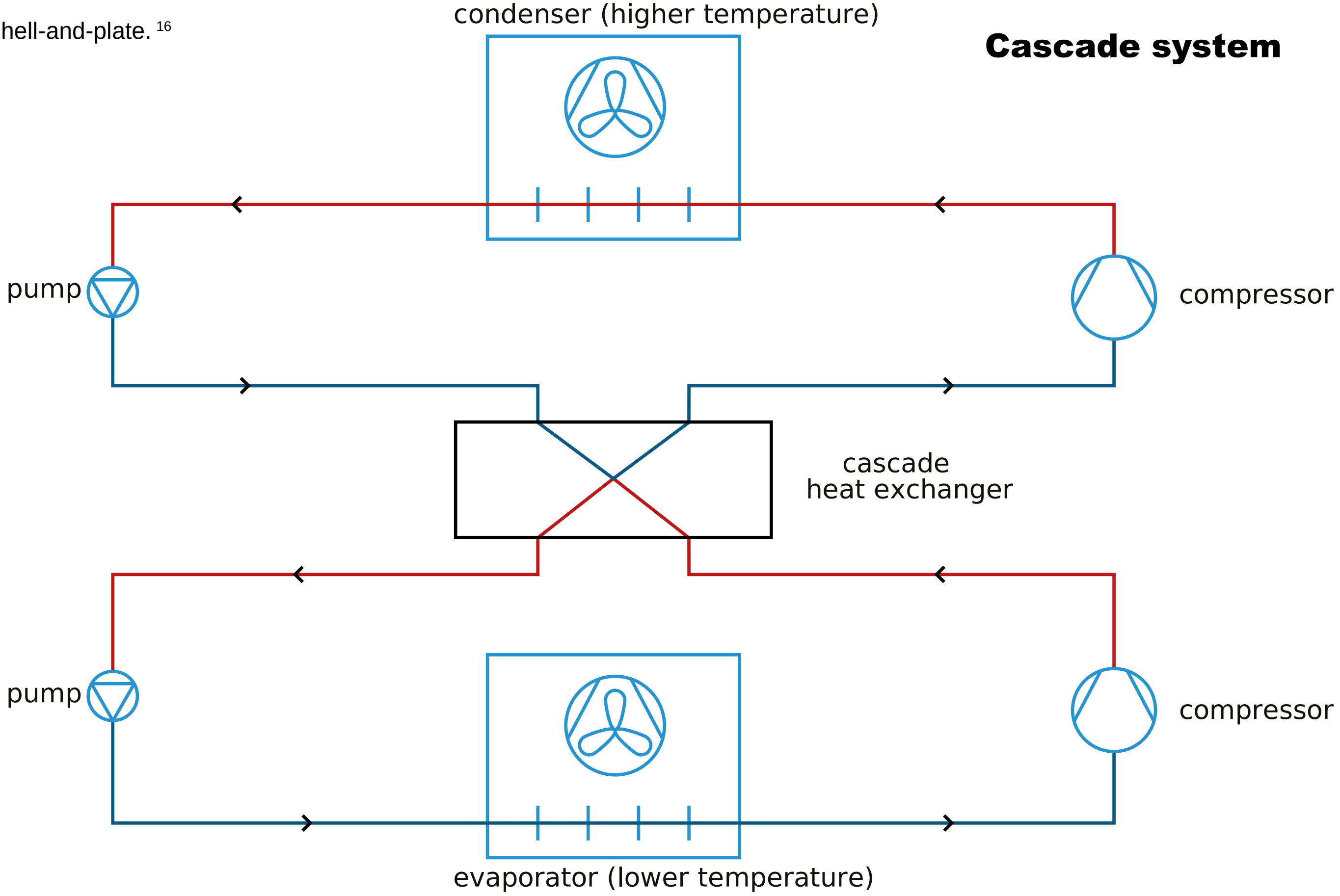
In some cases CO_2 is used in both stages; in low-stage in subcritical mode, in the high-stage it might be transcritical in high ambient temperatures. [14]

An advantage of cascade systems is that the pressure is lower compared to a refrigeration system that uses only CO_2. In refrigeration systems employing only CO_2, the low critical temperature of CO_2 of 31.1°C [88°F] causes the operating pressures to reach relatively high levels, particularly at high ambient temperatures. In order to limit the pressures, the high-stage refrigeration system provides the condensing for the low-stage CO_2 system and thereby limits the pressure, which would exist if only CO_2 was used in a typical refrigeration cycle. [16]

The type of heat exchanger used between the ammonia system and CO_2 system is known as cascade heat exchanger and can be constructed in a number of different ways:

- Shell-and-tube;
- Welded-plate/brazed plate; or
- Shell-and-plate. [16]

Cascade system



sheccoBase sketch

Secondary/indirect systems

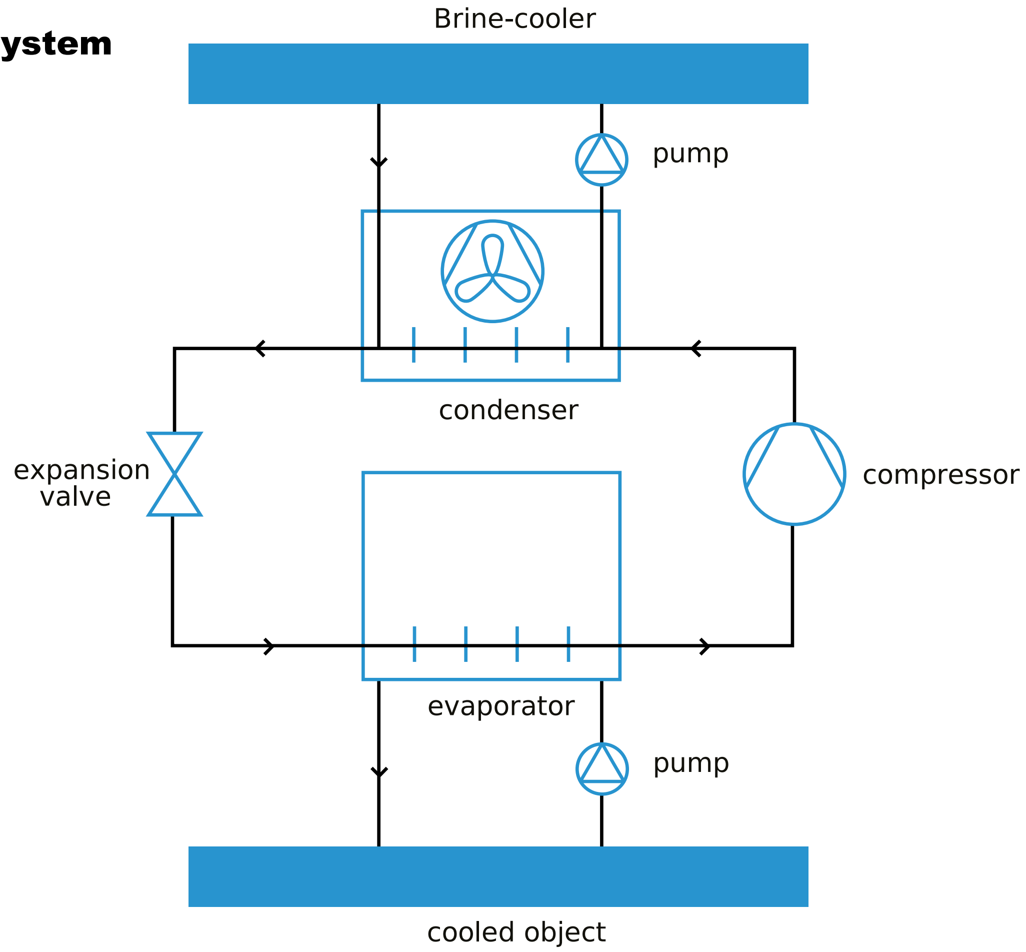
A secondary/indirect refrigerant system uses a centralized system to cool a secondary fluid (e.g. CO_2 in subcritical mode, secondary brine or glycol). The secondary fluid is pumped to each consumer. The consumers can be air coolers, processing equipment or glycol/chilled water heat exchangers. The primary refrigerant is confined to the machine room, so the primary refrigerant inventory is minimized, as are the risks to system personnel. [17]

Principle of an indirect refrigeration system [18]

The primary refrigeration cycle is shown in the center of the image. It contains all the required components – evaporator, compressor, condenser and expansion valve. The secondary refrigerant cycle on the lower side contains a heat exchanger between the refrigerated space and the secondary fluid and a pump to transport the secondary fluid from the refrigerated space to the evaporator.

The disadvantage of indirect systems is the additional heat exchange between the primary refrigerant and the secondary refrigerant. It leads to higher temperature differences between evaporation and condensation and thus higher pressure differences to overcome by the compressor; i.e. lower primary evaporating temperatures and higher primary condensing temperatures, or lower secondary condensing temperatures and higher secondary evaporating temperatures, due to losses in the heat exchange process. [10] Furthermore, the pumping power necessary for circulating the secondary fluid reduces the energy efficiency. Using volatile secondary refrigerants such as CO_2 can reduce the pumping power required. [16]

Indirect system



sheccoBase sketch

KEY COMPONENTS IN A TRANSCRITICAL CO_2 REFRIGERATION SYSTEM

Valves

To minimize the risk of pressure buildup in the system, measures must be taken in system design to ensure that pressure cannot build up in any portion of the system. All components, valves, piping, fittings, and joining methods must be verified to ensure pressure ratings above the maximum anticipated system pressures.

Pressure relief devices must be located appropriately to allow the system to vent safely in the event of a system shutdown or other event that causes pressure above system ratings. All points within the system must be allowed to vent back to the pressure relief valves without restriction. Check valves are typically utilized to allow portions of the system to vent back to receivers, where pressure relief valves are located. Any portion of the system that cannot vent back to the receiver must have its own pressure relief valve. [7]

Stainless steel is currently the most used and can be adapted for transcritical operation. Only the material thickness has to be adapted in order to resist high pressures. Alternatively, copper-iron alloy piping can be used with an appropriate pressure rating. [10]

As the same system can operate in either subcritical or transcritical mode, depending on the conditions, higher quality piping needs to be used for all direct CO_2 systems. Only in cascade systems, lower rated piping can be used because the pressure is controlled there. [10]

Apart from the high pressure, a special characteristic of CO_2 systems is that the liquid line is cold (compared to conventional refrigeration systems where operating temperatures are much higher.) Sometimes the temperature on the liquid line goes down to -10°C [14°F] but often it is at around 0°C [32°F]. [19]

Besides, the liquid lines in conventional systems are at condensing pressure that is higher than ambient temperatures. This means that conventional systems will have a heat loss from the liquid line; while in CO_2 systems, there will be a heat input to the liquid line. [19] Hence, the liquid line of a CO_2 system has insulation whereas conventional systems do not need this. [10] The heat loss in conventional systems will show as additional sub cooling, whereas it will show as **flash gas** in a CO_2 system. The flash gas will reduce the capacity of the expansion valve. [19]

However, the high pressure of the CO_2 system results in high-density gas and therefore a reduced capacity drop compared to other refrigerants. [19]

Compressors

Compressors need to be specifically developed for the use with CO_2, to withstand high pressures and to be adapted to operating conditions that are sometimes very demanding. There are also adapted lubricants.

Controls

Controls for a transcritical CO_2 system can be divided into four groups: gas cooler controls; receiver pressure controls; compressor capacity controls; and evaporator controls. In applications where heat reclaim is used, a number of control functions around the gas cooler have to be added. [21]

An important aspect in controlling the gas cooler is that in transcritical mode, pressure and temperature are no longer dependent on each other (see section on "Key characteristics"). Thus, they need to be controlled individually. [21]

Regarding compressor control, the standard settings are not always robust enough to ensure a safe and reliable control. This is because CO_2 is a more dynamic refrigerant than HFCs or others. [21]

Lubricants

Polyolester (POE) lubricants have good miscibility with CO_2 and are predominantly used as compressor lubricants in retail CO_2 systems. Because of the high solubility (of CO_2), higher viscosity lubricants are used when compared to those used with HFCs. This reduces the effect of oil dilution by refrigerant and therefore maintains the lubricant properties. [14]

POE oils are very hygroscopic (i.e., they readily absorb moisture), so care must be taken to ensure moisture does not enter the system. [14]

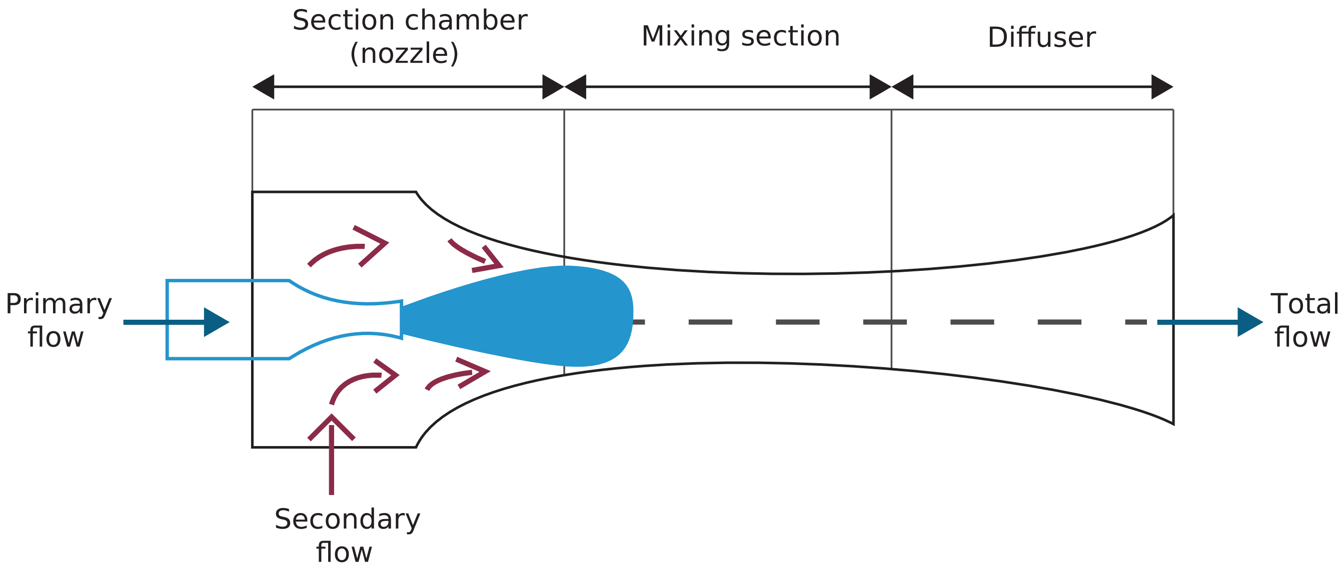
Technologies to improve efficiency of transcritical CO_2 systems: Ejectors, parallel compression, sub-cooling and adiabatic cooling

In addition to the different types of transcritical CO_2 systems, additional technologies like ejectors are being used in order to increase the efficiency of the systems. This is where most of the research and development is currently being done.

Today, there are many different types of ejectors, which are often patented by specific manufacturers. The use of ejectors has considerably increased the energy efficiency of transcritical CO_2 refrigeration systems and made it more efficient to use them in regions with high ambient temperatures. The basic working principle will be explained in the following.

A typical ejector consists of a motive nozzle, a suction chamber, a mixing section, and a diffuser. The working principle of the ejector is based on converting internal energy and pressure related flow work contained in the motive fluid stream into kinetic energy.[22]

SCHEMATIC OF A TYPICAL TWO-PHASE EJECTOR DESIGN



Adapted from Elbel, S. & Hrnjak, P. (2008)[22]

In basic terms, an ejector is a way to re-use energy in the refrigeration system- by not expanding the refrigerant but keeping the pressure relatively high. The fluid coming out of the gas cooler is not expanded, so that the pressure can be kept high and less work is required for compression. The gas in the suction line of the main compressor (low pressure) and the fluid coming out of the gas cooler (high pressure) are mixed in order to get a mixed refrigerant at medium pressure. [23]

More precisely, the primary flow is coming from the gas cooler, with the discharge pressure of the gas cooler, which is dependent on the ambient temperature and can be relatively high. The secondary flow is coming from the suction line of the MT side, with a relatively low pressure (because it has not been compressed). They are mixed to get the total flow. With this method, it is possible to increase the pressure of the total flow by a few bar, compared to the primary flow. Thus, the ejector is doing compressor work and creating a pressure lift. [10]

In a concrete example, the evaporation temperature is -5°C [23°F], corresponding to 30bar [435psi]. The discharge pressure is 70bar [1,015psi] and the pressure of the total flow will be 36bar [522psi] or receiver pressure, meaning the ejector causes a pressure lift of 6bar [87psi]. [10]

Then, the flow goes into the receiver where the liquid is separated from the vapor phase; and the vapor phase will go into the parallel compressor. [10]

Other ways to increase the energy efficiency of transcritical CO_2 systems are parallel compression, evaporative condensation, (mechanical) sub-cooling and adiabatic cooling. Ejectors and parallel compression make CO_2 systems more efficient while operating in transcritical mode. Evaporative condensation, (mechanical) sub-cooling and adiabatic gas cooling decrease the outlet temperature of the gas cooler and therefore force the system to operate longer in subcritical mode, thereby making it more efficient. [10]

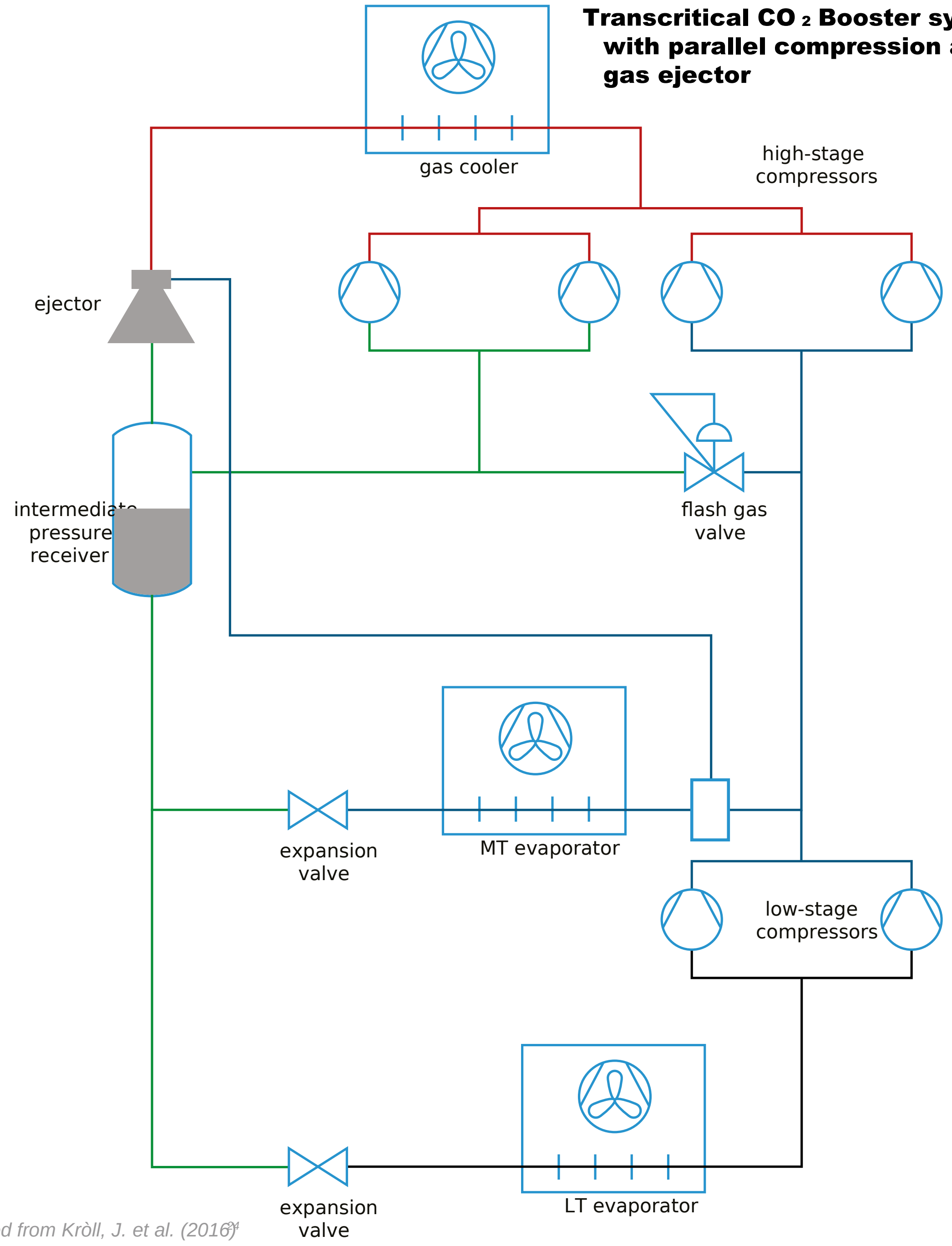
A sketch of a system with ejector and parallel compression is shown in the next figure. Each colored line indicates a different pressure level (from low to high: black, blue, green, and red).

Parallel compression is a solution that compresses the excess gas at the highest possible pressure level. It leads to a significant increase of COP in warm climates. [25]

To explain it in more detail: Parallel compressors compress the flash gas coming out of the receiver from receiver pressure to discharge pressure, which is higher than the suction pressure. A flash gas valve would have sent the flash gas to the MT suction by dropping the pressure. The parallel compressors make the flash gas valve obsolete for operation in high ambient temperatures. The saving occurs because the flash gas is compressed from a higher pressure than usual when a flash gas valve is used.[10]

Evaporative condensation uses water to cool the gas in transcritical CO_2 operation. An adiabatic gas cooler works on a similar principle but allows for the use of less water (only when it is required). [10]

Mechanical sub-cooling uses an additional small refrigeration cycle coupled with the main refrigeration cycle in order to provide cooling at high temperatures. [25]



Transcritical CO_2 Booster system with parallel compression and gas ejector

Adapted from Kròll, J. et al. (2016)[24]

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