WORLD GUIDE TO TRANSCRITICAL CO_2 REFRIGERATION

PART I

World Guide to Transcritical CO_2 Refrigeration

THIS PROJECT WAS SUPPORTED BY

WELCOME MESSAGE BY LEAD AUTHOR

As the use of transcritical CO_2 refrigeration systems increase at an exponential rate around the world, it has become apparent that there is a great need for reliable information from a neutral source. As such, sheccoBase, the "brain" behind shecco, has undertaken an extensive market study to analyze the current state of the global industry and various trends.

When we first started collecting data in 2008, we only counted 140 transcritical CO_2 systems – all of which were in Europe. Today, this number is well beyond 30,000 globally as the accelerated phase down of harmful synthetics drives the search for a more climate-friendly alternative. Most notably we have found that this technology is no longer only used in commercial refrigeration installations. More and more we are seeing success stories in small convenience stores and even larger industrial installations.

The number of transcritical CO_2 installations keeps growing as industry finds innovative ways to realize the potential of CO_2, even in warmer ambient climates previously thought incompatible with transcritical systems. Ice rink applications in particular are also becoming ever-more popular globally.

Thanks to extensive market research and data collection by the inhouse sheccoBase Market Development team, we are proud to present this "World Guide to Transcritical CO_2 Refrigeration." Our hope is that it will serve as a resource to help drive the accelerated uptake of this highly sustainable and energy efficient HVAC&R technology. That is why it will be freely available, at no cost, as our contribution to help drive "clean cooling."

The Guide will be published in three separate parts after which the entire combined resource will be available for download online. Part 1 will look at CO_2 as refrigerant, covering the history, policy measures and basic technical aspects related to this gas. It will also include a chapter on applications, showing case studies from around the world where transcritical CO_2 has been successfully deployed.

In Part 2, we will specifically look at convenience stores as well as commercial refrigeration installations, sharing market research and data regarding the number of installations worldwide and key market trends. Part 3 will cover industrial applications, as well as barriers and opportunities for the uptake of transcritical CO_2 systems, looking at the future market potential and trends.

Allow me a moment to thank our sponsors who have made this guide possible, many of whom have been key drivers of the uptake of natural refrigerants globally. Some of them will be sharing their expertise and experience by means of partner case studies and interviews, which will feature in Part 2 and 3 of the Guide.

Disclaimer: With technology moving so quickly, the numbers in this Guide might soon be out of date. Make sure to follow us online and on social media to get the latest updates on CO_2 and all other natural refrigerants too.

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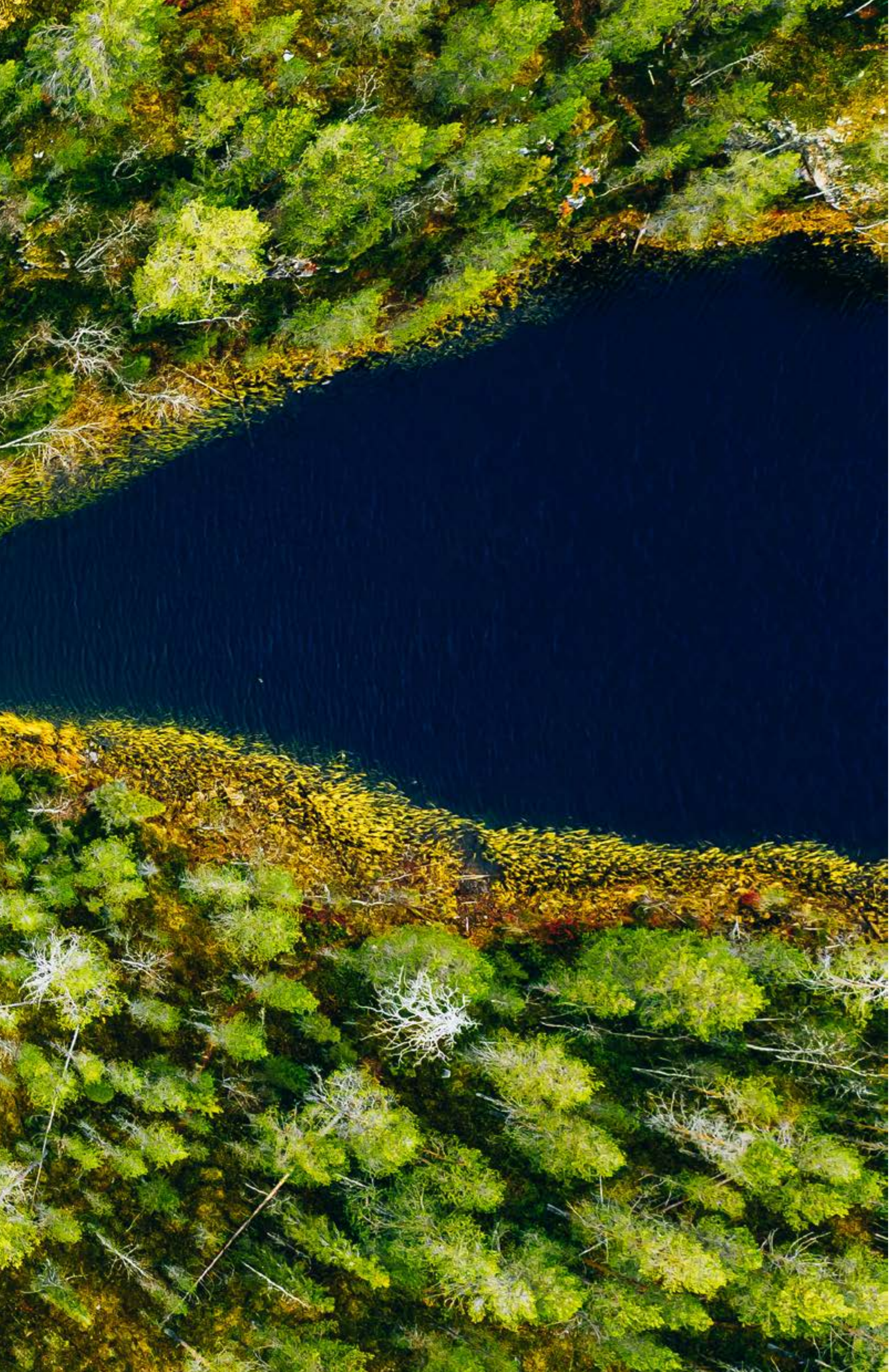
ABOUT THIS GUIDE



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 does neither contribute 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 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.

READ ON PAGE 10

CHAPTER 2:
Applications of transcritical CO_2

This chapter shows examples of applications of transcritical CO2 around the world, from its beginnings in commercial supermarkets to new convenience store and industrial applications as well.

READ ON PAGE 30

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 refrigerant.

COMING SOON

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?

COMING SOON

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.

COMING SOON

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.

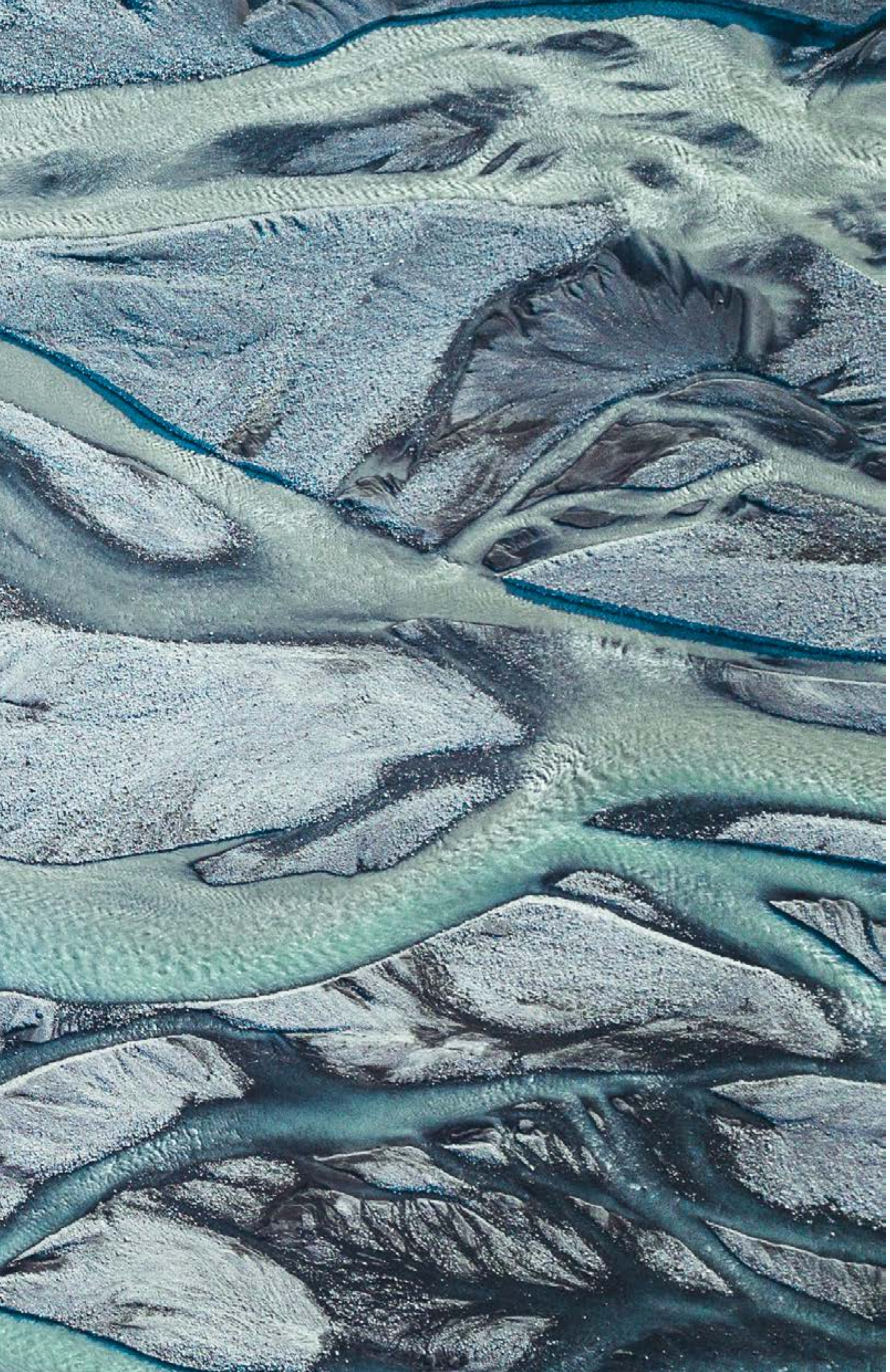
COMING SOON

CHAPTER 7:
The future of CO_2

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.

COMING SOON

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.

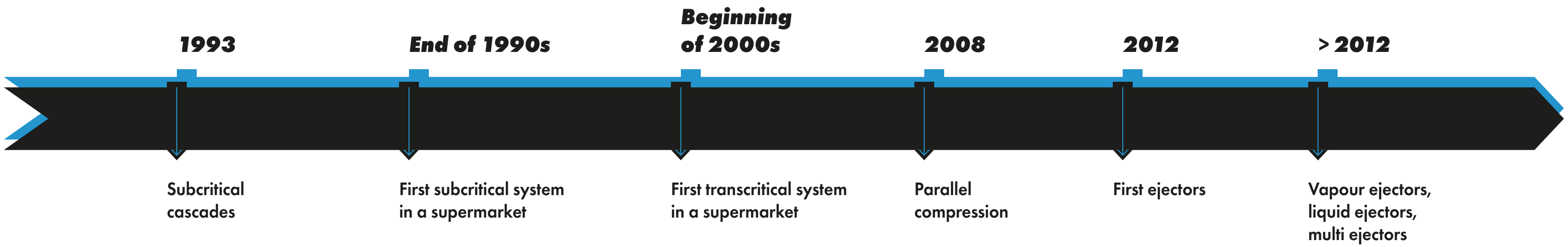
SHORT HISTORY OF CO_2 AS REFRIGERANT

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



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.

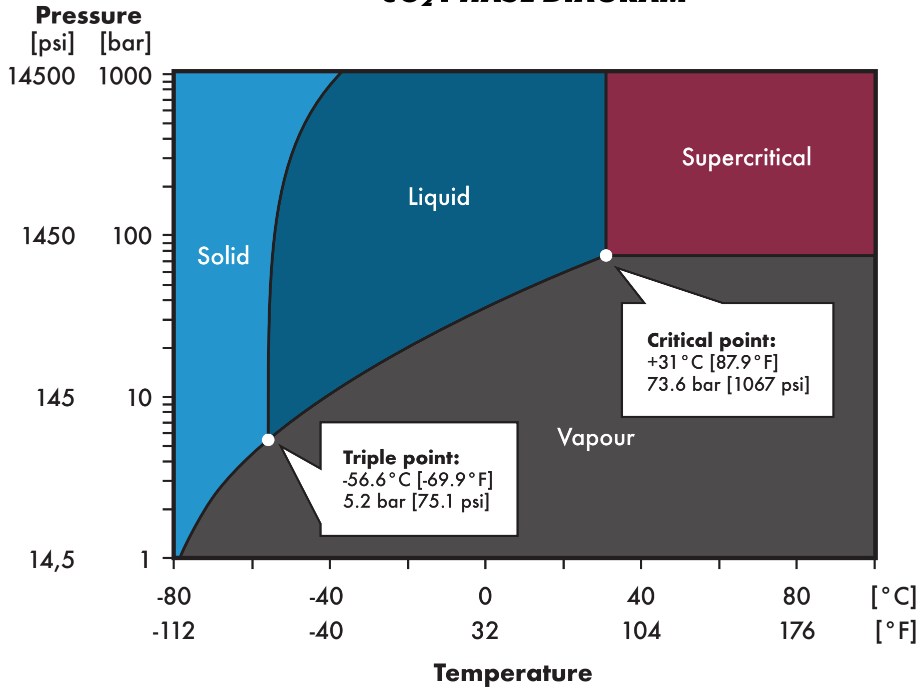
CO_2 is classified as an A1 refrigerant, with low toxicity and low flammability[7].

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 trans-critical 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



Adapted from Danfoss Handbook on Food Retail CO_2 Refrigeration Systems[9]

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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].

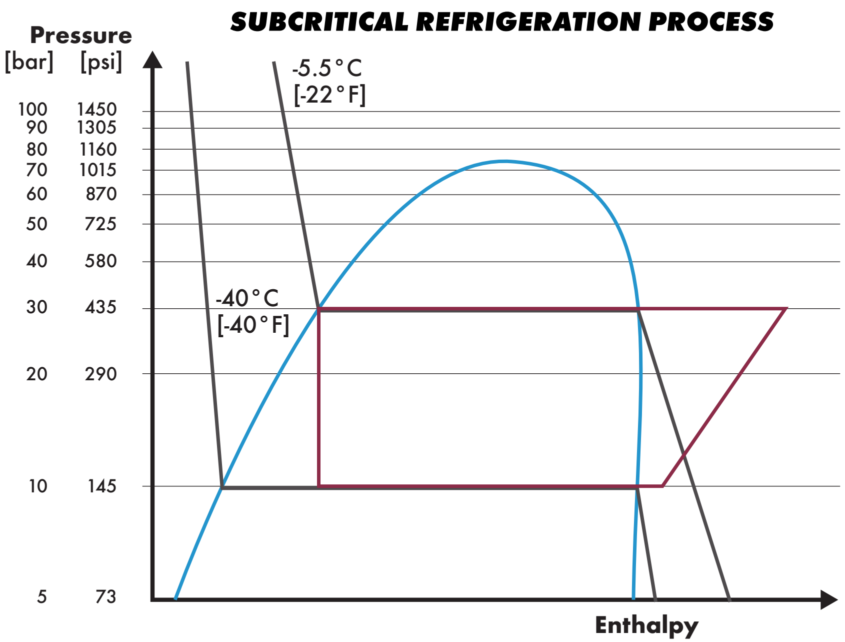
Operating pressures of subcritical systems are between 5.7bar and 73.6bar [82.7psi and 1,067psi], corresponding to a temperature of -55°C to 31.1°C [-67°F to 88°F] (all in vapor state). A single stage subcritical system has some disadvantages, for example limited temperature range and high pressure.[9]

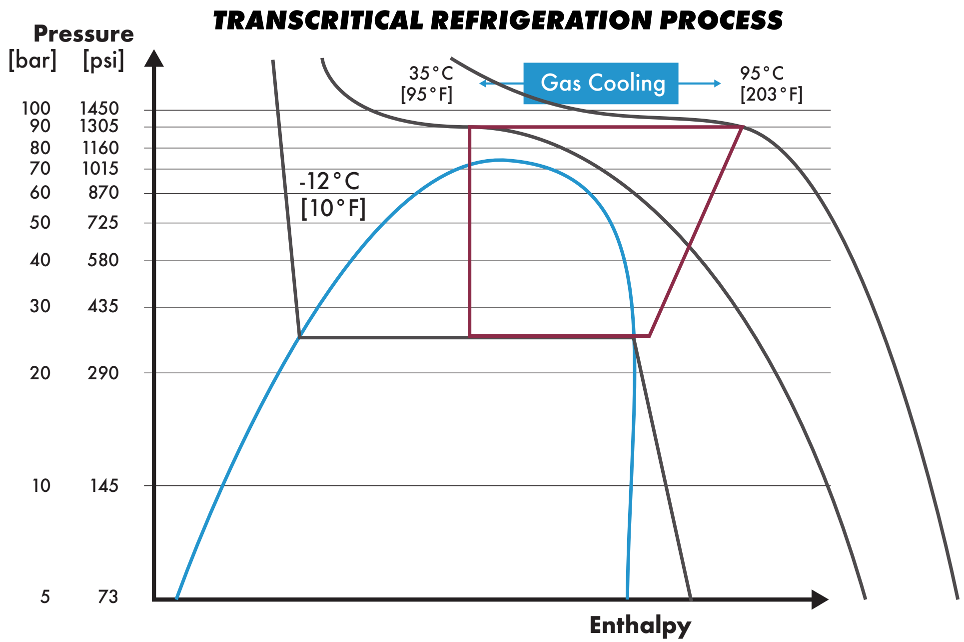
The pressure can be limited to such an extent that commercially available components like valves, compressors and controls can be used.[9]

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]





Adapted from Danfoss Handbook on Food Retail CO_2 Refrigeration Systems

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The Life-C4R project is a 3-year (2018-2021) international marketing project that, thanks to Epta FTE Full Transcritical Efficiency system, will substantially contribute to **replacing HCFC and HFC greenhouse refrigerants with CO_2 in commercial refrigeration**, in a very simple, efficient and reliable way in any country, with any external temperature, allowing **10% energy and 20% installation and maintenance savings.**

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The heart of the project is the **FTE system technology** in its 2.0 version, that allows to fully replace old refrigerants with CO_2, a **natural, non-toxic and non-flammable fluid**, in a simple, efficient and reliable manner, in any climate situation anywhere in the world.

In the 2.0 version, the **FTE Full Transcritical Efficiency** is fully integrated with the power pack thus requiring no extra space in the technical room and further reduced installation and startup times.

ETE Extreme Temperature Efficiency is the new Epta Technology that complements FTE to further enhance the efficiency of CO_2 int he warmest climate conditions, designed to operate also with one temperature stage systems and industrial refrigeration.

The Life-C4R project has received funding from the European Union under grant agreement n° LIFE 17 CCMT/IT/000120

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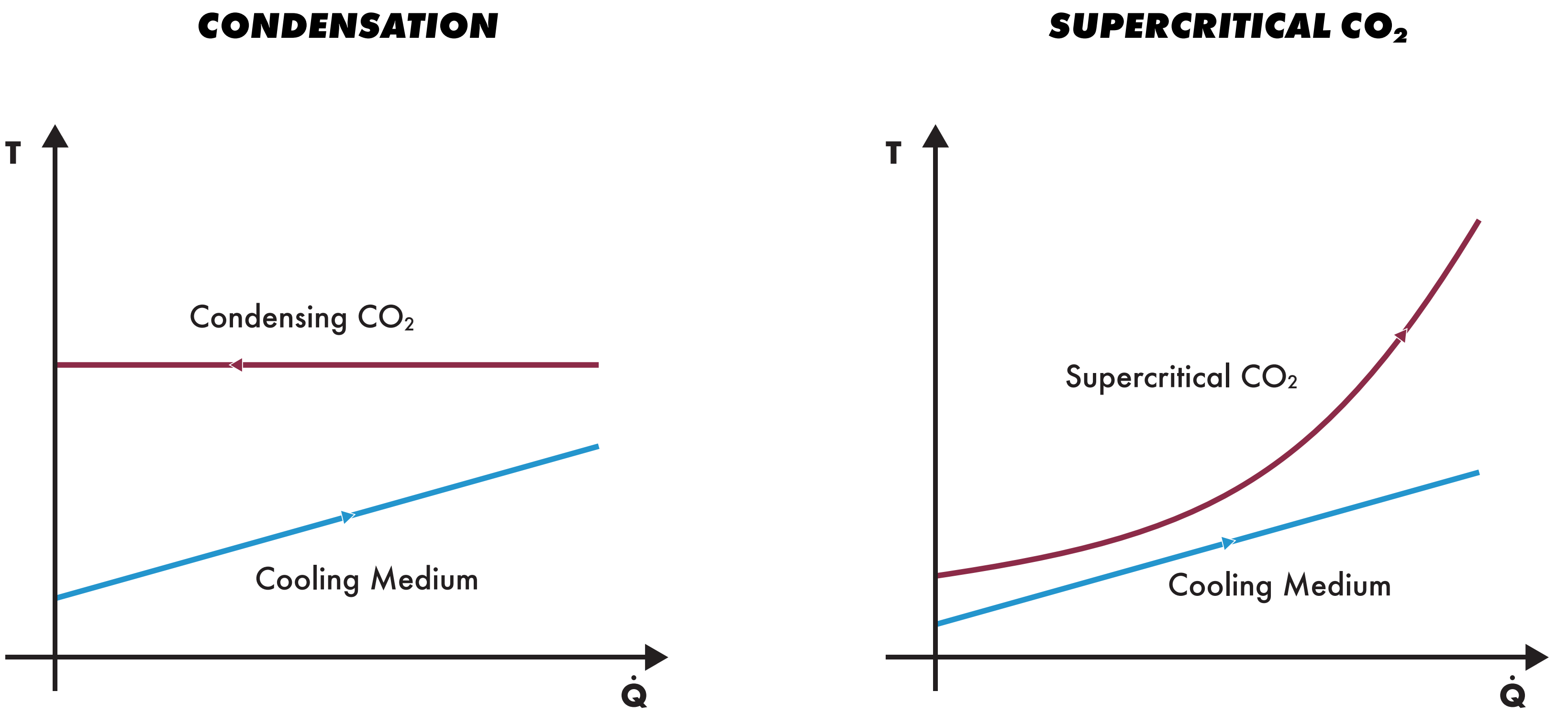
Using CO_2 is advantageous because of its heat transfer properties.[11] In a supercritical fluid, pressure and temperature are no longer dependent on each other during the heat rejection process[9]. During a phase change, such as condensation, the temperature stays constant. In transcritical CO_2 systems, 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 subcritical 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

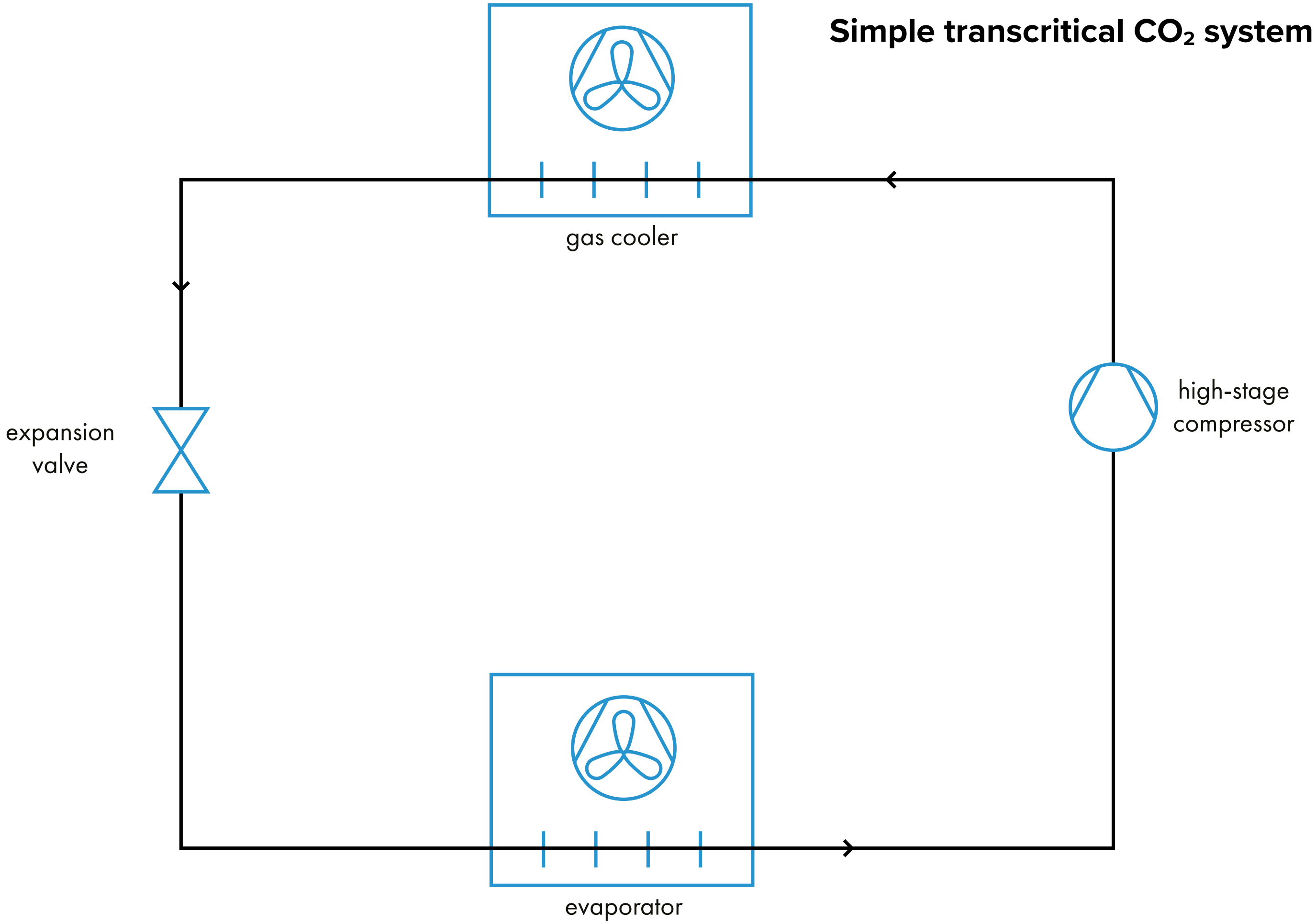
In the following, different types of CO_2 systems are briefly described. They are the simple transcritical CO_2 system, single-stage system, simple booster system, cascade system and secondary/indirect system. The following CO_2 systems are able to operate in trans-critical mode: a simple transcritical 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]

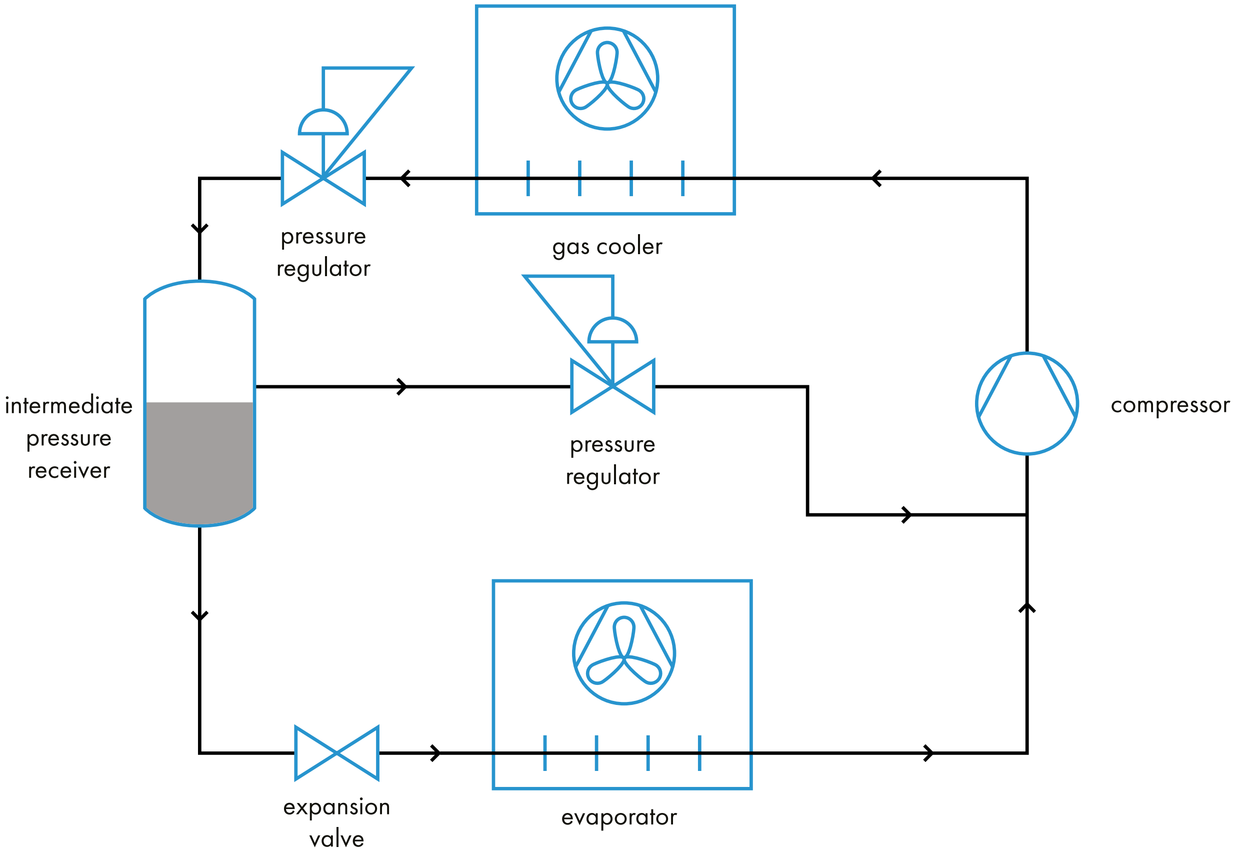
In a single stage transcritical system, the gas cooler pressure is controlled to provide either optimum capacity or optimum efficiency while maintaining the pressure below the maximum allowed at all times. The simple diagram shows how this pressure is controlled in a typical system with single stage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



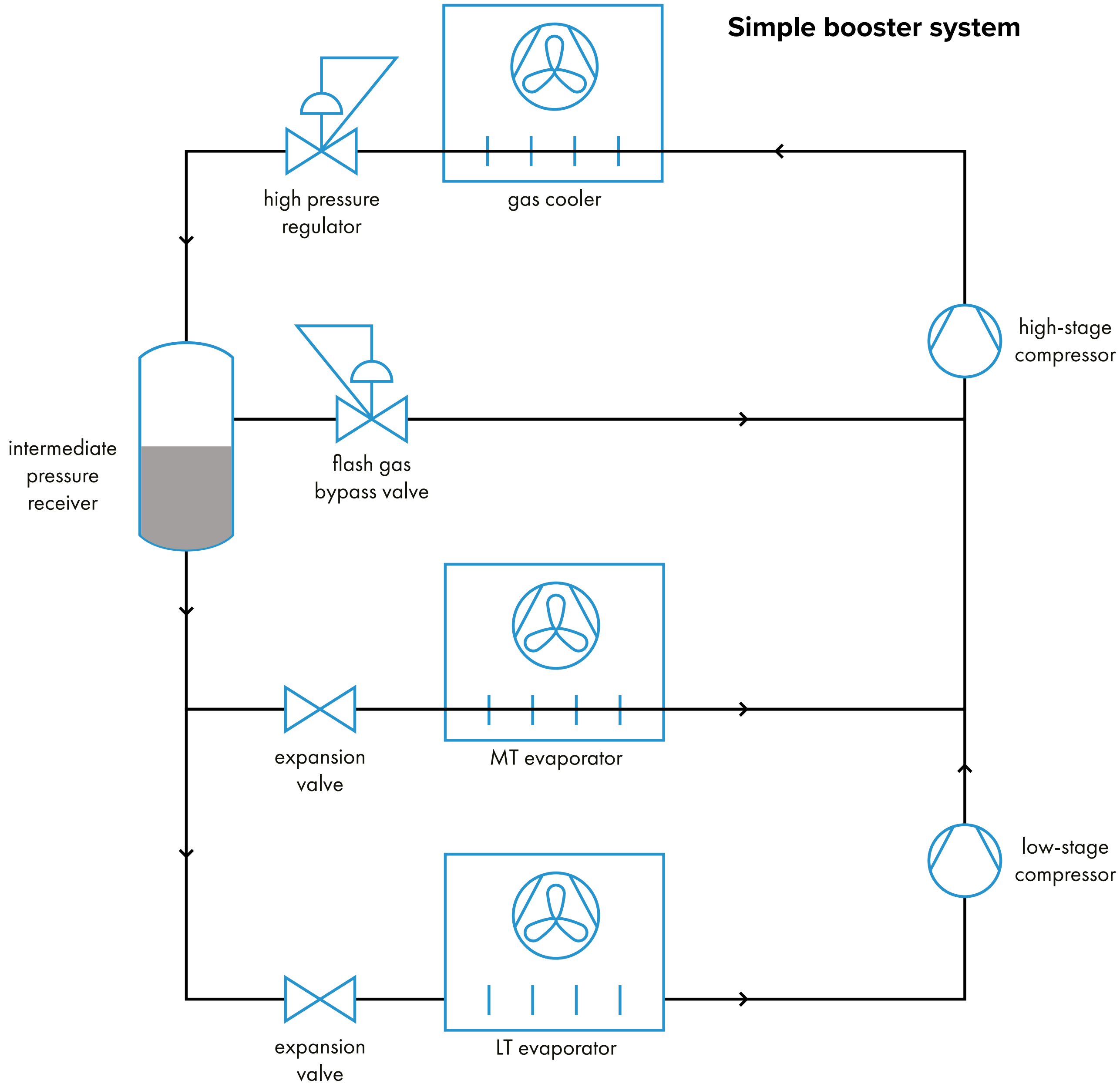
Adapted from Guide by Emerson on Commercial CO_2 Refrigeration Systems[14]

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).

Simple booster system



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

Cascade systems

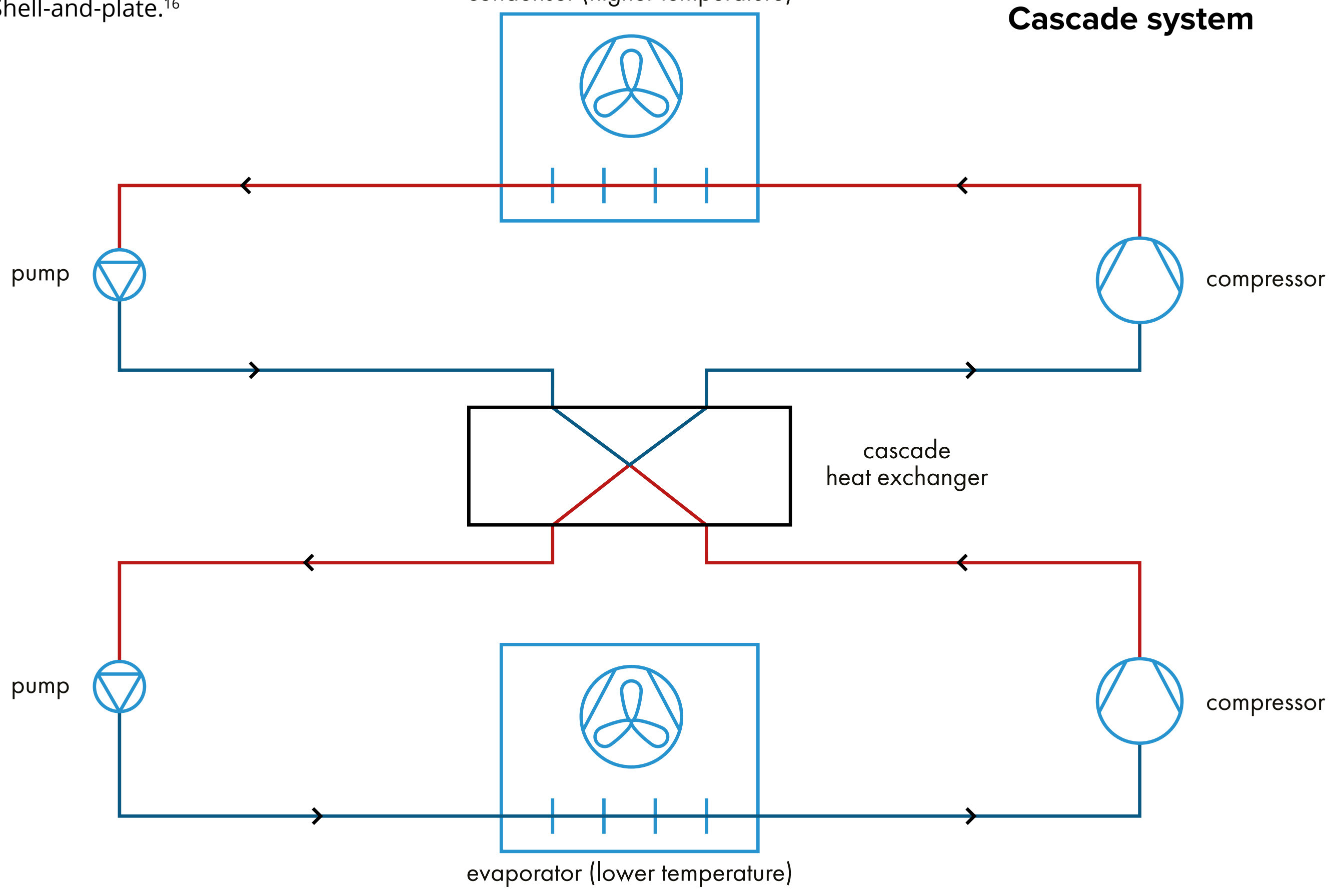
A cascade system uses a combination of two centralized refrigeration systems. The high temperature refrigeration system (ammonia, HFC, HC) cools the lower-temperature refrigeration system (usually subcritical CO_2).[15 16] This means that the heat rejected by the condensing CO_2 is absorbed by the evaporating 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]



sheccoBase sketch

Secondary/indirect systems

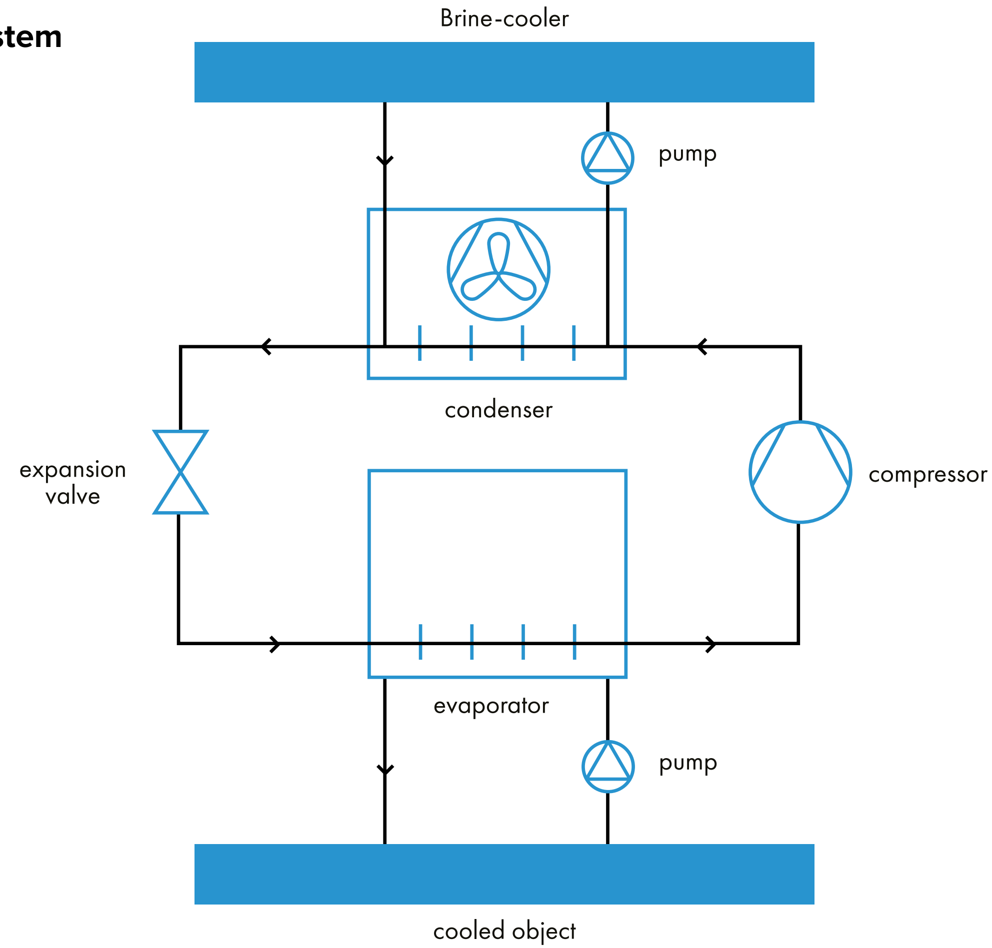
A secondary/indirect refrigerant system uses a centralized system to cool a secondary fluid (e.g. CO_2 in subcritical mode, secondary brine or glycol). The secondary fluid is pumped to each consumer. The consumers can be air coolers, processing equipment or glycol/chilled water heat exchangers. The primary 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]

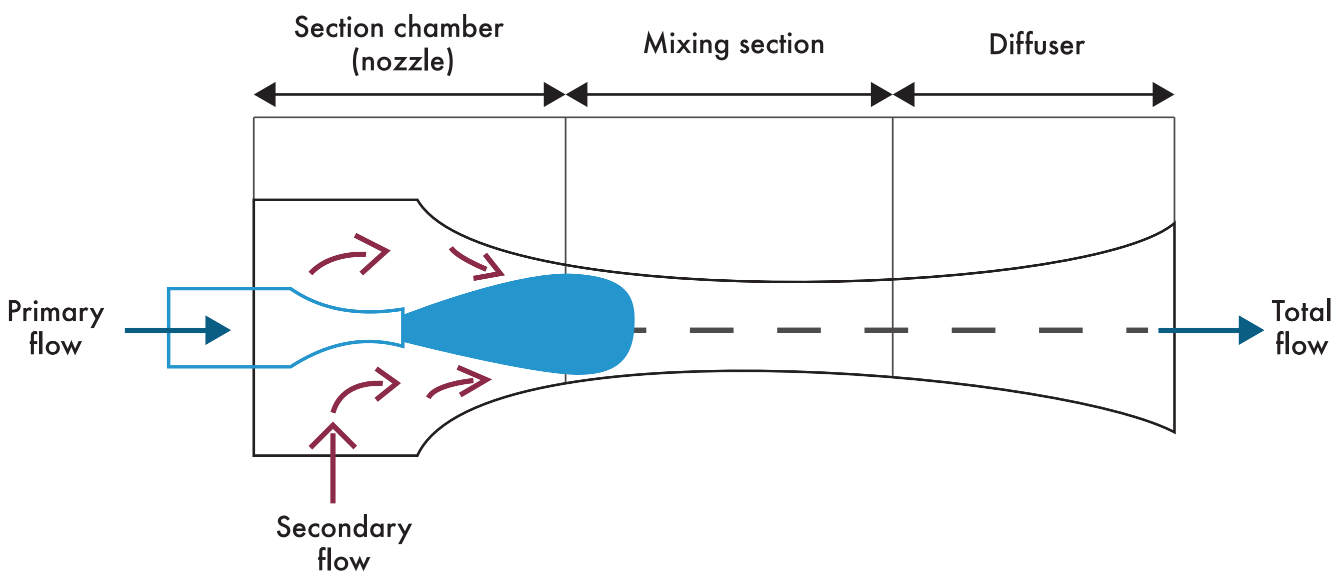
Technologies to improve efficiency of transcritical CO_2 systems: Ejectors, parallel compression, sub-cooling and adiabatic cooling

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).

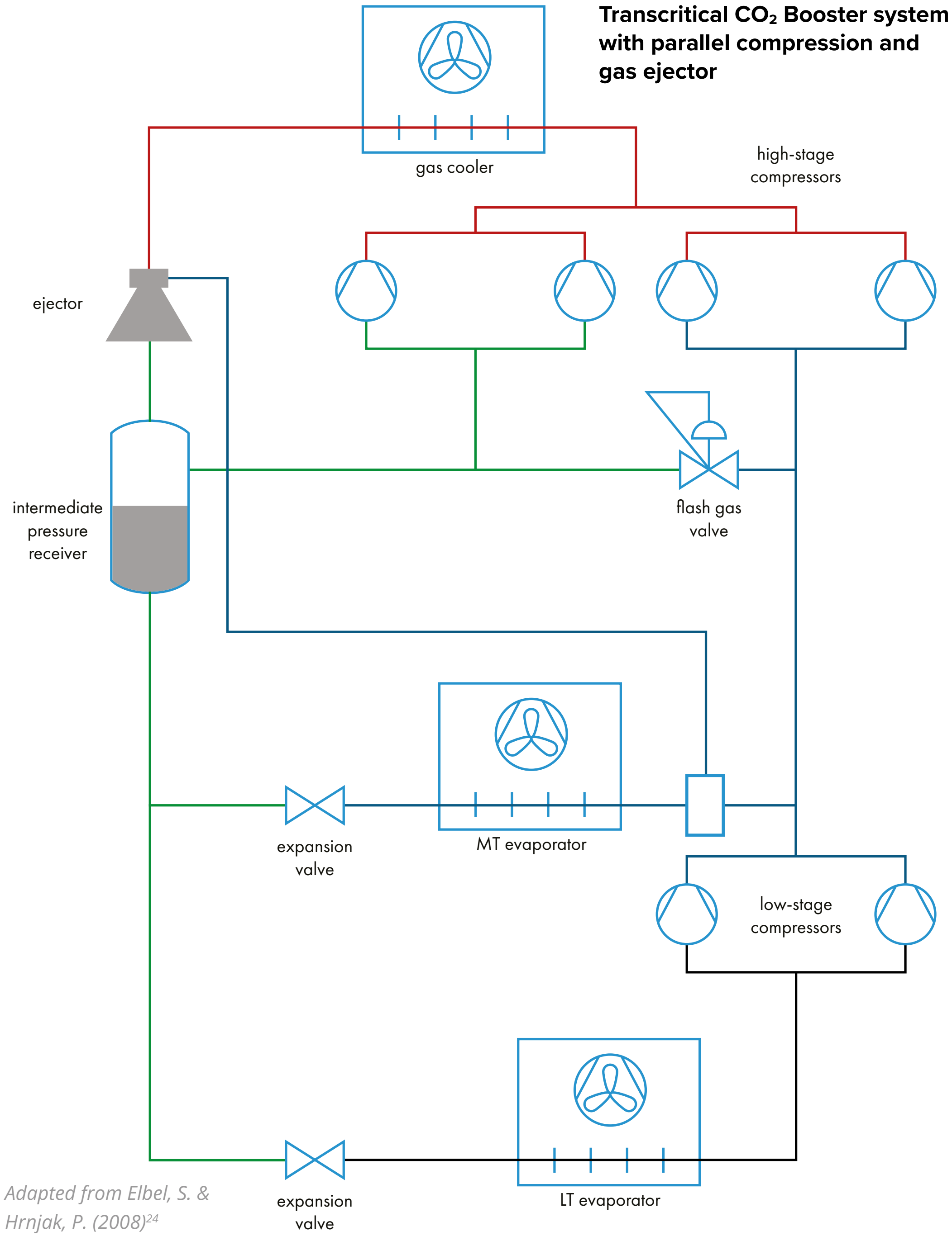
Parallel compression is a solution that compresses the excess gas at the highest possible pressure level. It leads to a significant increase of COP in warm climates.[25]

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]

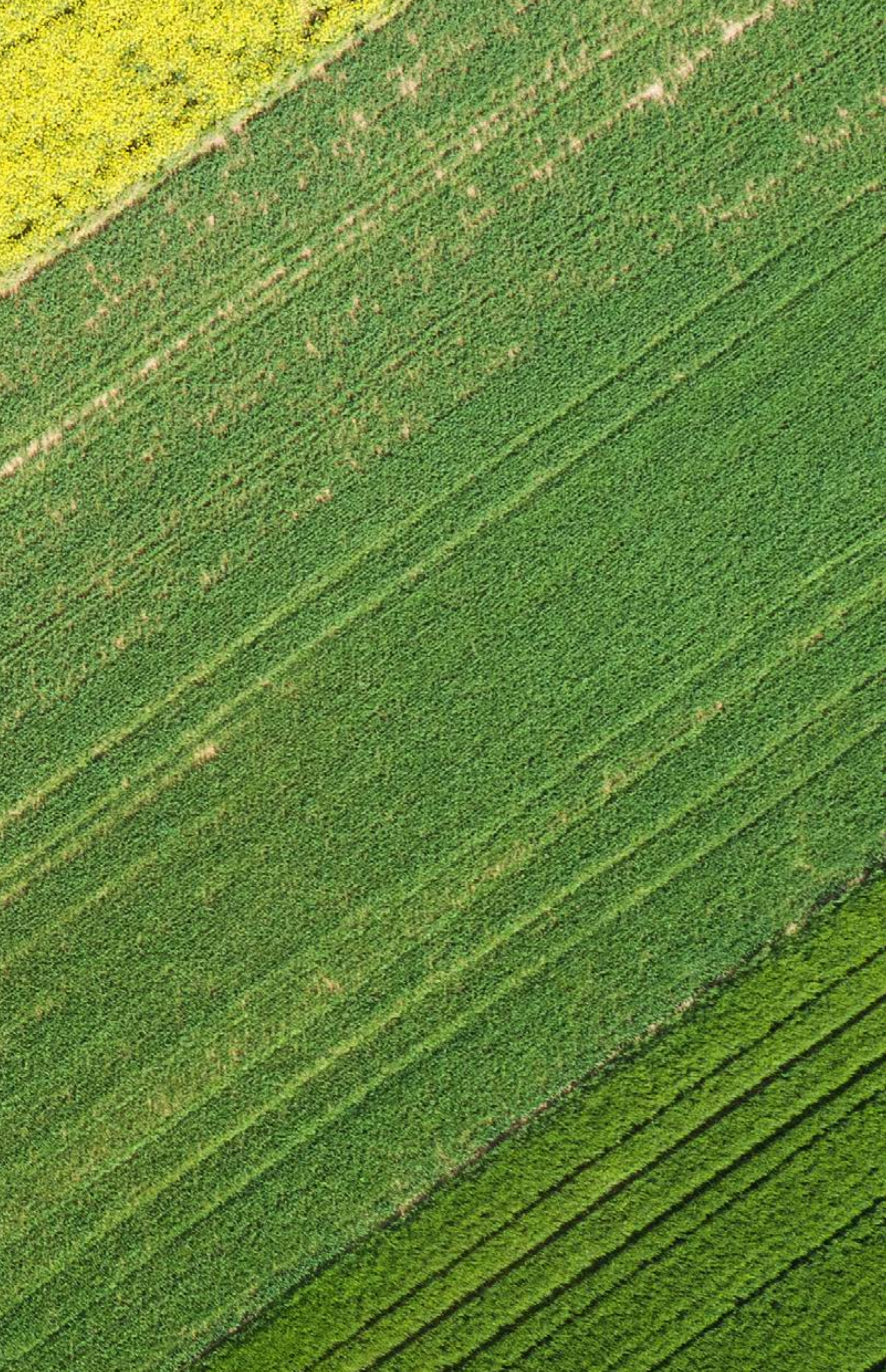
Mechanical sub-cooling uses an additional small refrigeration cycle coupled with the main refrigeration cycle in order to provide cooling at high temperatures.[25]

Transcritical CO_2 Booster system with parallel compression and gas ejector



Adapted from Elbel, S. & Hrnjak, P. (2008)[24]

APPLICATIONS OF TRANSCRITICAL CO_2



An overview

Transcritical CO_2 technology has been deployed in a variety of applications across the world for many years. From traditional supermarket applications to convenience stores and industrial cold storage applications; even on cruise ships and for ice rinks – there are hundreds of examples of successful installations globally.

The following pages showcase examples of a multitude of different transcritical CO_2 installations, varying in size and location, categorized by type of application. Whether in a small, convenience store type of installation, or the more conventional commercial retail one; even industrial projects – transcritical CO_2 is worth considering when designing an HVAC&R installation. Here is how others have done it...

SMALL STORE APPLICATIONS

CONVENIENCE STORES

[1]**Europe:** European retailer Carrefour has installed a full-CO_2 transcritical remote unit at a Carrefour City store in Vannes, Brittany. Opened in October 2017 and located in the city center of Vannes, the store has a commercial surface of 293m^2 [3154ft^2]. To save space for the refrigeration plant, Carrefour installed the refrigeration systems in the store's yard.

The transcritical CO_2 refrigeration system is a two-stage central unit with 22kW [6.3TR] of medium-temperature (MT) cooling and 2.2 kW [0.6TR] of low-temperature (LT) cooling. All refrigerated display cabinets are equipped with doors except the snacking segment. Carrefour has also installed doors on all refrigerated cabinets of the store, as well as LED lighting to increase the energy performance of the store.

[2]**Europe:** A Delhaize convenience store in the heart of Belgian capital Brussels uses two CO_2 condensing units. The two new CO_2 condensing units were installed in a franchised Shop & Go store on Boulevard Adolphe Max. The supermarket has a footprint of 250m^2 [2,691ft^2] and opened at the end of June 2018.

One of the units serves the medium-temperature cabinets, and other serves the frozen food cabinets. They were commissioned in late June.

[3]**Japan:** In the framework of the convenience store (CVS) concept, Lawson has opened a CVS store that has 263m^2 [2,831ft^2] and provides around 3,000 kinds of products. The CO_2 refrigeration system for this store helps reduce the energy consumption by 20% in comparison to 2010's standard HFC system.

Half of the 20% energy savings is thanks to the CO_2 system and the other half due to energy saving features of new CO_2 showcases (i.e. sliding glass doors). LED lighting, improved thermal insulation, energy management system and electricity generated with installed solar panels contribute to planned total 50% energy saving of this store opened in February 2014. The system features one 10HP [7.5kW; 2.1TR] unit to provide MT cooling, two 2HP [1.5kW; 0.4TR] units to provide LT cooling and a bottle cooler with built-in CO_2 refrigeration system.

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COMMERCIAL APPLICATIONS

SUPERMARKETS/ RETAIL

[4]**U.S.:** A 75,000ft^2 [6,968m^2] Seed to Table Market, a refurbished Albertsons store that opened in December 2019 in North Naples, Florida, the most southeastern state in the U.S., has installed a transcritical CO_2 system. The system includes three rooftop adiabatic gas coolers, which helps the system function efficiently in the balmy climes of southwest Florida.

Having recently been installed, the energy usage of the transcritical system has yet to be assessed. But, despite the high ambient of North Naples, the energy consumption of the system as compared to that of a traditional DX system is “parity, probably using a little more.”

[5]**U.S.:** Weis Markets, a Mid-Atlantic chain of 204 grocery stores, reported dramatic energy savings with transcritical CO_2 in 2019. The chain’s first transcritical system consumed less energy than three other store systems during an 8.5-month test.

Weis’s first transcritical CO_2 refrigeration system was installed at a 54,000 ft^2 [5,017 m^2] store in Randolph, N.J., in July 2018. Its energy usage during that period was 250,790kWh [71,654RTh], substantially below the energy consumed by the other systems, all based on HFC or HFO refrigerants: 32% less than a 1.5-year-old secondary glycol/DX system, 39% less than a seven-year-old distributed rack system, and 86% below a 23-year-old centralized DX system.

The test period included August and September 2018, when high ambient temperatures, particularly during a two-week period, challenged the efficiency of a transcritical system. Yet Weis’s unit consumed less energy during that period than the other systems.

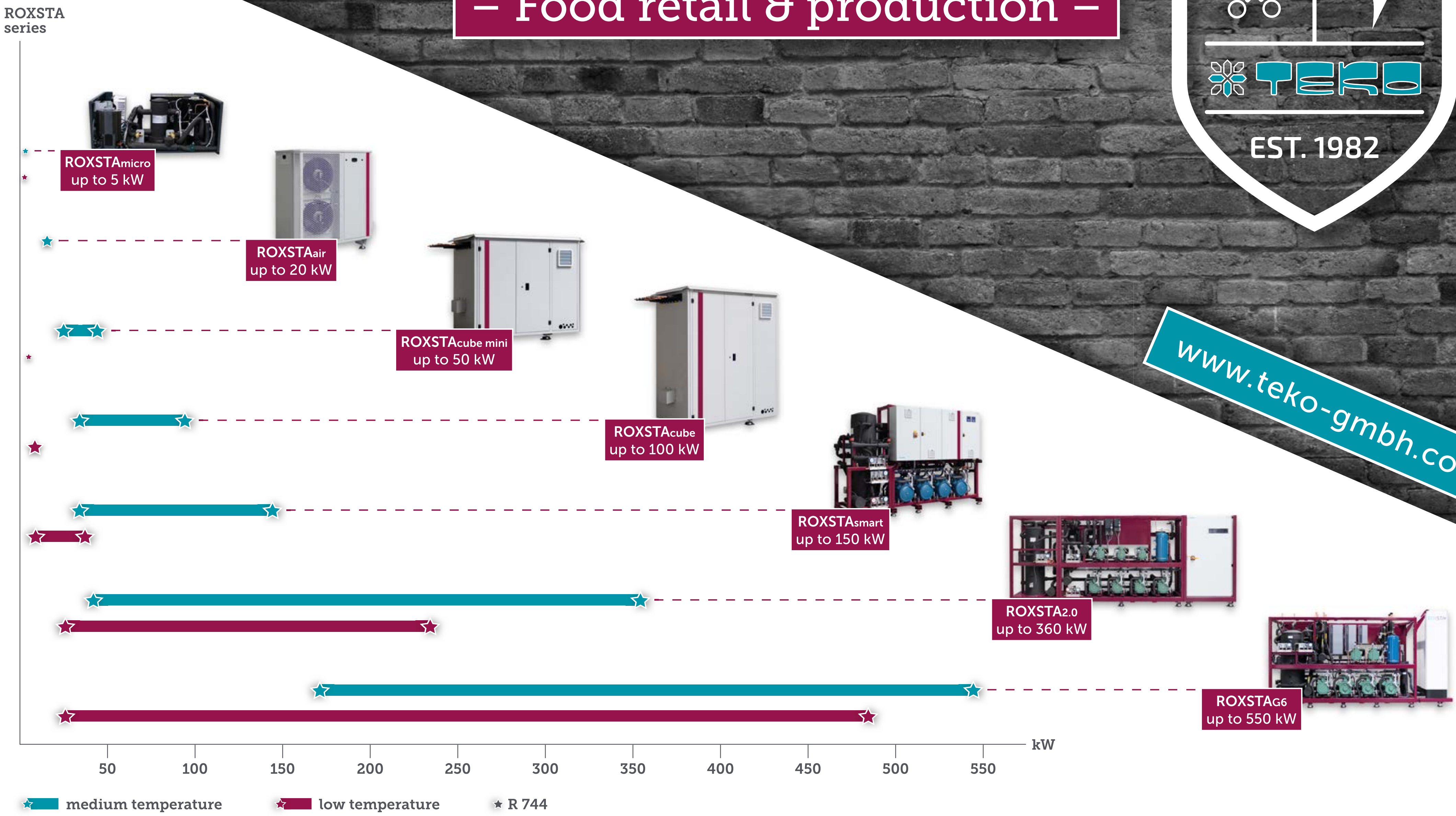
[6]**Europe:** An Italian supermarket chain is using groundwater as a cooling fluid to condense the CO_2 in a transcritical system in a remodeled store in Milan. The 400m^2 [4,306ft^2] remodeled store was officially opened in December 2019, after a two-month refurbishment period.

Using groundwater as a cooling fluid allows the system to run subcritically in the warm summer months and reduces the electricity consumption of the compressors. The groundwater used as a cooling fluid in the system is 15 to 20°C [59 to 68°F] warm year-round. This allowed to set a 25°C [77°F] condensing temperature in the system, using a plate heat exchanger. The use of groundwater, instead of air, to condense the CO_2, allows the system to run in subcritical mode even during the hottest summer months when the ambient air temperature is 27 to 28°C [81 to 82°F] or more.

In the winter months the system is designed to run in transcritical mode to satisfy the supermarket’s need for hot water. To achieve the needed hot water, the system

Sustainable CO_2 solutions for all sizes of application

– Food retail & production –



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employs heat recovery, which can recover up to 42kW [12.0TR] in winter, equaling "total" heat recovery, and increasing the system's COP to 4.2. The capacity of the Milan system is 30kW [8.5TR] for medium temperature, 6kW [1.7TR] for low temperature and 40kW [11.4TR] for high temperature (air conditioning).

[7]**Europe:** Migros Ticino, a cooperative that is part of Swiss retail giant Migros, installed its first transcritical CO_2 system in 2009 already. Now the company, which operates 33 grocery stores among other businesses, has taken its commitment to natural refrigerants one step further and installed its first fully integrated CO_2 system at a store in Riazzino, Switzerland, in the Italian-speaking section of the country.

The system provides for the store's refrigeration, winter space heating and summer air-conditioning requirements. The transcritical CO_2 compressor rack has subcooling, heat pump and chiller sections, and works with two separate water tanks providing the secondary fluid for the HVAC requirements. The system has been tested down to -5°C [23°F] in winter and up to 42°C [108°F] in late June, meeting the store's needs in all conditions, according to Rossi.

[8]**Europe:** German retail giant Metro recently replaced an inefficient, 20-year-old R404A refrigeration system at an outlet in Ruse, Bulgaria, with a transcritical CO_2 system equipped with ejectors – with zero downtime at the store. This was done in a move towards natural refrigerants and to save electricity. The transcritical CO_2 system is Metro AG's 18th with ejectors.

Metro's 7,000m^2 [75,347ft^2] Ruse store opened in 1999 and was due for an upgrade this year to improve its overall efficiency. In only four months (from May until end August), the entire refrigeration system was replaced, and various other improvements were made, including the addition of glass doors to fridges to minimize openings and thus save energy. The new system will realize a projected electricity saving of a minimum 20% for cooling and more than 35% on heating, explained Schulze.

[9]**South Africa:** Local retail/wholesale outlet Evergreens opted for a transcritical CO_2 refrigeration system in its brand new 22,000m^2 [236, 806ft^2] store in Johannesburg, which opened in August. The new store boasts the largest transcritical CO_2 installation in the South African commercial sector – and one of the largest commercial systems in the world – with a refrigeration capacity of 1.9MW [540TR] serving 167 loads.

The main distribution board manages the racks as well as the evaporator coils. The racks, each with medium-temperature and low-temperature circuits, cool about 167 points, including various cold and freezer rooms, freezer and cold cabinets, and chillers. Loads range in temperature depending on the product, with the freezer rooms being kept at -20°C [-4°F], the citrus at 2°C to 5°C [36°F to 41°F], and the avocados and bananas at 14°C [57°F]. This is because if it is too hot, it will ripen fruit too fast, and if too cold, will make the fruit go black.

The estimated heat rejection is around 384kW [109.7TR], and this is used to heat water from 20°C to 55°C [68°F to 131°F]. Hot gas defrost has been included instead of the normal element heater that uses a lot of electricity.

[10]**South Africa:** In September 2018, food retailer Pick n Pay (PnP) opened its first transcritical CO_2 store, based in Milnerton, Cape Town. Today, it has 16 transcritical stores in South Africa (as per a presentation during ATMOsphere Cape Town 2020) with a projected 32 by end of 2020.

The booster system with parallel compression was manufactured locally and the rack is fitted with 10 compressors, four of which run the medium-temperature side, two doing parallel compression, three running the low temperature, and one satellite low-temperature compressor. The compressors are piped to four circuits: -36°C [-32.8°F] to the fish island freezer; -28°C [-18.4°F] to freezer cabinets and freezer store; and -8°C [17.6°F] to the medium-temperature cabinets. Two compressors are piped to provide parallel compression of flash gas. Included in the rack is a plate heat exchanger to reclaim heat for heating of hot water to 55°C [131°F], which is used for washing and cleaning in the bakery, butchery, food preparation areas, and for staff ablution.

[11]**Australia:** Thanks to its natural refrigeration system, a significant reduction in carbon footprint is projected for the new IGA Supa retail and liquor store, which opened in Creswick, Australia in August 2019. "We will have a 47% reduction in our carbon footprint because we chose natural refrigerants over high-GWP refrigerants, and our emissions will be 6,209 CO_2e tons less per year," said the owner. They also heat the store and produce hot water from the excess heat generated by the CO_2 system, further reducing costs and emissions."

Other considerations that motivated the business case for a CO_2 system were cost savings, energy efficiency and future-proofing the store.

[12]**Australia:** A recently opened Woolworths Supermarket in Burwood, a suburb of Melbourne, Australia, is the first supermarket in the world to become associated with certification from the stringent Living Building Challenge (LBC) performance standard, in part by employing two transcritical CO_2 refrigeration systems and doors on all meat and dairy cases.

Three transcritical CO_2 refrigeration racks are being used by Woolworths in the shopping center, two for the supermarket's chillers and freezers, and one for the Dan Murphy's liquor store (part of the Woolworths group) located inside the center. Both systems include parallel compression. Doors have also been included on all meat and dairy cases, which will reduce the energy consumption by around 30%, by preventing cold air from spilling from the cases, noted Woolworths. Energy is also further reduced by use of waste heat from refrigeration to heat the store and switching off lights after hours.

[13]**New Zealand:** The Fresh Choice Papamoa and Countdown Hāwera food retail stores both opened in 2019, each with an energy efficient transcritical CO_2 system. With regards to energy efficiency and savings expected, both stores are expected to typically save “5% to 8% over a new, well-engineered equivalent HFC system.”

Countdown Hāwera in Taranaki is New Zealand’s first «Be Accessible»-accredited supermarket, designed to be inclusive and accessible to everyone regardless of ability. Fresh Choice Papamoa, part of the Woolworths New Zealand group, boasts a unique heat reclaim system. Instead of having two heat exchangers on the rack, only one heat exchanger was used both for the hot water and the HVAC systems.

[14]**South America:** In 2019, Makro, a division of Dutch conglomerate SHV Holdings, has installed a transcritical CO_2 system at its new Valle del Lili supermarket in Cali, Colombia. With more than 3,400m^2 [36,597ft^2] of sales space, the store has achieved Leadership in Energy and Environmental Design (LEED) certification thanks to the measures put it place to reduce water and energy.

The installation features a transcritical CO_2 refrigeration system with parallel compression. The cooling capacity is 130kW [37.1TR] on the medium-temperature side and 4kW [1.1TR] for low temperature. As a special safety feature, the rack has been equipped with a controlled suction-gas super heater, which reduces the “oil throw” in the compressors and ensures the stable operation of the system, even if the cooling cabinets work under discontinued super heating. In addition, the installation includes a gas cooler (cooling capacity: 254kW/72.2TR), electronic expansion valves, and self-service doors – all to maximize energy efficiency and to reduce the store’s carbon footprint.

[15]**China:** One of China’s first transcritical CO_2 systems – installed in a remodeled store – has been installed in 2019. The transcritical CO_2 system was installed at a CSF Market store in Beijing in July 2018 as a part of a three-month store renovation project. The system replaced the store’s old R22 system.

The transcritical CO_2 system installed at the CSF Market store includes a parallel-compression system. All the different configurations and technologies available for transcritical CO_2 systems such as ejectors, parallel compression and booster configurations, are directed towards gas cooler outlet temperature control. According to the manufacturer, the customer is very satisfied with the energy savings. The system deploys heat recovery, which made the system save energy compared to the former R22 system.

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INDUSTRIAL APPLICATIONS

REFRIGERATED WAREHOUSING/ COLD STORAGE

[16]**U.S.:** Hannaford, a Scarborough, Maine-based division of Ahold Delhaize, is one of the first U.S. grocers to employ a transcritical CO_2 system in a refrigerated warehouse. Hannaford's CO_2 warehouse also contains one of the world's largest refrigerated spaces (250,000ft^2; 23,226m^2) to use a transcritical system. The warehouse supplies 85 of Hannaford's approximately 190 stores in New York, New Hampshire, Vermont and Massachusetts.

Four transcritical racks are planned in what is a replacement of the warehouse's original, almost 30-year-old R22 system. Three of the racks are medium-temperature, two-stage, intercooled systems, while the low-temperature rack (the first installed) is single-stage, with ejector defrost.

[17]**Japan:** Japanese cold storage operator Hamamatsu Itaku Soko reduced energy use by up to 35% at one of its facilities after replacing an R22 system with a transcritical CO_2 system. In 2018, Hamamatsu Itaku Soko replaced a 22-year-old R22 system at its Yonezu Cold Center facility with the transcritical system. The cost of the installation was supported by Japan's government subsidies for natural refrigerant systems. The old R22 unit was reaching its lifetime end after running for 22 years.

The R22 unit in 2017 consumed 854,898kWh [244,257RTh]. By contrast, in 2018, the CO_2 unit consumed 553,842kWh [158,241RTh], a drop of 35%, and in 2019, 562,417kWh [160,691RTh], a 34% reduction.

[18]**Japan:** Fukuoka-based Yoshio Ice Manufacturing & Refrigeration (Yoshio Ice) installed three Japanese-manufactured CO_2 transcritical systems at one of its cold storage facilities in April 2018. The region experiences some of Japan's hottest and most humid climates with temperatures sometimes reaching 35°C [95°F] during the summer months.

The three CO_2 transcritical systems service one 4,700m^3 [133ft^3] frozen storage room (at -25°C [-13°F]), as well as a 3,700m^3 [105ft^3] cold room (at 5°C [41°F]) and a 4,700m^3 [133ft^3] loading area (at 5°C [41°F]). The power consumption for the period from April to December 2018 was 27kWh/m^3 [0.22RTh/ft^3]–less than what was predicted (around 35kWh/m^3 [0.28RTh/ft^3]), and far less than Japan's industry annual average of around 61kWh/m^3 [0.49RTh/ft^3].

[19]**Australia:** South Coast Stores, an Australian wholesaler in the remote town of Nowra, New South Wales, has opted for a transcritical CO_2 system that uses solar energy and employs the waste heat from the refrigeration system for hot water and heating requirements. The cold-storage component was commissioned in January 2019, followed by the retail space in February. Other refrigeration options, including ammonia and HFCs, were rejected.

The commercial viability of an ammonia plant versus a CO_2 plant with solar PV was found to be unattractive, and therefore a full CO_2 plant with booster and parallel compressors and an adiabatic gas cooler was chosen as the lowest-cost option. The CO_2 system provides 256kW [55.8TR] of total cooling capacity.

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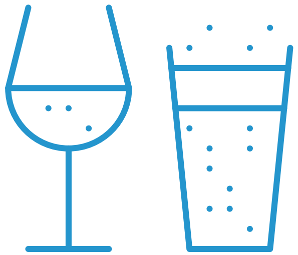
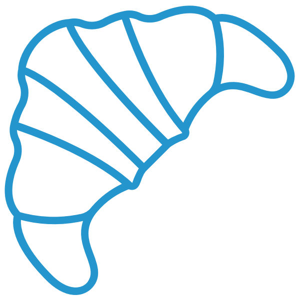


WINERIES AND BREWERIES

[20]**Japan:** In Japan, transcritical CO_2 is experiencing an expansion into the sector of food production and food processing. Companies such as Asahi Breweries, which makes one of Japan's most well-known lagers, along with margarine production facilities and packaged ice manufacturers, are currently installing transcritical CO_2 refrigeration systems.

[21]**Europe:** High up in the picturesque mountains of South Tyrol, northern Italy, at the nine-centuries old Abbazia di Novacella/Kloster Neustift, two CO_2-based water-brine chillers serve a high-efficiency CO_2 transcritical system with gas coolers and heat recovery. Each of the chillers, installed in August 2017, has a cooling capacity of 60kW [17.1TR]. The two units are used to cool must when it increases in temperature during the fermentation phase; at the same time, heat recovery produces sanitary water at 90°C [194°F] for cleaning the wine barrels. In the system, the water chiller, depending on the cooling load request from the air-conditioning system, generates cold water.

It can operate in several ways. In the first operating mode, it rejects the heat into the ambient air. A second operating mode is used when hot water is required. A three-way valve transfers the available heat to a water cylinder, and the mass flow of refrigerant bypasses the condenser/gas cooler. A third option is to reheat the water in the cylinder. Here the CO_2 passes through both the heat recovery heat exchanger and the condenser/gas cooler. In this manner, it is possible to produce sanitary hot water almost for free.



BAKERIES

[22]**Europe:** The site of BACU Bakery in the Netherlands was equipped with its first transcritical flooded chiller. The cooling capacity is 550kW [157.1TR], the evaporation temperature is 1°C [34°F]. Propylene Glycol is used in the chiller and heat recovery is deployed for heating water.

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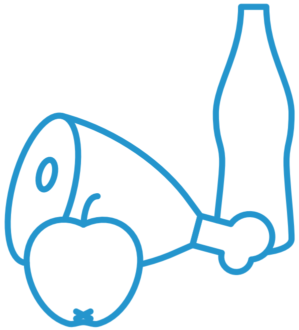
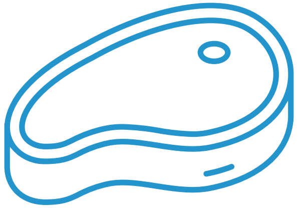
FOOD AND DRINKS PROCESSING



FOOD PROCESSING

[23]**South Africa:** To meet an increase in the demand for their popular range of Mediterranean Delicacies branded products, BM Food Manufacturers opted to completely revamp their 18-year-old plant in Cape Town. The interior of the 1,200m^2 [12,916ft^2] building, with its simplex R22 refrigeration units, was totally gutted. The new plant needed to meet EU standards, be energy efficient, and have minimal impact on the environment. In the processing of ready-to-eat soups and prepared meals, the refrigeration plant consumes the largest portion of power.

The new CO_2 plant has a trans-critical booster pack with parallel compressors. The pack has seven semi-hermetic compressors, all fitted with variable frequency drives (VFDs) for capacity control. Three compressors operate on the medium temperature (MT) circuit (-7°C [19°F]), two on the low temperature circuit (-32°C [-26°F]), and two provide parallel compression on the MT. The MT circuit maintains the temperature (0–4°C [32-40°F]) in five cold rooms, three double-blast chiller tunnels, and a blast chiller. Heat recovery is used to heat water to between 40°C and 45 °C [104°F and 113°F]. The LT circuit has a blast freezer that can also operate as -25°C [-13°F] cold room.



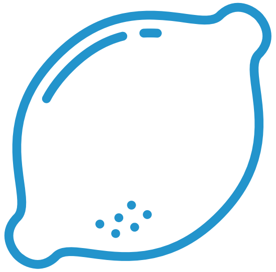
MEAT PROCESSING

[24]**U.S.:** The world's largest transcritical CO_2 refrigeration system has been installed and commissioned at Yosemite Foods, a California-based pork and meat supply company. With a total cooling capacity of 4MW [1,137TR], it is the largest transcritical CO_2 refrigeration system installed globally. The company Yosemite recently relocated and expanded to the city of Stockton, where it opened a new 200,000ft^2 [18,580m^2] meat processing facility.

It is here where five transcritical CO_2 refrigeration racks power the cooling needs for the facility's quick chiller, process water chiller and cold/freezer rooms. The system also employs heat reclaim to produce process hot water. In order to mitigate reductions in energy efficiency due to the plant's location in central California, where ambient temperatures can be high, the system uses adiabatic condensers and parallel compression.

[25]**South Africa:** The new Meat World production facility in Springs boasts an energy efficient, state-of-the-art trans-critical CO_2 refrigeration plant that will raise the technology standard in South Africa. The heat load for the system consisted of amongst others between 80 and 160 tons [79 imperial tons and 158 imperial tons] of fresh meat as well as 1,000 tons [984 imperial tons] of frozen meat passing through the facility daily. This all added up to a combined heat load of 840kW [240TR] for both the medium and low temperature applications. Additionally, the client required that the system could supply 10,000l [2,200gal] of hot water per hour as well as 2,000l [440gal] of chilled water for various factory and processing functions.

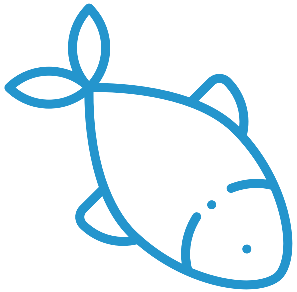
The final equipment offered and installed for the CO_2 system were as follows: Two outdoor multiple compressor rack plant rooms each handling half of the overall load to keep the system balanced. The following are specifications for each plant room: Racks capable of delivering 431kW [123.1TR] each to serve both medium and low temperature applications, each rack consists of eight compressors all equipped with service valves on the suction, discharge and oil side to allow for isolation if required, as well as pressure relief valves. Furthermore, the system is quipped with a vapor multi ejector.



FRUIT PROCESSING

[26]**South America:** One of the leading fruit processing companies in Peru was recently supplied with a transcritical CO_2 system. Friopacking – an engineering and construction company specializing in food processing plants – was in charge of the installation, which took place in the city of Trujillo. The fruit-processing operator could not be identified without its permission.

The transcritical system serves 1,750m^2 [18,837ft^2] of refrigerated storage, with a low-temperature capacity of 54TR [189.0kW], and a medium-temperature capacity of 21TR [73.5kW]. The control package keeps the system's COP at maximum levels at all times.



FISH PROCESSING

[27]**Europe:** DFDS Logistics Ltd., a logistics and freight shipping company headquartered in Copenhagen, Denmark, announced in October 2019 that it had purchased 50 CO_2 refrigerated shipping containers to use in its short-sea (coastal) shipping service.

In addition to being in line with sustainability initiatives, the CO_2 shipping containers are helping shipping companies mitigate future business risks related to environmental regulations and technology phase-outs. According to the statement issued, DFDS has emblazoned each of its new 45ft [13.7m] containers with the slogan 'Naturally Chilled: No synthetic refrigerants – kinder to the environment'.

[28]**U.S.:** Global Seas, a private fisheries management company based in Seattle, Washington, has installed a CO_2-based refrigeration system using recirculated seawater on its F/V Northern Defender trawler. The system was chosen for its compactness and cost-effectiveness. The Northern Defender was built in 1979, and the original synthetic refrigeration system had become outdated, and needed replacing.

The Northern Defender, a 45m trawler fishing in the Bering Sea, off the Alaskan coast, needed a system that could keep up to 308,443kg [680,000lbs] of pollock fresh on the several days' journey back to port. For this, Highland Refrigeration built a 500kW [142.2TR] recirculated seawater (RSW) system that chills the catch with 0 to -1°C [32 to 30°F] seawater. The system had to fit into a space only 8m [26.2ft] long, 1m [3.3ft] wide, and 2m [6.6ft] high.

NICHE APPLICATIONS/ OTHER

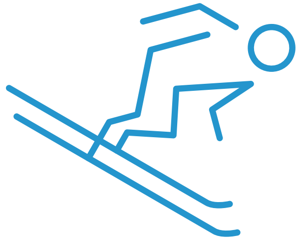
ICE RINKS

[29]**Canada:** A transcritical CO_2 system for an outdoor ice trail was installed at the College Park section of Toronto, Canada. Opened in December 2019, the Barbara Ann Scott Ice Trail is an oval-shaped, 5m (16.4ft)-wide path that doubles for a walking loop in the summer.

The system's capacity is 50TR [175.0kW], which is enough HP to maintain the ice surface in all conditions, yet the piping and the CO_2 pumps are much smaller and more efficient than standard rink systems. According to the manufacturer's website, the system costs roughly half as much to operate as other options. In part that is because the CO_2 system is a direct system, making it more efficient than a secondary system. Instead of removing heat at multiple steps, the refrigerant in this system goes straight to the ice floor, removes the heat from it, then uses the same refrigerant to carry it and remove it.

[30]**China:** The Beijing 2022 Organizing Committee has officially announced its plan to use CO_2 refrigeration systems for several ice venues in the Beijing 2022 Winter Olympics. This will be the first time the technology is used in China and at the Olympic Games.

CO_2 systems will be used in «the Beijing 2022 speed skating, figure skating and short track venues, as well as the ice hockey training venues. R449 will be used in the ice hockey and curling venues.



SKI SLOPES

[31]**Europe:** In January 2020, Norway's first year-round indoor ski arena, named SNØ, opened in Lørenskog, just east of capital city Oslo. The snow for the venue is cooled by natural refrigerant CO2. The arena is fitted with three transcritical racks and delivers 3.1MW [885TR] of cooling in what is the largest CO_2 transcritical installation in Norway.

The platform will maintain temperatures at -4°C [25°F] and be able to deliver temperatures as low as -12°C [10°F]. It integrates modulating vapor ejector technology as a standard feature to improve energy efficiency. It is asserted that the platform can deliver energy savings of up to 30% on an annual basis compared to standard transcritical CO_2 systems.

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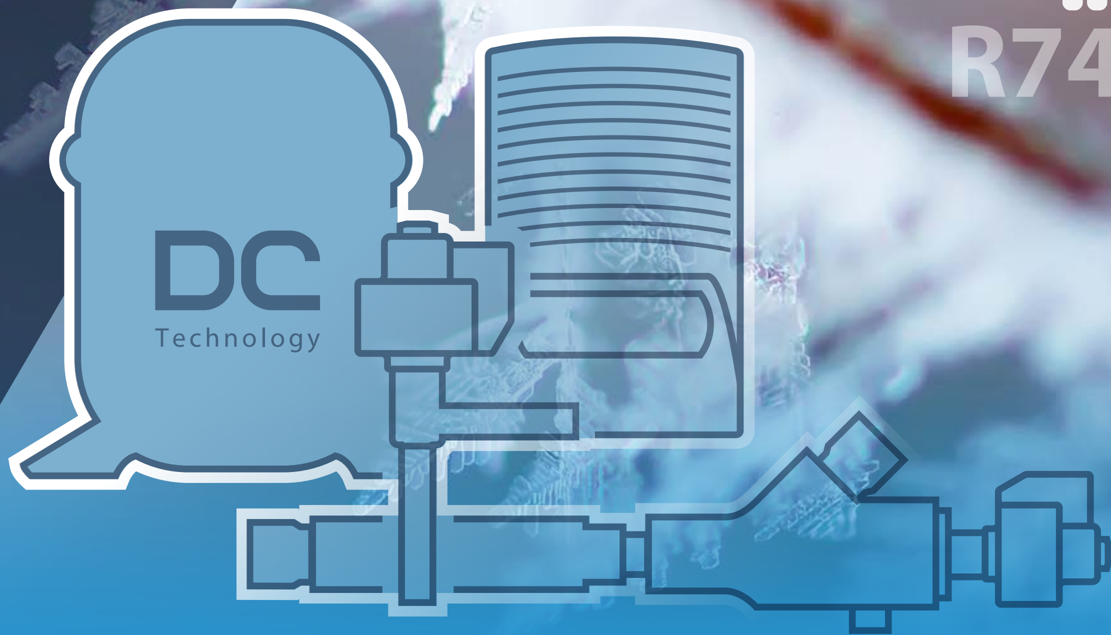

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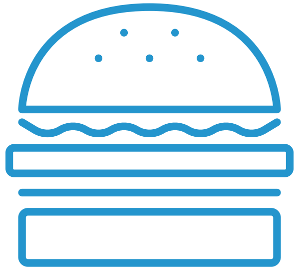

CRUISE SHIPS

[32]**China:** Two cruise ships in China are going to be equipped with a transcritical CO_2 refrigeration system. All food and beverage on the ships will be refrigerated with this system. They are the first two cruise ships ever to be built in China, according to the manufacturer of the CO_2 system. The first ship will be delivered in 2023.

FAST FOOD

[33]**Europe:** U.S. fast food chain Burger King has chosen a transcritical CO_2 system as preferred condensing units for its restaurants in Spain. It marks the first time that Burger King has used CO_2 and it has since ordered more.

Spain has a warm climate throughout the year with temperatures reaching above 40°C [104°F] and so having the right and reliable refrigeration solution was essential. This system is designed to operate in warm temperatures and is using components that can handle 80 bar [1,160psi] service pressure and it can operate with ambient temperatures reaching up to 43°C [109°F].

PHARMACEUTICAL PROCESSES AND LABORATORIES

[34]**Europe:** At the site of multinational biotechnology group in Basel, Switzerland, transcritical CO_2 is used for cold storage rooms for pharmaceuticals. A transcritical CO_2 double-stage system serves two cold rooms where most of the products are stored at -20°C [-4°F]. The cooling capacity is two x 71kW [20.2TR], with four compressors. The compressor capacity is 12.5kW [3.6TR]. A total of 110kg [242.lbs] of CO_2 per chiller are used. The system primarily runs in subcritical mode, harnessing groundwater to cool the CO_2 and improve the efficiency.

PRODUCT TESTING

[35]**U.S.:** A new innovation/technology centre in Downtown Minneapolis where Jack Link's Beef Jerky tests new products has been kitted out with a transcritical CO_2 system. The system delivers a low-temperature capacity of 36.4K BTU/hr [10.7kW; 3.1TR] and a medium-temperature capacity of 575.5K BTU/hr [16.9kW; 4.8TR] to the 10,000ft^2 [929m^2] processing area.

The transcritical system leverages heat reclaim to create hot water used to preheat the water required for the wash down of the processing area. A unique aspect of the Jack Link's project is that the CO_2 discharge gas is cooled in a heat exchanger by chilled (40°F-50°F/4.4°C-10°C) water provided via underground pipes by Clearway Energy's Energy Centre. The cooled water prevents the CO_2 system from ever entering transcritical mode, in which high ambient temperatures prevent the gas from condensing.

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