Cold Storage Transcritical CO_2 Refrigeration Systems

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Comprised of its Core Partners, the Global Cold Chain Foundation (GCCF) and the Controlled Environment Building Association (CEBA), the Global Cold Chain Alliance (GCCA) represents all major industries engaged in temperature-controlled logistics. GCCA unites partners to facilitate communication, networking, and education for the perishable food industry. For more information about GCCA, visit www.gcca.org.

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The Global Cold Chain Alliance will be the recognized authority in forging a universally strong cold chain where every product retains quality and safety through each link.

Mission

The Global Cold Chain Alliance unites partners to be innovative leaders in the temperature-controlled products industry.

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Executive Summary

Introduction

Regulatory pressures from OSHA, DHS, and the EPA along with risk exposure reduction initiatives from insurance companies have forced owners of public refrigerated warehouses (PRWs) to reduce or eliminate the use of ammonia (NH_3) refrigerant in their refrigeration systems. Solutions to date, have primarily focused on the reduction, not the elimination, of NH3 charge through use of Low Charge NH3 or CO_2/NH_3 Cascade refrigeration systems. Owners in the PRW community seeking to eliminate the use of NH3 completely have really only had synthetic refrigerants as an option and the future regulatory outlook for synthetic refrigerant is murky at best.

Transcritical CO_2 refrigeration systems provide owners a path that completely eliminates the use of NH_3 and provides a relatively clear regulatory outlook due to CO_2 being an A1 refrigerant, non-toxic and non-flammable. Transcritical CO_2 while being a relatively new technology in North America was first developed and adopted for small systems, automotive/mobile and vending. The early successes of these small-scale systems translated into food retail and eventually cold storage applications in Europe. With the early innovation chasm bridged in Europe, the use of transcritical CO_2 has become mainstream in Europe with more than 16,000 installations. Within the last decade, the use of transcritical CO_2 started to infiltrate the North American market, primarily in northern climates where ambient conditions were favorable to transcritical CO_2. The successful implementation of the early systems in North America combined with recent technological advances and recent successful applications in the industrial refrigeration and PRW communities are allowing greater market penetration in North America, positioning transcritical CO_2 for mainstream adoption in the PRW community.

Fundamentals of Transcritical CO_2 Refrigeration Systems

The principle functions and operations of transcritical CO_2 refrigeration systems follow the basic mechanical vapor compression cycle: compression, condensation, expansion and evaporation. Compression takes gas produced at the evaporator and raises it to a higher pressure with a corresponding increase in temperature. The heat absorbed from the space along with the heat of compression can then be rejected to a heat sink: air, water, etc. Through the heat rejection process, the high pressure/high temperature refrigerant gas condenses to a liquid. The pressure and temperature of the liquid refrigerant is then reduced through the expansion process where a low pressure/low temperature two phase fluid (gas/liquid) is formed. The gas portion is referred to as flash gas. The low pressure/low temperature two phase liquid then enters an evaporator or is further expanded to a lower pressure/lower temperature mixture. Heat from the space or product evaporates the liquid component of the refrigerant into all low pressure/low temperature vapor where it is then drawn back to the compressor to complete the cycle.

The heat rejection process in a transcritical CO_2 refrigeration system is the primary difference when compared to a traditional refrigeration system and occurs in what is called a gas cooler. For the heat rejection from the refrigeration system to occur, the heat sink must be at temperature lower than the condensing temperature. The traditional value for condensing temperature in a refrigeration system has been 95°F. This temperature, however, is higher than CO_2's critical point: 88.5 degrees F. Hotter than this point, the fluid can no longer exist as both liquid and vapor, and at an increasing temperature cannot be liquified by pressure alone. The CO_2 fluid, when at a temperature higher than the critical point is considered a supercritical fluid and has properties similar to both gas and liquid at the exist of the gas cooler. This supercritical fluid is then expanded to a pressure that is lower than the critical point into a flash tank resulting in an equilibrium mixture of liquid and vapor. The cold liquid is what is used for refrigerating and fed to the evaporators. The vapor, on the other hand, has little value and is ultimately recompressed.

It should be noted that If the heat sink temperature is adequately below the critical point, the transcritical CO_2 refrigeration system will operate sub-critically — meaning condensation will occur during the heat rejection process as with most refrigeration systems. Operating in the sub-critical region provides the greatest energy efficiency. Up until recently, it was assumed that transcritical CO_2 had to be limited to cooler geographical regions — often referred to as the CO_2 equator.

The gas cooling heat rejection process does offer an opportunity for heat recovery to further improve the system efficiency. The heat available compression is considered high grade heat and can produce water temperatures high enough to use for desiccant regeneration, washdown water, and domestic hot water heating underfloor heating. The high grade heat is the result of CO_2's higher high mass flow rates and high compressor discharge temperatures compared to other refrigerants.

Another noticeable difference in a transcritical CO_2 system is the physical size of the compressors. For different reasons, the compressors used in transcritical CO_2 systems are smaller than those found in traditional industrial refrigeration systems. The reason for this is twofold:

- Historically, the compressors used for industrial applications were developed for smaller food retail/commercial applications.
- The thermophysical properties of CO_2 require a smaller swept volume than compressors used for NH_3 and synthetic refrigerants.

The majority of transcritical CO_2 installations to date have utilized reciprocating compressors 50 horsepower or less with manufacturers only recently developing incrementally higher horsepower compressors. One major compressor manufacturer has acknowledged the development of a large horsepower screw compressor that should dramatically reduce the number of compressors needed in an industrial transcritical CO_2 system.

As alluded to previously, the physical size of the compressors does not translate directly to less capacity. When comparing CO_2 thermophysical properties to other refrigerants, it becomes quite apparent that the vapor density of CO_2 is significantly higher. This high density equates to a reduced volumetric flow rate but high mass flow rate vapor. Mass flow is directly proportional to the refrigerating effect.

Designers of transcritical CO_2 systems often can take advantage of the small physical size of the compressors and may be able to design the system with more suction pressure levels. It is common in cold storage applications utilizing traditional refrigeration systems to have one to two suction pressure levels while transcritical CO_2 may have three, four, or even more as needed. These multiple suction pressure levels improve the system coefficient of performance (COP) by more accurately matching suction pressures to room temperatures. This has the effect of reducing the compression ratios by allowing flash gases to be compressed at higher suction pressure levels.

The evaporators are comparable to other evaporators used in traditional refrigeration systems although some have suggested that, as a result of the favorable thermophysical properties of CO_2, evaporators can be made smaller than the traditional NH_3 design.

Advancements in Technology

As with any new technology, larger market acceptance brings with it new opportunities for innovation as well as economies of scale. For transcritical CO_2 systems, this has meant focused innovation to improve the system COP to a level comparable to traditional NH_3 refrigeration systems. Today, those innovations can be seen through the development of adiabatic gas coolers, parallel compression, ejectors and advanced control systems.

Adiabatic gas coolers are similar to air-cooled condensers but utilize the concept of evaporative cooling in order to lower the air temperature prior to contact with the actual heat exchanger. The drier the incoming air, the lower the temperature can be dropped prior to entering the heat exchanger. The evaporative cooler pads do require water to keep them wetted (when ambient conditions require this lower temperature) but at a considerably reduced level when compared to evaporative condensers. The utilization of an adiabatic gas cooler allows for sub-critical operation nearly all year for cool or dry climates and substantially reduced hours of transcritical operation in warmer, humid climates. The adiabatic cooler not only increases system COP but it has also, effectively, eliminated the CO_2 equator.

Designers can also take advantage of the smaller, less expensive CO_2 compressors to provide an additional compressor suction level for the flash gas, produced from expanding the supercritical CO_2 fluid. This eliminates a pressure loss, which previously added no benefit, by allowing all of that vapor to be compressed back up to the gas cooler pressure but at a much lower compression ratio. This additional compression operation is referred to as parallel compression.

The pressure differential between the compressor discharge and the flash tank allows the designers to use a device known as an ejector, to re-pressurize the flash gas to a useful level.

An advanced control system that uses algorithms to optimize the energy consumption is employed to determine the optimum gas cooler pressure as well as when to use the parallel compressors, ejectors, variable frequency drives, etc. It should be noted that there may be times when it is more energy efficient to be operating in the supercritical realm rather than sub-critically. The advanced control system is used to control the gas cooler pressure for optimal energy efficiency and optimization of heat recovery if employed.

Total Cost of Ownership

The amount of energy consumed by any refrigeration system represents only a portion of the cost of ownership picture. For a total cost of ownership (TCO) comparison, the energy costs; construction costs; water, sewer, chemical treatment costs; maintenance costs; and regulatory compliance costs all must be taken into account.

Energy

When the topic of transcritical CO_2 refrigeration arises, an early concern expressed by many is the cost of energy. And, in the world of cold storage, energy consumption contributes significantly to overall operating costs. Two relatively common but very expensive mistakes made in analyzing a refrigeration system are related to the assumptions and the depth of the analysis approach.

- Design points versus ASHRAE data: For years, a basic “quick-and-dirty” approach to assessing system performance is to calculate the specific energy consumption at a 95 degrees F ambient temperature. This has been a standard for many years, but has little applicability in reality. The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) has been collecting and storing weather data for cities all over the world. This data allows the designer to predict energy consumption daily for virtually any type of refrigeration system. An overwhelming number of cities spend few, if any hours, operating at a 95 degrees F condensing temperature. In the case of CO_2, the penalty for this type of analysis is severe. A related problem to this analysis is that, often, the analyst will look only at the compressor horsepower. While the compressor is a significant consumer of electric power, it is, by far, not the only one.
- Steady state or steady state with transient operations: In the world of industrial refrigeration, refrigeration systems do not operate under steady-state conditions for long periods of time. Most evaporators must be defrosted and, depending on the type of defrost methodology and control strategy, defrosting can be a significant factor in energy consumption. Rarely, however, is defrost factored into the energy analysis. Facilities are also, typically, adjusting compressor speeds, compressor sequences,

and fan speeds based on changing load profiles. This situation is further aggravated by resetting operating points such as in convertible rooms as well as periodic blast freezing.

A large component of energy consumption in traditional refrigeration systems is the defrosting of the evaporators. It is a widely accepted practice in the cold storage industry to use the heat of the refrigeration system to provide the heat for defrost, such as hot gas defrost. In a transcritical CO_2 refrigeration system, this hot gas defrost can be viewed as energy neutral in part because of the high quality of heat available. The hot gas supply is taken directly from the compressor discharge and returned to the flash tank following defrost. The process follows the same path on a pressure-enthalpy diagram as if it had gone through the gas cooler/condenser. Any additional gas used for heat recovery applications would follow the same path as well. This heat recovery could be used to offset natural gas heating or electric heating costs for washdown water, hydronic office heating loops, boiler feedwater, or even possibly sold to neighboring facilities for other needs. To fully realize the potential of heat recovery, the potential opportunities should be explored early in the design.

Construction

The initial construction costs, often referred to as first cost, of any refrigeration system heavily weighs into the TCO. When comparing traditional systems to transcritical CO_2 systems, one of the obvious cost of construction savings comes from the smaller pipes associated with transcritical CO_2 systems, which mean less spending on structural supports and building and pipe hangers/support. Plus, costs are also lower because of faster installation, savings in material, and savings in insulation. Perhaps less obvious, initially, is the smaller physical size of compressors and other machinery room components, which can be packaged into factory fabricated compressor rack systems. The factory fabrication of the compressor racks eliminates much of the uncertainty of construction in the field and has been shown to shorten the entire construction cycle.

CO_2's chemical properties are such that it is considered an inert gas allowing designers to compare different materials of construction including high strength copper. The material compatibility combined with the smaller pipe sizes and the A1 refrigerant classification, enables designers to choose tubing over pipe thicknesses found in traditional ammonia refrigeration systems. The use of tubing substantially changes the installation methodology opening the door for brazing, orbital welding, and bending of the tubing for elbows.

Few would argue with the old adage that time is money. Faster installation schedules have been shown to be quite realistic with transcritical CO_2 refrigeration systems when compared to traditional systems. Through the application of concurrent construction of the factory fabricated compressor racks, time savings from installation of smaller pipe sizes, and time savings from faster installation methodologies, the cost saved or avoided by a faster installation can become a key element in the overall decision-making process.

Water, Sewer, and Chemical Treatment

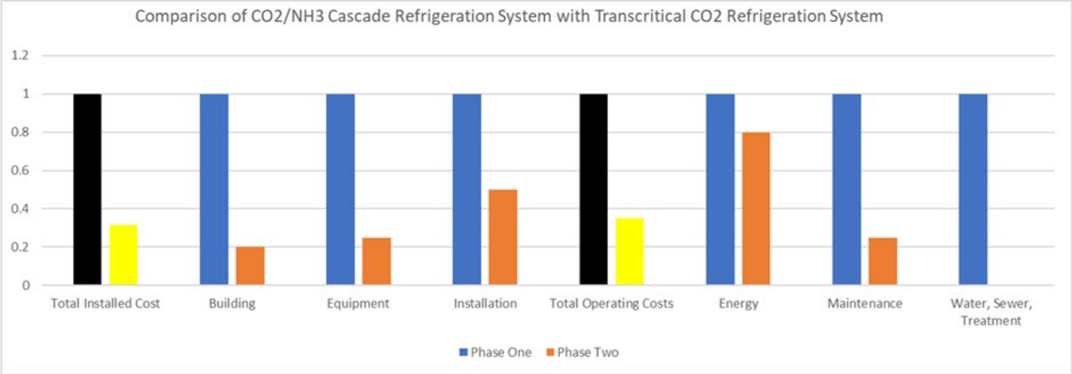
While the use of evaporative condensers and cooling towers is prolific in the traditional refrigeration system design, it is not an option in transcritical CO_2 refrigeration systems today. The gas coolers/condensers commonly found in transcritical CO_2 systems use little or no water when compared to evaporative condensers and cooling towers. Also, due to the nature of their designs, the transcritical CO_2 gas cooler/condensers require no chemical treatment of the water.

Regulatory

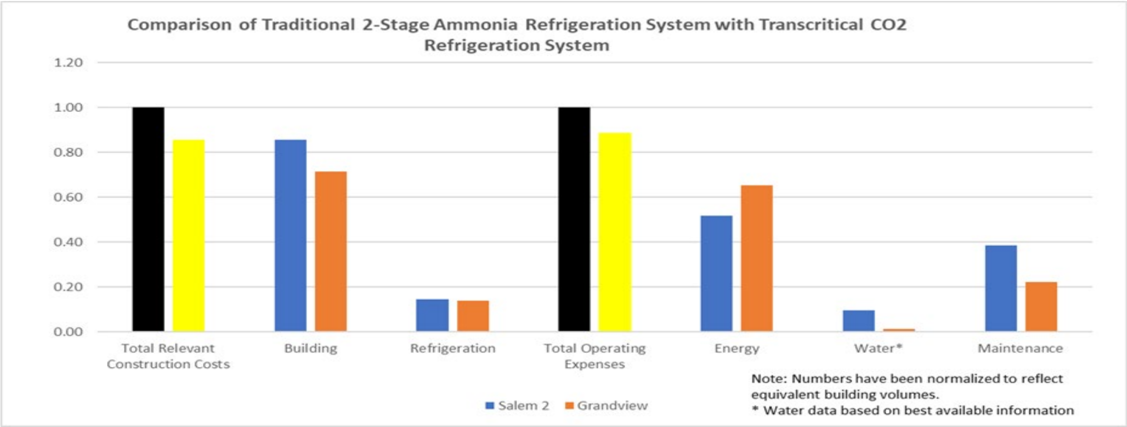
The chemicals used for the treatment of water for the traditional evaporative condenser or cooling tower often add to the regulatory burdens of a facility. Removing these regulatory burdens along with elimination of the PSM and RMP requirements can become a significant cost savings in the TCO for a transcritical CO_2 refrigeration system. It should be noted that the general duty clause still requires the owner to provide a safe work environment.

Case Studies

The two case studies presented in this paper have both used TCO in their respective analyses. The first case study is a higher temperature cold storage facility constructed in two phases. Storage operating temperatures were 32 degress F to 50 degrees F, and the storage capacity of the first and second phases were 3.5 million cubic feet and 2.5 million cubic feet respectively. The first phase of the refrigeration system was a Cascade CO_2/NH_3 system and had a total annualized system COP of 14.7. The second phase refrigeration system was a transcritical CO_2 system and had a total annualized system COP of 18.1. Comparing the TCO of the two phases, it becomes clear that the transcritical CO_2 system far outperforms the Cascade CO_2/NH_3 system.



The second case study presents a comparison of Henningsen Cold Storage's highly efficient low charge NH3 Salem II refrigeration system and their Grandview, Wash., transcritical CO_2 refrigeration system. The TCO comparison shows that while the energy consumption was slightly higher for the transcritical CO_2 refrigeration system, the TCO was less. It should be noted that both of these case studies were in ambient climates that favored the application of transcritical CO_2 but the authors foresee the TCO for transcritical CO_2 to be better or very comparable to traditional refrigeration systems for nearly all ambient climates.



Conclusions

From the case studies, it is clear that transcritical CO_2 can be successfully applied to the cold storage industry and is extremely viable in terms of TCO. The perceptions of transcritical CO_2 being limited to smaller scale application is proving to be incorrect by early adopters. The chasm between early perceptions of transcritical CO_2 refrigeration and reality is being bridged and mainstream market acceptance is accelerating through the use of continual technological advancements and thorough, thoughtful design. The major refrigeration equipment manufacturers are developing the products that will allow a scale-up to the industrial refrigeration market requirements and, it appears, will allow transcritical CO_2 refrigeration to enter the mainstream of industrial refrigeration systems. Transcritical CO_2 refrigeration has not only entered the market as a potential solution to reducing regulatory burden, but it is also proving to have staying power on in its own merits.

Transcritical CO_2 Refrigeration Systems for the Cold Storage Industry

Introduction

Over the past decade, there has been a rapidly accelerating interest in the basic nature and design of industrial refrigeration systems for both food processing facilities as well as cold storage facilities. The level of interest has been particularly intense for the cold storage industry because of many factors. Perhaps the first factor on the list was the desperate search by owners of cold storage facilities (the community known as public refrigerated warehouses[PRWs]) to find a solution to the increasing regulatory pressures from government entities, such as the Environmental Protection Agency, EPA, DHS, and OSHA. Five or six years ago, the focus was on reducing ammonia charge to deflect the burden of a formal PSM program on the facility. A number of novel solutions were outlined in a paper presented to the GCCA Assembly of Committees by this author in 2014 (1). At that time, CO_2 was one of the potential options, however, primarily in the context of what is referred to as a cascade system: essentially two different refrigerants working together, one at the higher temperatures and one at the lower temperatures. The concept has been utilized to a large extent throughout Europe and to a lesser extent in North America. The attractiveness of the system was that each refrigerant (typically ammonia and CO_2) exploited the strengths of its thermodynamic characteristics and minimized the disadvantages at the same time. However, despite all of the advantages of this dramatic reduction in ammonia charge, the fact remained that ammonia has been and, likely, always will be classified as a B2L refrigerant: high toxicity, low flame propagation. CO_2, on the other hand is classified as an A1 refrigerant: low toxicity, no flame propagation.

In terms of meeting the primary objective of reducing and/or eliminating the regulatory pressures posed by EPA and OSHA, CO_2 is very nearly the perfect refrigerant. Nevertheless, CO_2 is not without its challenges. CO_2's thermophysical characteristics limit the temperature at which heat can be efficiently rejected at, what is commonly known as, the condenser and its lowest evaporating temperature is slightly higher than that of ammonia. Because of CO_2's density compared to air, there is a remote possibility that a major leak in a confined environment could lead to an asphyxiation hazard. However, thanks to some outstanding creativity and innovation in Europe and North America, many of the historical deficiencies of CO_2 as a practical refrigerant have been minimized or overcome.

Up to the time of publication of those initial papers on low charge systems, most transcritical CO_2 systems in North America were constructed for relatively small-scale systems: automotive, vending machines, and food retail stores, the latter of which represents a good-sized leap in refrigeration capacity over the first two. As with most things in our world today, the pace of technology advancements continues to accelerate and transcritical CO_2 systems have been the beneficiary of many advancements. And, while CO_2 refrigeration is far from new, the barriers that had historically limited its success have come crashing down. Over the past 4 or 5 years, we have seen steady growth in the use of transcritical CO_2 refrigeration in the PRW world.

This paper will explore the recent history of the technology, the changes which have taken place over the past five years, and what we can reasonably expect to see in the next five. It will cover the following:

- A fundamental description of what is meant by transcritical refrigeration.
- The current, but waning, perception the marketplace sees with respect to its utilization.
- The technological advancements developed to minimize or eliminate these perceived issues.
- The TCO
    - Energy consumption
    - Operating and maintenance costs
- Case studies
- Conclusions

Transcritical CO_2 System Basics

What is meant by the term "transcritical CO2 refrigeration"?

According to the dictionary, "transcritical" is not a word. "Trans-critical" denotes process of moving across a defined boundary. In the case of pure refrigerants, such as ammonia or CO_2, this boundary is the critical point of the fluid – the point at which the density of liquid and vapor are identical and, therefore, are indistinguishable from each other. In Figure 1 below, CP designates the critical point. When the refrigerant is "under the dome," it exists as a two-phase fluid (liquid and gas) and that region is denoted the sub-critical region. As we move from left to right under the dome, we are adding heat to the mixture and the percentage of gas increases until we reach the right most line, at which point, the mixture is all gas. Conversely, if we move from right to left we are removing heat from the mixture and the percentage of liquid increases until we reach the left most line, at which point, the mixture is all liquid. The process of moving from left to right is known as evaporation and from the right to left is known as condensation. It is important to understand that this only happens when we are operating at temperatures and pressures which keep us under the dome.

As the temperature and pressures change and move upward and cross the boundary, the refrigerant enters the supercritical region. This process is referred to as "transcritical," where the refrigerant moves out of the subcritical region and enters the supercritical region, or vice versa.

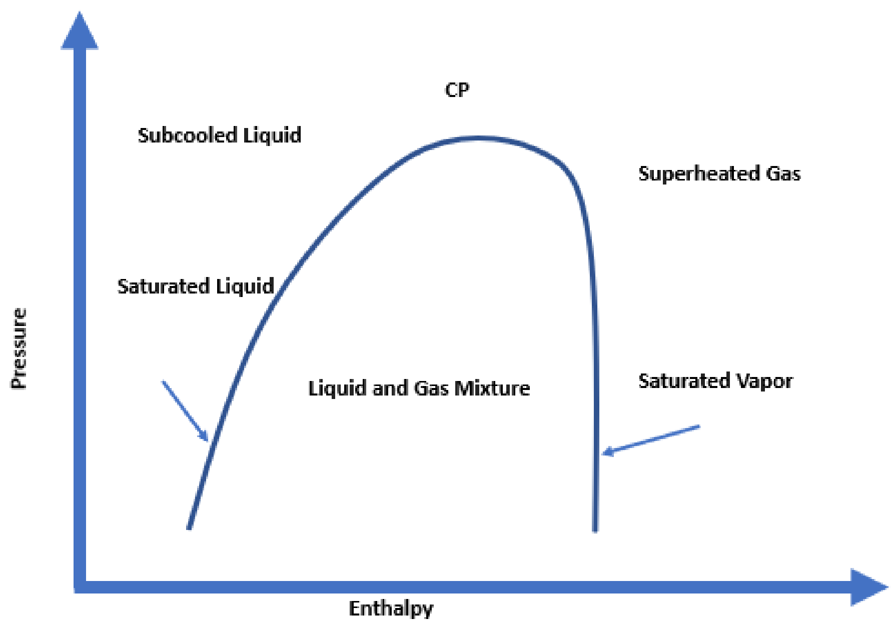


Figure 1 Fundamental Refrigerant Pressure-Enthalpy Diagram

What should be noted from the previous diagram is that the optimum place to operate is in the two-phase region as this is the region where heat transfer is at its most effective.

Why is this important?

In order to understand what makes a transcritical CO_2 refrigeration system so different than an ammonia refrigeration system, we have to first understand the fundamentals of refrigeration cycle.

There are four basic processes that occur in a fundamental refrigeration cycle. It must be emphasized that the figures, as described, represent only the basic processes. Optimized refrigeration systems add numerous sub-processes based on numerous variables in order to maximize the efficiency and/or capacity of the system.

Compression – the process of pressurizing the refrigerant vapor to a significantly higher pressure and temperature after the refrigerant has been evaporated.

Condensation – the process of rejecting the heat from the compressed vapor to a heat sink, most typically the ambient. The heat that is being rejected is a combination of the heat “absorbed” by the evaporators and the heat created by the process of compression. This heat rejection condenses the refrigerant vapor to refrigerant liquid and is done, theoretically, without a change in pressure or temperature except at the very beginning of the process. This initial heat rejection is referred to as desuperheating. If heat rejection continues to occur after all of the vapor has condensed, the additional heat rejection is called subcooling.

Expansion – the process of dropping the high pressure/high temperature liquid from the condenser to a much lower pressure and temperature. The result of this process is a colder two-phase mixture of gas and liquid. Typically, the gas is sent back for recompression while the liquid is sent to the evaporators to do the actual refrigeration.

Evaporation – the process of transferring heat from the room or product into the liquid in the evaporators. As heat is added, the liquid evaporates. The resultant gas is usually sent back to the compressors.

How do these processes compare to ammonia refrigeration?

As noted, the fundamental refrigeration cycle remains the same for any vapor compression-based system. Different elements of the cycle may take on a somewhat different appearance or operate in a different domain. It is important to understand what makes the cycle different and how each process element ultimately affects the performance and reliability of the system.

Figures 2, 5, and 6 represent typical descriptions of the refrigeration cycles for ammonia and CO_2. Comparing each element of the respective refrigeration cycles, the reader will note that, in some cases, there is very little difference whereas in others, the difference can be quite significant as described in the following diagram.

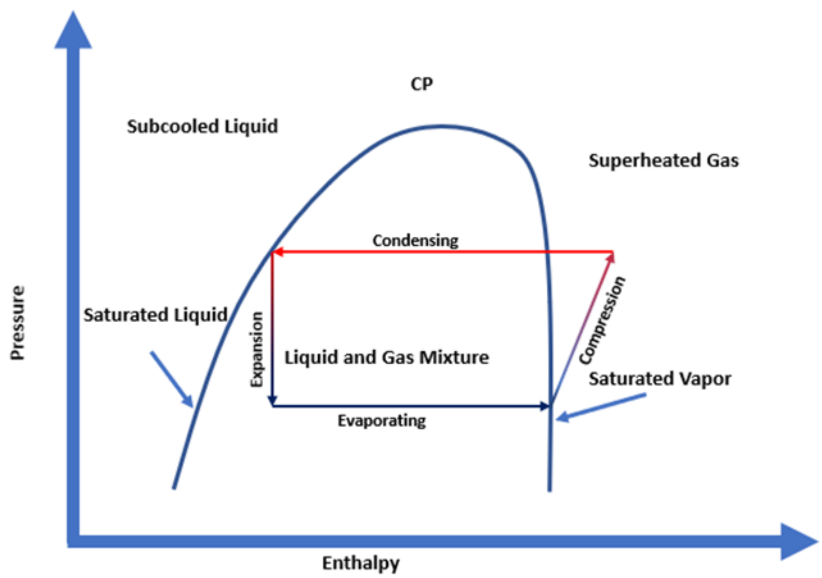


Figure 2: Refrigerant Pressure-Enthalpy Diagram with Basic Refrigeration Cycle

Compression

The general market perception of CO_2 compressors is that

- they are generally much smaller than typical industrial refrigeration ammonia compressors
- they have to be built with much higher-pressure ratings than those designed for ammonia
- they use a lot more power than ammonia compressors

- only reciprocating compressors are appropriate for the high-pressure application.

In general, there is an element of truth to all of the previous perceptions, however, much has changed or is changing.

They are smaller. Smaller can refer to capacity as well as physical size, and, in both cases, the word is appropriate. From a capacity perspective, the early modern-day interest in CO_2 started in the automotive and commercial markets. Refrigeration capacity requirements are far less demanding for commercial applications, and compressors for those applications have been scaled appropriately for many years. To date, the vast majority of industrial applications have focused on reciprocating compressors, 50 horsepower or less. However, several major manufacturers have begun to introduce higher horsepower into the market and a few others have announced their intentions to offer a much higher capacity screw compressor for larger industrial applications.

With respect to the actual physical size of the compressor, transcritical CO_2 compressors are smaller. Refrigerating capacity is directly related to the mass flow requirements for the application. However, a compressor is rated on the basis of volumetric flow. The volumetric flow requirement is a function of a refrigerant's heat capacity and density. CO_2 offers some interesting characteristics in this regard. Figure 3 compares volumetric flow rate requirements for a nominal small cold storage facility.

Another interesting *potential* dividend of the smaller compressors is that a typical cold storage facility using a transcritical CO_2 refrigeration system would use far more compressors than what would normally be present in an ammonia industrial refrigeration machine room. While many may view this increase in compressors as more maintenance, those facilities that operate at multiple temperature levels have an opportunity not typically seen in the industrial refrigeration facility. Most of today's industrial refrigeration facilities usually have two or three temperature levels. If the facility has more than two or three temperature levels, high pressure gas coming off of the higher temperature evaporators is "dumped" into low pressure suction lines for recompression. This leads to increased energy consumption as all of this lost pressure must be made up for in additional compression energy.

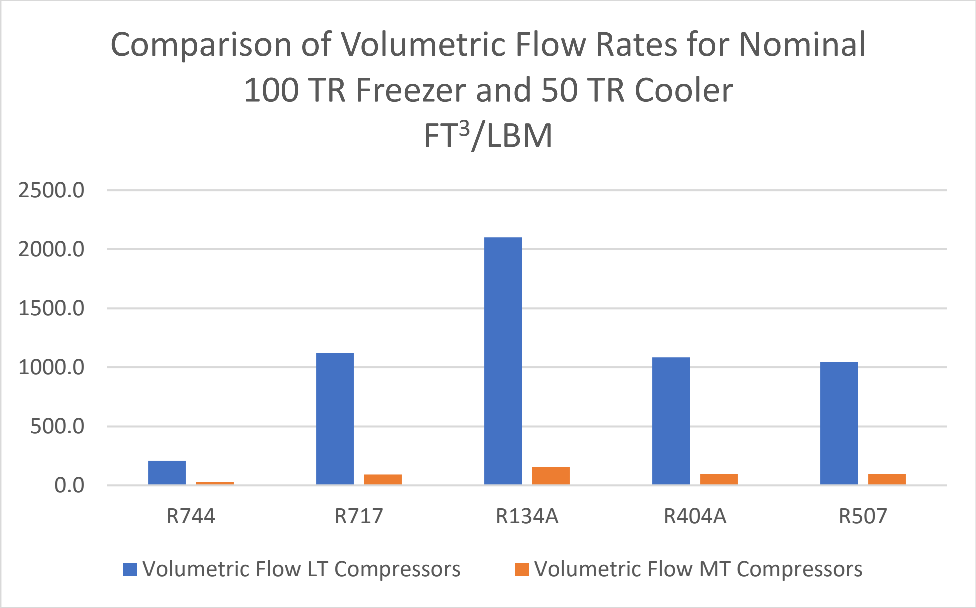


Figure 3: Comparison of Volumetric Flow Rates for CO2 and Other Common Industrial Refrigerants

While the difference between CO_2 and all of the other commonly used refrigerants is striking, the reader should note that the horsepower requirements are fairly similar between ammonia and CO_2. A side benefit which will be discussed later in this report are the significantly smaller pipe size requirements for CO_2 compared to ammonia.

They have higher pressure ratings. Without question, pressure ratings are significantly higher than the same for almost all other refrigerants. While the absolute values are significant (see Figure 4), they are really nothing out of the ordinary for most industrial applications. Interestingly, a positive element for CO_2 is the significantly reduced compression ratio as compared to ammonia and halocarbons. The low compression ratio and high pressure operation lead to higher volumetric and isentropic efficiencies [(2)] than for other refrigerants. Unfortunately, this good isentropic efficiency does not necessarily translate to a higher compressor COP as compared to ammonia, but it significantly reduces the gap.

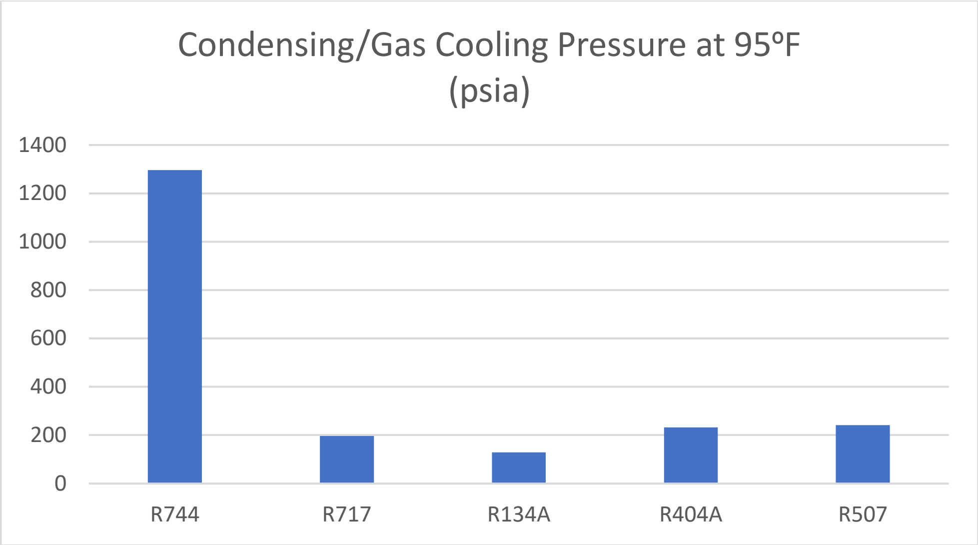


Figure 4: Comparison of High Side Pressures Among Typical Refrigerants

They use more power. In general, this perception stems from the difference in compressor COP when comparing one refrigerant to another. As shall be shown later in this report, the bottom line for all owners is the power bill, which is directly related to system COP not just compressor COP. CO_2 has the potential to make up a lot of ground once the entire system is taken into account and not just the compressor. Unfortunately, while compressor COP is fairly easy to simulate analytically, evaluating system COP is a much bigger challenge.

Only reciprocating compressors can be used in transcritical CO_2 systems. This has generally been true for the systems installed to date. However, in the future, one manufacturer has announced it will bring a high horsepower screw compressor to the market. How this will impact some of the other impressions about CO_2 compressors remains to be seen, but it takes a significant investment to create a machine capable of handling much higher pressures than it was originally designed to handle while, at the same, delivering high performance. It is very clear, that company leaders willing to make this kind of investment must believe there is a significant future for high pressure CO_2 compressors in the industrial refrigeration market.

Condensation and Gas Cooling

One of the basic principles behind the second law of thermodynamics is that heat flows in one direction only — from hot to cold. For that reason, when it is desired to remove heat from a high temperature gas, that gas must be at a higher temperature than the heat sink to which heat is transferred. As shall be discussed later in this report, this is an extremely important point in understanding one of the most fundamental challenges to the use of CO_2 as a refrigerant. Figure 4 is a duplicate of Figure 1, but with the fundamental refrigeration cycle added. The important point to note is that, in this example, the process takes place below the critical point. As a result, when heat is removed, the gas turns to liquid as it moves from right to left on the diagram. This is typical of most refrigerants and represents what one would expect for a single stage ammonia refrigeration system shown in Figure 5.

A transcritical CO_2 system, however could look considerably different as noted in Figure 6 where the cooling of the gas takes place above the critical point. Rejection of the heat in this region does not result in liquid formation. The process, however, can be optimized in terms of energy efficiency depending on the actual ambient temperature and the temperature of the two-phase mixture in the receiver.

Additionally, because the cold storage industry typically uses a large percentage of freezers in each facility, the basic cycle is normally modified for improved efficiency and capacity. In most cases, both refrigerants utilize a two-stage system (essentially two sets compressors: high stage for coolers and low or booster stage for freezers). Terminology sometimes varies as the two-stage ammonia system is called just that; whereas, the two-stage CO_2 system is often called a booster system. These two stage systems are noted in Figures 5 and 6.

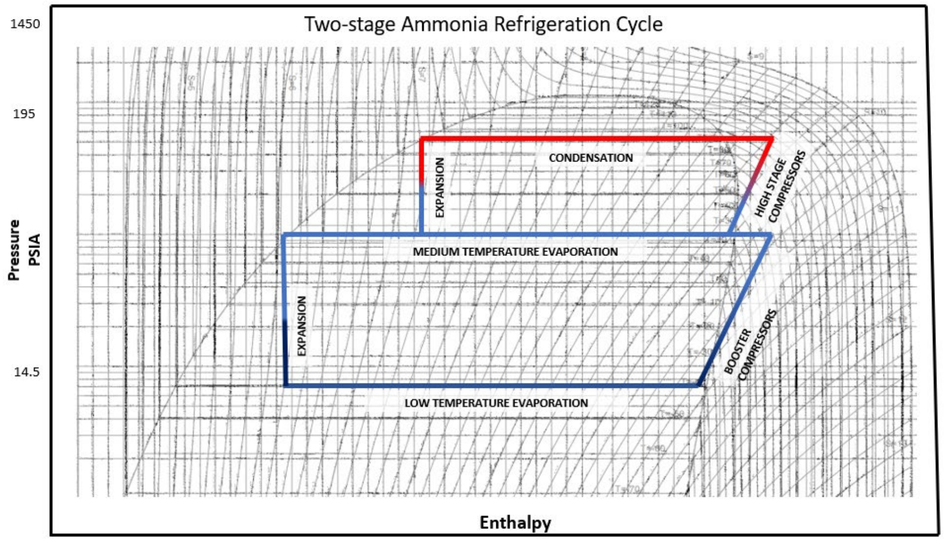


Figure 5: Two Stage Ammonia Refrigeration Cycle

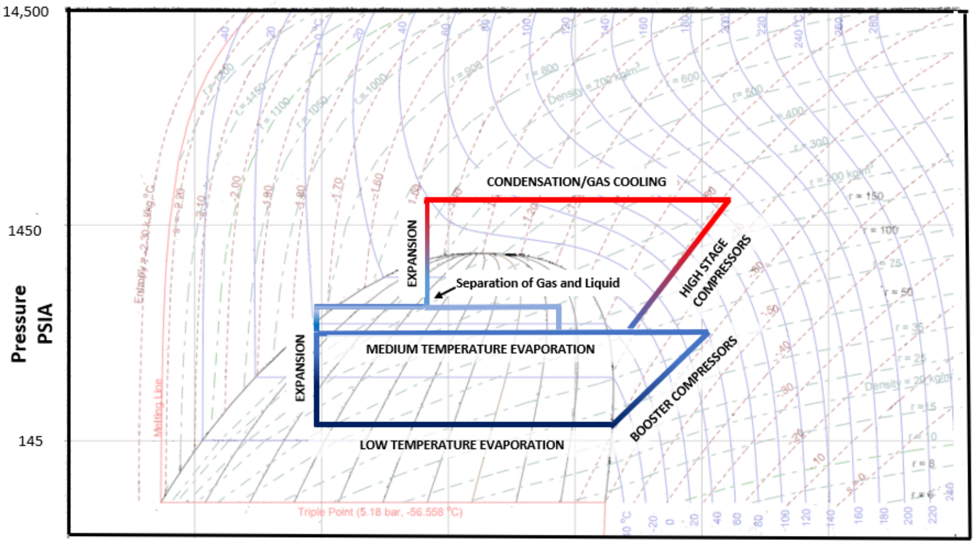


Figure 6: Transcritical CO_2 Booster System

What's important about the critical point?

The historical established design standard in the United States has long been a refrigerant condensing temperature of 95 degrees F. For an ammonia system and most halocarbon systems, this poses no unusual challenges as their critical point temperatures are well above 95 degrees F. For a CO_2 system, on the other hand, the critical point is approximately 88 degrees F. This, of course, poses two significant challenges.

1. If the system is expected to condense at 95 degrees F and the critical point is 88 degrees F, how can the vapor condense?
2. Furthermore, if the gas is cooled in the supercritical realm, what happens to system efficiency?

The first question was addressed earlier. The "gas" can still be cooled. The heat exchanger used to do this cooling is no longer called a condenser, but rather a gas cooler. It should be noted that in the supercritical realm, the fluid is often referred to as a gas but in reality it is neither a gas or a liquid.

The answer to the second question is a bit more interesting and necessitates the follow-on question, "Why is the standard condensing temperature 95 degrees F?" The short answer is, it keeps the analysis conservative and simple and usually represents a worst-case scenario for most climates in the United States and Canada. The bigger picture, however, shows that it also imposes a severe, generally undeserved, penalty on CO_2. In order to reject heat in a traditional tube and fin heat exchanger, common practice dictates that the temperature difference (TD) between the refrigerant and the air should be around 10 degrees F. This implies that the air should be at a temperature of 85 degrees F. And, while it is certainly true that the outside air can reach 85 degrees F, the real question is, "for how many hours a year?" For a large part of North America, this condition might exist for a few hundred hours or less each year. Fortunately, the tools now exist to perform a much more complete and accurate assessment of the performance of a transcritical CO_2 system for actual locations throughout North America and based on years of historical weather data. Additionally, as shall be discussed later, the technology exists to further reduce the number of hours of operation in the supercritical realm up to and including no hours at all.

As a final comment on the subject of condensing and gas cooling, it must be noted that, when compared to other typical refrigerants, there exists significant opportunity to utilize the waste heat for other uses in the facility or transform the transcritical CO_2 refrigeration system into a highly efficient heat pump system. The following are two properties of CO_2 that create this opportunity:

1. the relatively high mass flow of a CO_2 refrigeration system
2. higher compressor discharge temperatures.

It is not uncommon to see compressor discharge temperatures as high as 240 degrees F in transcritical CO_2 systems, whereas ammonia discharge temperatures are around 180 degrees F and in R-507 systems discharge temperatures can be as low as 150 degrees F. The high compressor discharge temperature of transcritical CO_2 systems allows for more sensible heat exchange (desuperheating) before condensation begins to occur. During condensation, heat is exchanged in an isothermal and isobaric process, referred to as latent heat transfer. The sensible heat reclaim in CO_2 systems can be as high as 70 percent, whereas in ammonia and R-507 sensible heat reclaim is only approximately 20–25 percent with remaining heat rejection/reclaim being a latent heat transfer process usually at a much lower temperature. This lower temperature limits the value of the reclaimed heat as it will only heat a secondary fluid to a temperature lower than its current temperature.

In facilities where there is a need for high-grade heat, a transcritical CO_2 system can be designed and optimized to reclaim more heat than the actual refrigerating effect, thus making a transcritical CO_2 system well suited for both heat reclaim and heat pump applications. The large sensible heat and high temperatures available enables the designer to fit the heat reclaim to various heating needs of the building or processes. At the high temperature end, 171 degrees F water could be generated for applications such as desiccant regeneration, boiler feedwater pre-heating, and wash-down water. At the mid-range temperatures, 95 degrees F to 131 degrees F fluid can be generated to provide domestic hot water heating and hydronic heating. At the low temperature end, 59 degrees F glycol/water can be generated for underfloor freezer heat and water pre-heating applications.

The sensible heat transfer process is best described by the equation:

$$\boldsymbol{Q = \dot{m} \cdot c_p \cdot \Delta T}$$

Where:

Q = heat exchanged, Btu/hr
$\dot{m}$ = mass flow rate, lb_m/hr

c_p = specific heat at constant pressure, Btu/(lb_m · °F)
ΔT = difference in temperature of the inlet and outlet of the heat exchanger, °F

From the previous equation, it is evident that the amount of heat exchanged is directly proportional to the mass flow rate and the temperature differences, whereas specific heat varies only slightly in most cases.

The mass flow rate of the refrigeration system is dependent on the latent heat of vaporization and system load. Table 1 compares the latent heat of vaporizations and mass flow rates of ammonia to CO_2 in a facility with a 100 TR Freezer and 50 TR Cooler application. The condensing pressure for the ammonia system is 195 pounds per square inch absolute (PSIA) and the gas cooler pressure for the CO_2 system is 1296 PSIA. The relatively low latent heat of vaporization of CO_2 requires nearly a five times larger mass flow rate as compared to ammonia. It should be noted, however, that the larger mass flow rate of CO_2 does not equate to an energy penalty of the same magnitude at the compressor due to the high-density of CO_2 previously discussed. This results in a relatively low volumetric flow as compared to ammonia and is shown in Figure 7.

Using the same 100 TR Freezer and 50 TR Cooler from the previous example, Tables 1 and 2 provide a tabular comparison of the inputs to the sensible heat equation and demonstrate that there is nearly 10 times more sensible heat available for heat reclaim opportunities.

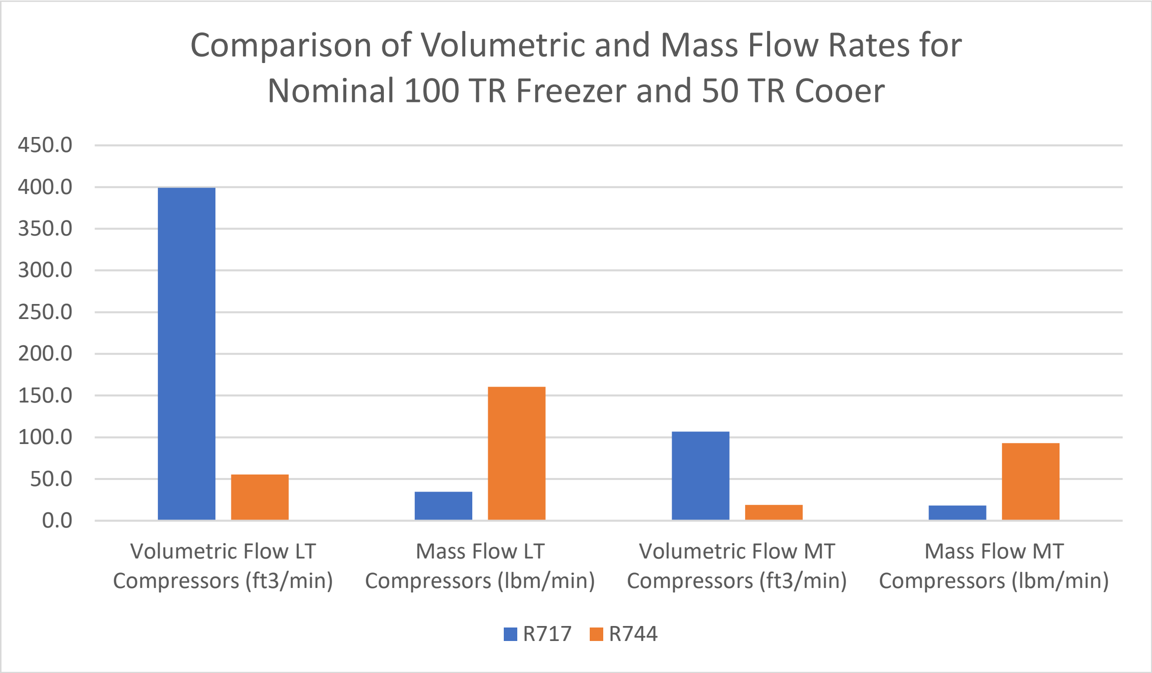


Figure 7: Comparison of Volumetric and Mass Flow Rates

Refrigerant	Evaporating Temperature	Latent Heat of Vaporization	Mass Flow Rate	To[illegible] NH3 Mass [illegible] Rate
	(°F)	(Btu/lbm)	(lbm/min)	(lbm/[illegible]
R-717	-10	576.28	34.71	52.[illegible]
R-717	20	553.01	18.08	
R-744	-10	124.64	160.46	
R-744	20	107.50	93.02	

Table 1: Ammonia and CO_2 Mass Flow Rates for 100 TR Freezer and 50TR Cooler

Refrigerant	Discharge Temperature	Outlet Temperature of Heat Recovery HX	ΔT	Specific Heat
	(°F)	(°F)	(°F)	(Btu/lbm·°F)
R-717	180	95	85	0.7183
R-744	240	95	145	0.8659

Table 2: Ammonia and CO_2 Sensible Heat Comparison

Expansion

As discussed previously, expansion is the process of taking high pressure, high temperature liquid and dropping/expanding the pressure to a much lower value which, in turn, also drops the temperature. The process also results in the formation of both liquid and gas.

Multiple Expansions – Unless the facility has only one temperature level, the refrigerant continues to undergo subsequent expansions to lower and lower temperatures. The initial expansion comes from the gas cooler. Additional expansions occur throughout the overall process, the number of which depends, typically, on the number of temperature levels. As with the initial expansion, each expansion results in a mixture of gas and liquid. The gas has little value refrigerating value but, in many cases, the pressure is still high enough to be put to good use as shall be shown later on. What happens to this gas depends on the configuration of the refrigeration system. The liquid, on the other hand, is the useful part of the process being directed to either an evaporator or to a further expansion.

From the gas cooler – as previously discussed, the nature of the refrigerant as it exits the gas cooler is a fluid which is not distinguishable as either a gas or a liquid. Because of this, the typical expansion valve is not suitable for the application.

Fortunately, a special valve was developed exclusively for this application and has proven to be extremely reliable in over a decade's worth of service. This initial step of expansion usually results in liquid cold enough to feed the cooler or dock evaporators. The gas is usually removed from the receiver and sent to a group of compressors or to a gas ejector.

Intermediate Expansions – Most cold storage facilities require a number of different temperature rooms and, as such, require intermediate expansion processes. It is technically possible to expand only once down to a very low temperature and use very cold liquid; however, there is a tremendous pressure penalty to be paid in the process. (One of the useful benefits of having multiple compressors is the ability to utilize dedicated suction pressures for each temperature level, thus resulting in energy savings.) In this case, the cold liquid from the previous process is expanded down to a lower temperature and pressure very similar to what is done in any traditional refrigeration system.

Overfeed or Direct Expansion – Most of the cold storage facilities constructed over the past five years in the United States and Canada have utilized direct expansion for the liquid feed to the evaporators. Many European companies are of the mindset that a minimal overfeed ratio is a better option. Low overfeed rates, theoretically, require smaller evaporators and require lower compression rates than direct expansion systems. Systems with direct expansion evaporators do not require a mechanical pump to fed the evaporators thus eliminating an energy consumer. This argument, at best, will take several years to settle and, perhaps, never be agreed upon by the world community.

Evaporation

In general, evaporation in a transcritical CO_2 system is fundamentally the same as in any other refrigeration system. However, because of the thermodynamic properties of CO_2, some interesting advantages are anticipated [2].

Heat Transfer Coefficients – While there has not been a great deal of work in the area of direct comparisons of heat transfer coefficients between ammonia and CO_2, most of the comparisons are made to that of R22 which, in turn, has been compared to ammonia. Taken by itself, the heat transfer coefficient of ammonia is significantly higher than for CO_2. However, as noted previously, the mass flux/pressure drop characteristics of CO_2 present some great opportunities. As noted by Nelson [10] and Visser et.al.[8], the steep curve of pressure drop versus temperature drop, means that CO_2 evaporators can tolerate much higher mass flows without sacrificing as much temperature drop. This allows for an evaporator design with fewer feeds and longer circuit lengths, typically resulting in similarly sized evaporators (CO_2 and NH_3). Additionally, it has been demonstrated that much lower recirculation rates [10] are required when compared to traditional ammonia recirculated liquid systems. This of course leads to lower pumping power. It has been suggested, but not adequately demonstrated yet, that CO_2 evaporators can be made smaller than an equivalently performing ammonia evaporator.

There are also a few caveats associated with the use CO_2 that are worth noting:

- **Water** in any refrigeration system is a detriment to the system performance in that it depresses the *actual* evaporation temperature, which leads to higher energy consumption. In a CO_2 system, it is especially critical to take the proper steps to remove water prior to entering the low temperature region. A second more insidious problem is related to the water solubility in CO_2. As shown in Figure 8, the water solubility is very low at temperatures below 0 degrees F. The end result of high water concentration at low temperatures is the formation of ice crystals which can lead to blockage in control valves and strainers. The solution, however, is relatively straightforward and simply involves the installation and maintenance of the appropriate filter/drier.

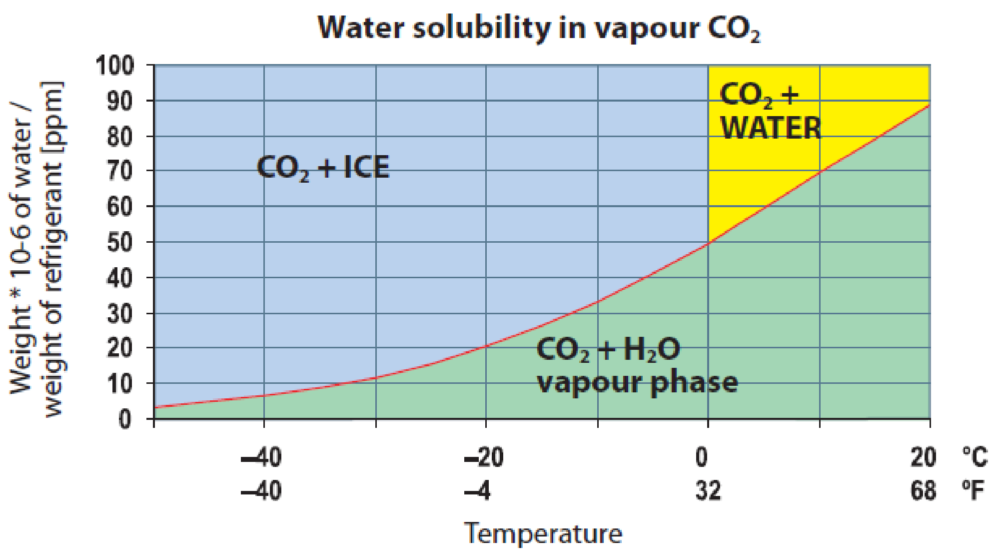


Figure 8: Water Solubility in CO2 as a Function of Temperature (4)

- **Oil** in a transcritical CO_2 system must be treated differently than the oil in an ammonia system. Excessive oil in an evaporator can seriously degrade the heat transfer coefficient, thereby reducing the overall performance of the evaporator. It can also impede flow through the strainer as it tends to solidify at low temperatures. It is recommended that a device such as an oil still be installed to remove oil before it travels to the low side of the system.

Oil can also have other detrimental effects on the refrigeration system, not the least of which is the compressor. The primary reason behind this is the miscibility or lack thereof between the oil and the CO_2. Areas of interest studied during the run tests include

- viscosity at various temperatures along with the viscosity index
- water content

- total acid number
- density
- metal content.

There are a number of different oils which have been used in transcritical CO_2 reciprocating compressor applications. Table 3 represents a summarizing comparison of the leading oil candidates:

	Advantages	Disadvantages
PAO	Experiences with CO_2 compression Compatible with CO_2 and NH_3	Immiscible Oil return concern Heat transfer concern
AN	Compatible with CO_2 and NH_3 Partial miscibility with CO_2 Limited solubility with CO_2	Limited experience
POE	Very miscible with CO_2 Flexible chemistry	Hydrolysis potential High dilution Incompatible with NH_3
PAG	Compatible with CO_2 and NH_3 Flexible chemistry Controlled solubility with CO_2	Oil return issues
AN/PAG	Compatible with CO_2 and NH_3 Partial miscibility with CO_2 Limited solubility with CO_2	Limited experience

Table 3: Advantages and Disadvantage of Various Lubricant Chemistries with CO_2 Refrigerant [5]

The authors of the technical report conclude that the alkyl naphthalene (AN) lubricant offered the best combination of desirable characteristics and their limited testing confirmed good results. It was suggested, however, that more testing on all lubricants was necessary in order to draw hard conclusions. Most of the recent systems installed in North American cold storage facilities have utilized the POE lubricant. Key to successful, long term operation are annual oil sample analyses from the compressors and use of high efficiency oil separators.

- **Defrost** – As noted early on in this report, most of the early transcritical CO_2 systems have been for commercial and supermarket applications. There has been a long history of electric defrost in these markets. The industrial market seems to be overwhelming insistent on doing defrost with hot gas. The requirements are a bit more demanding, but the die seems to have been cast: if it's industrial, it's probably going to be a hot gas defrost system.

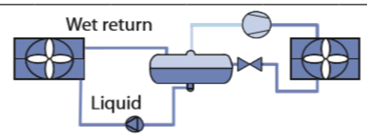
In summary, evaporator designs for CO_2 systems and ammonia systems appear to be very similar in size. Clearly, changes will be required due to the nature of the mass flow and higher pressure of CO_2 when compared to ammonia but, to date, there have been no reports of any significant issues in designing nor manufacturing an evaporator coil for CO_2 service.

Exceptional Characteristics of Transcritical CO_2 Systems

While there are certain characteristics of transcritical CO_2 systems that require special considerations, there also are those that separate them in a positive way from other refrigerants. It is appropriate to point out these exceptional characteristics, however, it should be noted that the following list does not imply that these benefits do not exist with other refrigerants. They typically do not offer the same level of benefit as a transcritical CO_2 system:

- The benefits of a refrigerant that has no flammability or toxicity is readily apparent. It is of note that because of its density, there always is a remote danger of asphyxiation in the event of a major leak into a confined space. CO_2 sensors are therefore a requirement in most facilities; however, in most systems installed over the past decade, an entire charge could be released into a room without fear of exceeding the threshold PPM limit.
- In addition to its minimal dangers to life and product, CO_2 has no ozone depletion potential (ODP) and minimal global warming potential (GWP). This, of course, makes it far less likely to be the subject of future environmental legislation.
- The densities of CO_2 are such that pipe sizes (especially the larger suction lines) are, generally, a fraction of what they would be with any other refrigerant as shown in Figure 9.

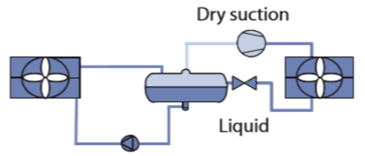
Comparison of pipe cross section area
Wet return / Liquid lines



	Refrigerant			R 134a		R 717		CO_2	
	Capacity	kW	[TR]	250	[71]	250	[71]	250	[71]
"Wet return" line	ΔT	K	[F]	0.8	[1.4]	0.8	[1.4]	0.8	[1.4]
	Δp	bar	[psi]	0.0212	[0.308]	0.0303	[0.439]	0.2930	[4.249]
	Velocity	m/s	[ft/s]	11.0	[36.2]	20.2	[66.2]	8.2	[26.9]
	Diameter	mm	[inch]	215	[8.5]	133	[5.2]	69	[2.7]
	"Wet return" area	mm²	[inch²]	36385	[56.40]	13894	[21.54]	3774	[5.85]
"Liquid" line	Velocity	m/s	[ft/s]	0.8	[2.6]	0.8	[2.6]	0.8	[2.6]
	Diameter	mm	[inch]	61	[2.4]	36	[1.4]	58	[2.3]
	"Liquid" area	mm²	[inch²]	2968	[4.6]	998	[1.55]	2609	[4.04]
Total pipe cross section area	"Wet return" + "liquid" area	mm²	[inch²]	39353	[61.0]	14892	[23.08]	6382	[9.89]
Liquid cross section area		%		8		7		41	

L_{eqv} = 50 [m] / 194 [ft] - Pump circ.: n_{circ} = 3 - Evaporating temp.: TE = –40[°C] / –40[°F]

Comparison of pipe cross section area
Dry suction / Liquid lines



	Refrigerant			R 134a		R 717		CO_2	
	Capacity	kW	[TR]	250	[71]	250	[71]	250	[71]
"Dry suction" line	ΔT	K	[F]	0.8	[1.4]	0.8	[1.4]	0.8	[1.4]
	Δp	bar	[psi]	0.0212	[0.308]	0.0303	[0.439]	0.2930	[4.249]
	Velocity	m/s	[ft/s]	20.4	[67]	37.5	[123]	15.4	[51]
	Diameter	mm	[inch]	168	[6.6]	102	[4.0]	53	[2.1]
	"Dry suction" area	mm^2	[$inch^2$]	22134	[34.31]	8097	[12.55]	2242	[3.48]
"Liquid" line	Velocity	m/s	[ft/s]	0.8	[2.6]	0.8	[2.6]	0.8	[2.6]
	Diameter	mm	[inch]	37	[1.5]	21	[0.8]	35	[1.4]
	"Liquid" area	mm^2	[$inch^2$]	1089	[1.69]	353	[0.55]	975	[1.51]
Total pipe cross section area	"Dry suction + liquid" area	mm^2	[$inch^2$]	23223	[36.00]	8450	[13.10]	3217	[4.99]
Liquid cross section area		%		5		4		30	

L_{eqv} = 50 [m] / 194 [ft] - Evaporating temp.: TE = –40[°C] / –40[°F] - Condensing temp.: TE = –15[°C] / –5[°F]

Figure 9: Comparison of Line Sizes for Various Refrigerants in an Equivalent Refrigeration System (4)

- Available heat – As noted previously, there is great potential for the waste heat created through the compression process. The reader may be surprised to find that there are more uses for the high-grade heat than thought possible with other refrigeration systems.
- Materials compatibility – Taken as a whole, the properties of CO_2 lend themselves to a high degree of compatibility with a large range of materials including most metallic materials. Proper care must be taken with various polymers used for sealing, not because of chemical incompatibility but rather physiochemical effects. These can take the form of permeation, swelling, and cavities and internal fractures (13). The effects are the result of solubility and diffusivity in certain materials.
- Product compatibility – Perhaps one of the biggest attributes of CO_2 is its impact, or better said, lack of impact on products stored in a facility. Aside from the remote possibility of asphyxiation due to oxygen displacement, CO_2 poses virtually no risk to any products in a cold storage warehouse.

Technological Advancements

Over the past decade, the interest in using CO_2 as a refrigerant in both commercial and industrial refrigeration applications has grown rapidly. Not surprising, this interest has spurred a great deal of research and development in both the areas of improving the basic refrigeration cycle and the components that are utilized in these cycles. Most of the improvements, to date, have been focused on the commercial/supermarket applications but there has been increasing activity in either developing new products for the industrial sector or scaling up those components that have already been proven for the commercial sector. Following are the highlights of some of these efforts with particular emphasis on the high pressure side of the refrigeration cycle.

Adiabatic Coolers

As discussed previously, gas cooling has typically been performed using air cooled heat exchangers similar in design in air cooled condensers. Air cooled gas cooling is performed when the system is operating in the supercritical realm. This equates to higher energy consumption. Over the past few years, the industrial refrigeration market has seen a marked increased in the use of adiabatic coolers. As shall be shown below, the use of an adiabatic cooler allows for increased hours of sub-critical operation in most geographical regions of North America. Moving from supercritical mode (sensible cooling) to subcritical mode (latent cooling) lowers the energy consumption of the system.

Adiabatic gas coolers utilize direct evaporative air cooling to pre-cool dry air entering the gas coolers by "trading" dry bulb temperature with wet bulb temperature. Water is circulated over absorbent corrugated media often referred to as adiabatic pads, placed at the air inlet to the gas cooler in front of the heat exchanger. As dry ambient air is drawn through the adiabatic pads, the dry air evaporates the absorbed water from the adiabatic pads and the dry bulb temperature of the air drops. However, the total heat content of the air has not changed – the air has simply "traded" dry bulb temperature with wet bulb temperature. The term adiabatic simply means that no heat transfer occurs in this process. For the gas cooler, all that matters is the temperature that the outside surface of the coil sees; in this case, a temperature lower than the critical point allowing for subcritical operation and, more importantly, latent heat transfer. Figure 9 shows a diagram of an adiabatic gas cooler/condenser.

The following provides an example of the adiabatic cooling process during extreme design day conditions. The ASHRAE 0.4 percent Cooling Design Day for Washington, D.C. is 94.5°F dry-bulb (DB) and 75.7°F mean co-incident wet-bulb (MCWB). Typical Adiabatic Pad saturation efficiency is 70 percent to more than 95 percent dependent on the adiabatic pad thickness, entering air velocity, and the adiabatic pad corrugation geometry. The temperature of the air after passing through the pads is defined as,

$$t_{DB,exiting} = t_{DB,ambient} - \frac{saturation\ efficiency}{100} \times \left(t_{DB,ambient} - t_{WB,MCWB}\right)$$

Saturation Efficiency (%)	$T_{DB, exiting}$ (°F)
70	81.3
80	79.5
90	77.6
95	76.6

Table 4: Dry Bulb Temperature of the Air after Passing Through the Adiabatic Pads with an Entering Dry Bulb Temperature of 94.5 degrees F

As Table 4 shows, even at the lowest typical Saturation Efficiency of 70 percent, 81.3 degrees F air will be entering the gas cooler heat exchanger. With the gas cooler sized for a 10 degrees F TD, the CO_2 outlet temperature of the gas cooler/condenser will be 91.3 degrees F. As shown in Figure 10, what has effectively taken place is the creation of a lower temperature heat sink (the cooler moist air) allowing the CO_2 to condense isothermally. Having used 0.4 percent ASHRAE data, 99.6 percent hours of the year the CO_2 gas cooler outlet temperature will be at or below 91.3 degrees F or conversely the outlet temperature will be above 91.3 degrees F for only 35.04 hours of the year. This allows for operating in the subcritical realm for the majority of the year, resulting in significant energy savings.

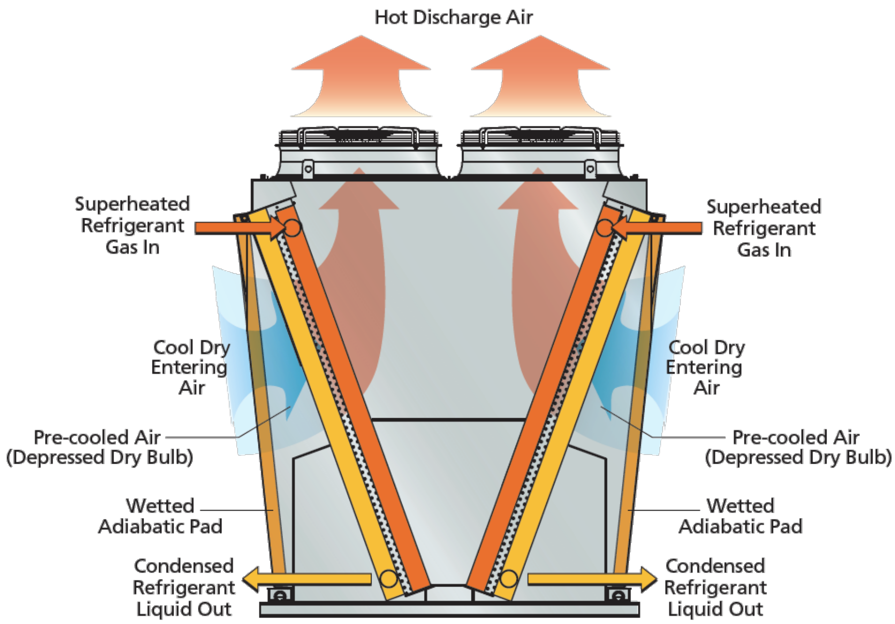


Figure 9: Diagram of an Adiabatic Gas Cooler/Condenser (3)

Figures 11, 12, and 13 pictorially describe the regions of the United States most dramatically impacted by the use of adiabatic cooling. The reader will note that all those in the United States will benefit through the use of adiabatic coolers. Some regions of the country should never have to operate in the supercritical region with the use of adiabatic coolers. High dry bulb temperatures have only an indirect impact on cooling when adiabatic coolers are employed whereas high wet-bulb temperatures limit the effectiveness of adiabatic cooling.

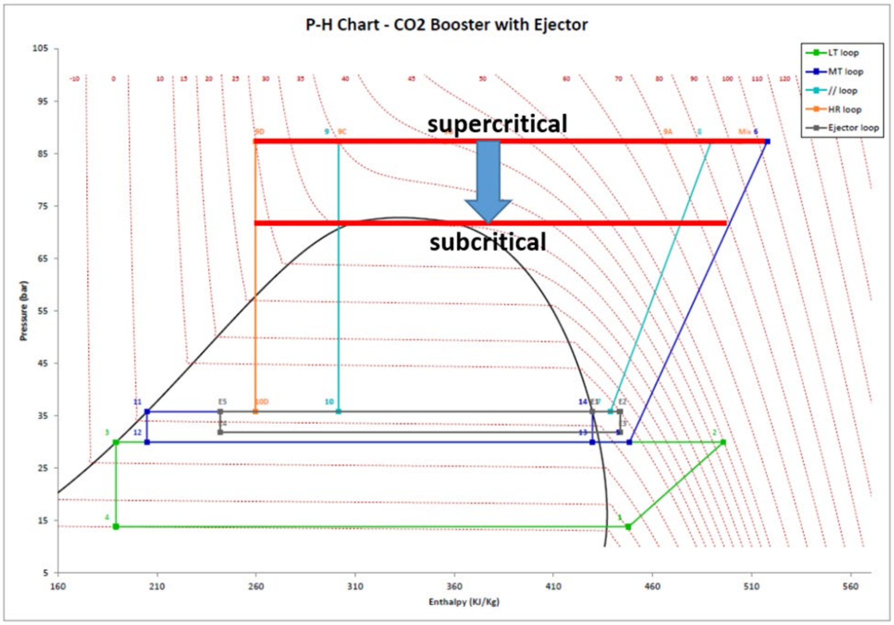


Figure 10: Impact of Adiabatic Cooling (11)

Figure 11: Regions of North America Requiring Super-Critical Operation More Than 2 percent of the ASHRAE Operating Hours Per Year When No Adiabatic Cooling is Employed ( )

Figure 12: Regions of North America With No Hours in a Year of Supercritical Operation When Using Adiabatic Coolers ( )

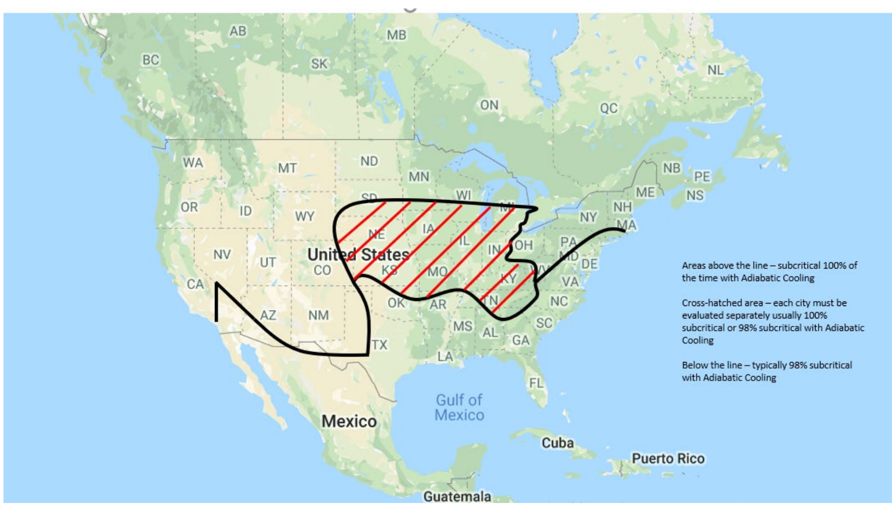


Figure 13: Effectiveness of Adiabatic Cooling in the Continental United States

Energy Recovery – High Pressure Gas

In most central ammonia systems today, the overall design of the facility utilizes a two-stage system. What this basically means is that low temperature evaporators send low temperature gas to a booster or low stage compressor. Once compressed, that gas is sent to a high stage compressor, which is then further compressed before entering the condenser. Because the typical transcritical CO_2 refrigeration system utilizes many small compressors, it is not generally cost prohibitive to put a device into the system that will take the high pressure gas off of the flash tank to generate a higher pressure gas which is then sent back to the gas cooler. Today, there are two devices that make this possible: a parallel compressor or an ejector. The reader should note that the following is a very simplified explanation as to how these devices work. There are a number of creative variations being utilized today, all of which lead to an overall increase in the system COP by reducing the compression ratio for, at least part of the total mass flow.

Parallel Compression

A transcritical CO_2 refrigeration system utilizing parallel compression adds one or two compressors per rack that are dedicated to compressing the gas in the flash tank. The fundamental concept behind the parallel compressor(s) is to reduce the compression ratio for some portion of the total suction gas required to be compressed in the high stage compressors. Figure 14 shows one version of a transcritical CO_2 system with one parallel compressor. In this particular configuration, a heat exchanger is also added in order to subcool the fluid coming off of the gas cooler while superheating the gas going to the parallel compressor:

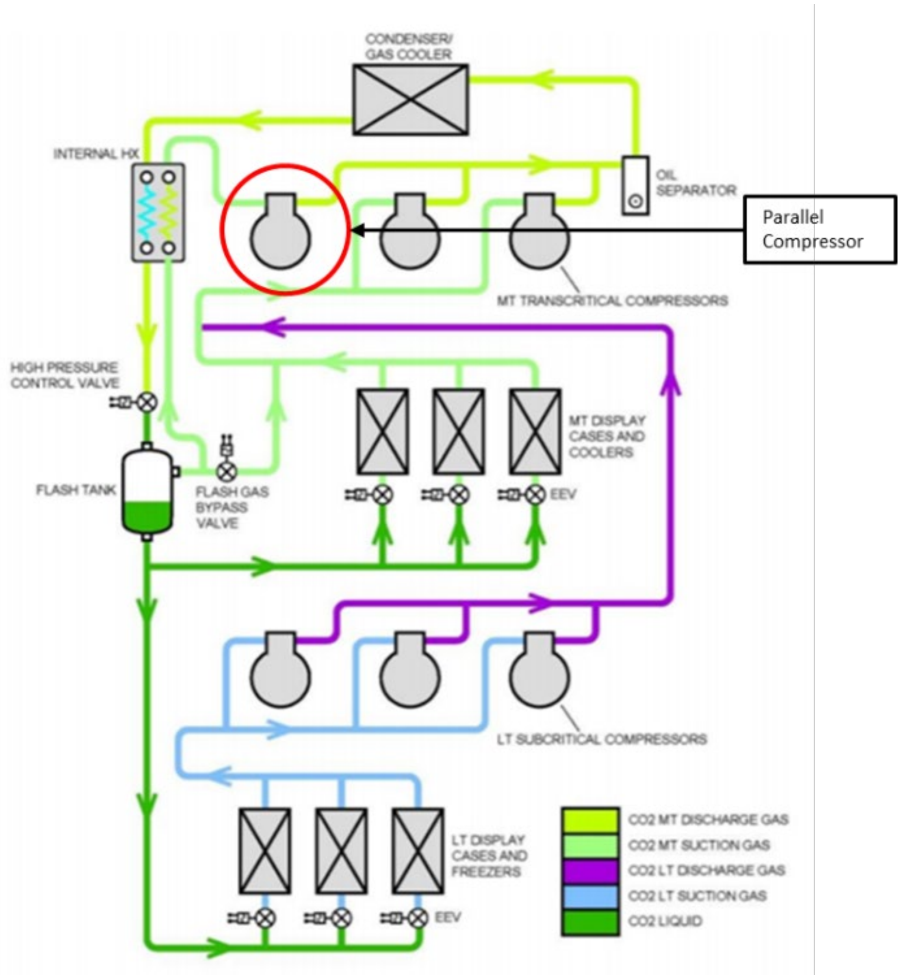


Figure 14: Two-Stage Transcritical CO_2 Refrigeration System With Parallel Compression(6)

The manufacturer ran computer simulations as well as conducted performance studies with both parallel compression and ejectors. In the case of parallel compression alone, it has been suggested that the overall energy consumption of the system could be reduced by 5 percent to 7 percent annually.

Ejectors

The basic concept behind ejector technology involves a process of taking the high pressure gas off of the flash tank and sending it through a flow nozzle, which increases the velocity of the gas while reducing the static pressure. Lower pressure gas (usually from the suction side of an evaporator) is then drawn into the throat of the nozzle as shown in Figure 15. Once the two flows have mixed, the mixture is sent into a diffuser that reduces the velocity while increasing the static pressure. One of the more challenging aspects of using an ejector is the need to control mass flow through the ejector at varying operating conditions. Two companies have come up with their own concepts of accomplishing this objective.

The same company that did the testing on the system with parallel compression also did similar testing on a system with ejectors and parallel compression. The results demonstrated a 6.5 percent to 11 percent improvement in energy consumption.

At the time of this report, ejectors have been of relatively low capacity. One company, however, is developing a high capacity ejector that should be in field testing before the end of 2019.

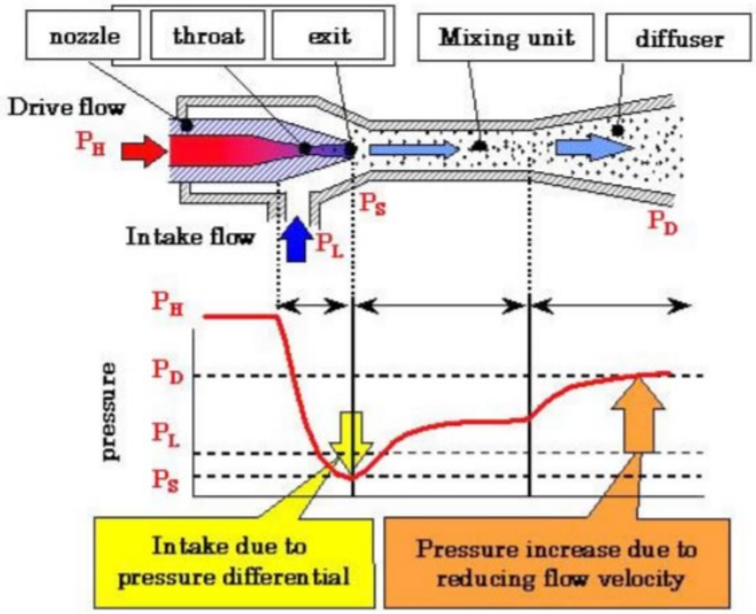


Figure 15: Cross Section of a Simple Ejector [7]

Controls

Last but certainly not least is the control system. Integrated with temperature and pressure sensors, motorized valves, and variable frequency drives, a state-of-the-art control system should have the ability to make timely responses as to how a facility operates at any given moment, saving energy and minimizing substantial transient swings without risk to people or product safety.

In any central refrigeration system, the controls and control algorithms are vital elements to good facility performance. As one might expect, the control system plays an even larger role in determining the overall efficiency of a transcritical CO_2 refrigeration system. Many of the devices and processes which can be controlled have already been documented in this white paper. A well-designed transcritical CO_2 system would likely utilize numerous devices and techniques described here. These processes and devices must work harmoniously in order to obtain optimum performance. Some of the devices or operating parameters that would be controlled include:

- Discharge pressure (when in the supercritical region)

- Mass flow to parallel compressor(s)
- Mass flow to ejector(s)
- High pressure control valve (from gas cooler)
- Mass flow to subcooler
- Flash gas bypass valve
- Heat recovery devices (not covered in this report)
- Variable frequency drives, fans and compressors
- Gas cooler control as a function of outdoor ambient temperatures (dry bulb and wet bulb)
- Water control for adiabatic gas coolers.

Gas Cooler Pressure Control

When it comes to most refrigerants that always operate in the subcritical realm, compressor COP increases as discharge pressure decreases. In the case of a transcritical CO_2 system, however, the decision regarding discharge pressure is more complex. In general, this is due to the fact that the heat rejection temperature is independent of the heat rejection pressure in the supercritical realm. It has been demonstrated that the optimum discharge pressure is a function of the outlet temperature of the gas cooler, the evaporator temperature, and the isentropic compressor efficiency. Clearly, the control system and its algorithms must be sophisticated in terms of maximizing energy efficiency.

A well designed and tuned control system is an important element in any refrigeration system when it comes to managing system performance, safety, and energy costs. It is seen as an even more important element when it comes to transcritical CO_2 refrigeration systems.

While there are many other variations on the basic transcritical CO_2 refrigeration cycle that may offer improvements in overall performance, it is beyond the scope of this white paper to document all of them. The important takeaway in this discussion is that there are numerous companies all around the world investing significantly in developing new technologies directed at bringing the technology into the mainstream of industrial refrigeration. The same can be said of numerous academic institutions. CO_2 refrigeration “went to sleep” for nearly a century but has been revived as the world seeks an answer to the problem of climate change and the regulatory pressures that surround it.

Total Cost of Ownership (TCO) – What we know today

The integration of transcritical refrigeration systems in the cold storage industry is still early. Consequently, there is not a great deal of information available to compare one system versus another. However, over the past several years, a number of transcritical CO_2 facilities have been commissioned and functioning per expectations today. These facilities not only have provided the industry with sound fundamental information on key parameters but have also provided us with unusually reputable comparisons to other refrigeration systems operating under similar conditions.

Cost Elements

When comparing a transcritical CO_2 refrigeration system to an alternative (packaged, central "stick built," cascade, etc.) the evaluator needs to look at all of the different elements which go into the TCO. How each element gets weighted in the analysis will depend on the owner's financial priorities.

- **Building** – The physical structure that will house the refrigeration system can play a significant role in the decision-making process. Land values, construction costs, and requirements for revenue generating space all come into play:
  - Is there a need for a separate machine room and, if so, how much space is required for that room?
  - Are there external packaged systems which will be mounted on a roof and, if so, how much extra structural support is required to support those packages?
  - What is the nature of the piping system located between the "central plant" and the evaporators (size and length)?
  - What costs need to be built in due to the uncertainties of construction (weather, local labor, etc)?
- **Equipment** – Today's components for transcritical CO_2 systems have primarily evolved from the commercial refrigeration sectors. As a general rule and when compared to central ammonia systems, compressors are lower horsepower, gas coolers are used in place of evaporative condensers, and valves are continuing to evolve in order to meet the size and pressure requirements of today's industrial requirements for CO_2 systems. Some of the factors that influence an apparent trend towards lower priced equipment include:
  - Commodity components – While it is still early in the market transformation, many of the components used in transcritical CO_2 system racks are mass produced. This may manifest itself as cost savings for a large number of components as a result of the economies of scale.
  - Factory built – Over the past two decades, more effort has been devoted to pre-fabrication of subassemblies in a controlled environment shop. Contractors quickly discovered that they could control numerous variables that they previously had to just "hope" for the best outcome. A natural extension of this effort led to the development of low charge ammonia packaged systems and much of

the same philosophy has been incorporated into the fabrication of CO_2 "rack" systems.

- Piping Costs
  - Materials – Which materials are compatible with the refrigerant in question? Piping for ammonia systems has a limited number of options when it comes to compatible materials as compared to CO_2 systems. Additionally, the methods of pipe joining, as will be noted, provide a number of options.
  - Diameters – As noted under the section "Exceptional characteristics of transcritical CO_2," pipe diameters (especially in traditionally large suction lines) are significantly smaller for transcritical CO_2 systems. Aside from the obvious savings in basic material, smaller pipe also provides a means of simplifying material handling requirements.
  - Tube versus pipe – It has been demonstrated that tubing is (copper or stainless) are well suited for transcritical CO_2 systems as long as it meets the temperature and pressure requirements. This has the potential, not only, for basic material cost savings but labor savings as well in that elbows can often be replaced by tube bends.

- **Installation**
  - Piping support structures – Continuing with the previous discussion on pipe size, the diameter and weight of the pipe place transcritical CO_2 systems in a very favorable position when it comes to the supporting structure for that pipe or tube. Fewer and lighter pipe stands and hangers reduce installation costs.
  - Insulation practices – Insulation continues to be a necessity; however, smaller pipe diameters reduce the cost of insulation. The fact that the majority of new installations are utilizing stainless steel tubing reduces the amount of prep work required for the insulation.
  - Time requirements – The owner/GC should evaluate what the impact of the system type will be on the overall time requirements of the project. This evaluation should include actual construction time as well as lead-time for equipment.
  - Laydown requirements – While it may not seem like a significant variable, the cost of installation is influenced by the physical space requirements of on-site equipment. This, not only, includes the impact of that physical space but also the logistics of moving people and equipment around the space occupied by that equipment.
  - Pipe joining requirements – Traditionally, central ammonia systems have been constructed of carbon steel piping joined by either stick or

MIG welding. As material costs have changed and mechanical integrity requirements have tightened, there has been a trend towards stainless steel piping joined by TIG welding. TIG welders are, generally speaking, not abundant in the industry and while many view this as a superior welding process, the costs have increased. The use of stainless steel tube in many sites has not lessened the joining requirements but the use of orbital welders has proven to provide a high quality reliable joint. Others have used high strength copper alloys joined together by brazing. This is a third reliable approach to pipe/tube joining.

- Material handling requirements – In an effort to provide a factory built high quality product, many contractors have turned to pre-fabrication of subassemblies in their shops. This certainly reduces the number of variables in the field but also increases the importance of proper material handling equipment and techniques. The same can be said for siting the CO_2 rack package and gas cooler. However, the difference here is the size of the piping and the diminished need for specialized material handling.

- **Energy**

Energy consumption is one of the highest ongoing costs in the world of cold storage. This cost has many variables associated with it: climate zone, facility construction, insulation, utility rate structures, etc. It is important to understand that the cost of energy is only partially a function of compressor COP and the owner would be wise to understand all of the costs that comprise the monthly utility bill.

- Steady state performance – This is probably one of the easiest analytical assessments to make in comparing different systems; however, depending on the amount of detail evaluated, provides only a partial picture of the true cost of energy. As shall be noted below, there are many other factors which, depending on the design of the system, can be either a further detriment to energy efficiency or provide a positive attribute.
- Defrost – Defrost is always an energy consumer. How big of a factor it is, however, depends on a number of elements.
    - Source of hot gas/disposition of hot gas condensate – Generally, the hot gas used for defrost comes from the compressor discharge or the saturated vapor off of the high pressure receiver (HPR) [12] . Saturated vapor poses a challenge because it is the act of condensing the gas that provides the heat to melt the ice on the coil. If the gas starts to condense before it reaches the evaporator, it will lose its effectiveness. Therefore, the hot gas is often a combination of compressor discharge gas and gas taken

off of the HPR. In the case of transcritical CO_2 systems, the gas is typically taken off of the compressor discharge.

The big difference in the two systems, however, is what happens to the gas/liquid refrigerant once it leaves the evaporator. In the case of ammonia and synthetic refrigerants, the mixture is usually dumped into the medium or low temperature suction lines after which it must be recompressed. In the case of transcritical CO_2 systems, the condensed refrigerant from the medium temperature evaporators can be directed to the flash tank, following the same path as if the gas had gone through the gas cooler. For this reason, the claim has been made that there is no compressor penalty with CO_2. What enables all of this is the high pressure of the CO_2 as compared to other refrigerants. What can be seen as a disadvantage by some turns out to be an advantage in the case of defrost.

- Frequency of defrost – The number of times an evaporator must be defrosted is obviously directly related to the overall system efficiency and energy consumption. There are many factors that contribute to the number of defrost cycles and evaporator coil must go through on a daily or weekly basis. While there may be a correlation between the ultimate number of cycles and the type of refrigerant used, there is no obvious advantage between one or the other.

- Waste heat recovery – As noted previously in this report, the potential for high grade waste heat recovery is quite high for CO_2. In evaluating different types of systems, the owner should explore all of the possibilities of taking advantage of the "BTU's" available for heating purposes.
- Matching compressor compression ratios with temperature levels – A subject alluded to earlier is the potential for matching multiple temperature levels in a cold storage facility to the compressors on the rack. This is not something that is readily available in most central facilities.

- **Maintenance**

Maintenance is an ongoing, thankless activity in the operation of a cold storage facility, and it has a number of different implications when it comes to the type of refrigeration system chosen for the operation. The most obvious implication is the cost of routine and periodic maintenance activities. It not only involves the actual activities but also the personnel requirements associated with those activities. Does the refrigeration system require technical skills above and beyond what would normally be expected for a similar facility. A second and perhaps even more important implication is the downtime associated with unscheduled maintenance. Disruptions in the operation of the facility as a result of routine scheduled maintenance can usually be minimized or, at the very least, planned for. Physical equipment breakdowns, on the other hand, can create a host of additional complications that must be considered when making a decision. The following is a partial list of some of the higher-level considerations an owner must go through when determining what type of system works best in the facility:

- Are there special skills or special equipment requirements?
- What are the implications of a major piece of equipment breaking down?
- What type of oil management requirements exist?
- How often and how extensive are the compressor overhauls?
- How often do shaft seals need to be overhauled?
- What are the mechanical integrity issues and requirements in terms of Inspections, repairs, and replacements?
- Are non-condensables a consideration? Although any refrigeration system can be plagued with the presence of non-condensable gases, those that operate under vacuum conditions are much more susceptible. Transcritical CO_2 systems always operate under positive pressure and usually do not have open drive compressors. The opportunities for gas migration into the system are, therefore, much more remote and less of a concern.
- What type of water management (water in the refrigeration system) requirements exist? Water can be present in both ammonia refrigeration as well as transcritical CO_2 refrigeration. In an ammonia system, it is removed through the use of an anhydrator. In a CO_2 system, filter/driers are employed as a means of water removal. Just as in the case of non-condensables, the opportunity for moisture to migrate into a transcritical CO_2 refrigeration system are less likely than for a system which operates in a vacuum.

Before choosing a system, the owner should research these questions in terms of the type of system, the reputations of the installing contractors, and testimonials from others who have installed the different types of systems.

- **Water, Sewer, Chemical Treatment**

The end-user community has experienced the pains of regulatory compliance associated with ammonia and PSM or RMP for the past decade. Water, water treatment disposal, and chemical use are not far behind in terms of significant and ongoing expenditures in the daily operation of a cold storage facility.

Most ammonia facilities utilize evaporative condensers that pay a price for all three elements listed above. Today, to the authors' best knowledge, there are no evaporative condensers for transcritical operation. High side heat rejection is accomplished through a dry gas cooler or an adiabatic gas cooler. Water is still a commodity for adiabatic coolers but to a much lesser extent than evaporative condensers. From a practical perspective, there are no sewer or chemical treatment elements.

- **Regulatory Compliance**

In any industrial facility, there will always be some form of regulatory auspices in order to ensure a safe working environment. The elements that have led to the requirement of a formal PSM system are not present with CO_2. This is primarily driven by the classification of CO_2 refrigerant as an A1 refrigerant. While it can never be said with certainty as to how the regulatory agencies will react in the future, it is most likely that the basic requirements for transcritical CO_2 systems will fall under the General Duty Clause, and, nothing more. Safety is always paramount in any facility and many owners understand the value of providing a safe working environment. Therefore, there will always be some expense associated with developing and maintaining a formal safety program.

As noted, each facility and each owner will have a different set of priorities and a unique financial "weighting" for each variable. The most important element, up front, is to identify those variables and make an objective assessment of what those costs will be, not only, in terms of first costs but also on-going costs impacting the life of refrigeration system.

During the course of study into the subject of this white paper, two very interesting opportunities for case studies came to light. The first case study involved a warehouse that was built with a CO_2/NH_3 cascade refrigeration system in 2012. That project eventually became known as Phase One. Five years later, a second nearly identical addition was completed, but this time the owner decided to make the move to transcritical CO_2. The second case study involves two Henningsen facilities. These facilities were in different locations in the Pacific Northwest but did not vary significantly in climate zones, square footage, and load profiles. In this case study, the comparison was between a traditional "stick built" ammonia refrigeration system and a transcritical CO_2 refrigeration system. It is rare to find a set of facilities which offer such good comparisons, let alone two sets of facilities.

Case Study 1 – Canada

In 2012, a cold storage facility was constructed in Canada utilizing a CO_2/NH_3 cascade refrigeration system. This project, now referred to as Phase One comprised just under 3.5 million cubic feet of refrigerated space. The application was for fruit and vegetable storage operating with refrigerant temperatures from 32 degrees F to 50 degrees F. The annualized system COP was calculated to be 14.7.

Two years ago, a second phase was added to the facility. It also was used for fruit and vegetable storage and comprised just under 2.3 million cubic feet. This phase, however, was constructed with a transcritical CO_2 refrigeration system. This part of the facility also operated with refrigerant temperatures from 32 degrees F to 50 degrees F and had an annualized system COP of 18.1.

Figure 16 documents the cost comparison of the two systems. Interestingly, equipment for both phases was supplied by the same manufacturer. Significantly, there was no separate mechanical room in Phase Two, only a small room located in the mezzanine of the dock.

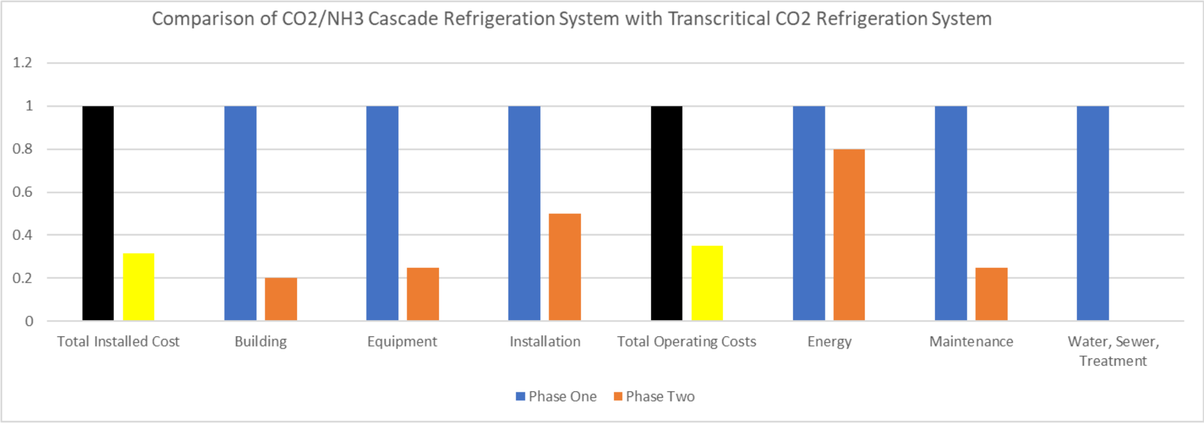


Figure 16: Comparison of First Costs and Operating Costs for Medium Temperature Cold Storage Facility

As the reader will note, there is virtually no element of the transcritical CO_2 system that does not outperform the CO_2/NH_3 refrigeration from a cost perspective. As both facilities are relatively new and designed and constructed by the same company, it is safe to assume that both were created with the same design philosophy with respect to energy efficiency.

Case Study 2 – Henningsen Cold Storage

For many years, Henningsen Cold Storage has been known as one of the most, if not the most, energy efficient cold storage companies in North America. So, it was of great interest when they decided that transcritical CO_2 refrigeration was worthy of an in-depth look for their next facility. After all, many industry professionals believed that transcritical CO_2 refrigeration was not as efficient as ammonia refrigeration; however, other important motivations beyond energy efficiency led them to investigate further. The director of engineering conducted a comprehensive study in order to determine if this was a good move on their part. They hired an outside energy consultant to perform an independent analysis on the overall energy impact this type of system would have for a site that was to be developed in Grandview, Washington. In the end, the decision was made to take the next step and employ this very different technology in the new facility. What made this decision even more interesting, however, is that Henningsen had recently commissioned an NH_3 facility in Salem, Oregon, that had a very similar size, climate conditions, and load profile. The Salem facility is known as Salem 2 as it is the second of two Henningsen facilities in the area. This effort would enable Henningsen to perform the type of comparison that is very difficult to find in the cold storage community.

As has always been the case with the company, a tremendous amount of data was collected to make a very thorough assessment with regard to how the two systems stack up against each other. This data not only included the energy analysis but also all the other operating costs either directly or indirectly associated with the type of installed refrigeration system. Henningsen was also kind enough to share this information. Figure F below shows the comparison of a year's worth of data between the two facilities as well as a first cost comparison.

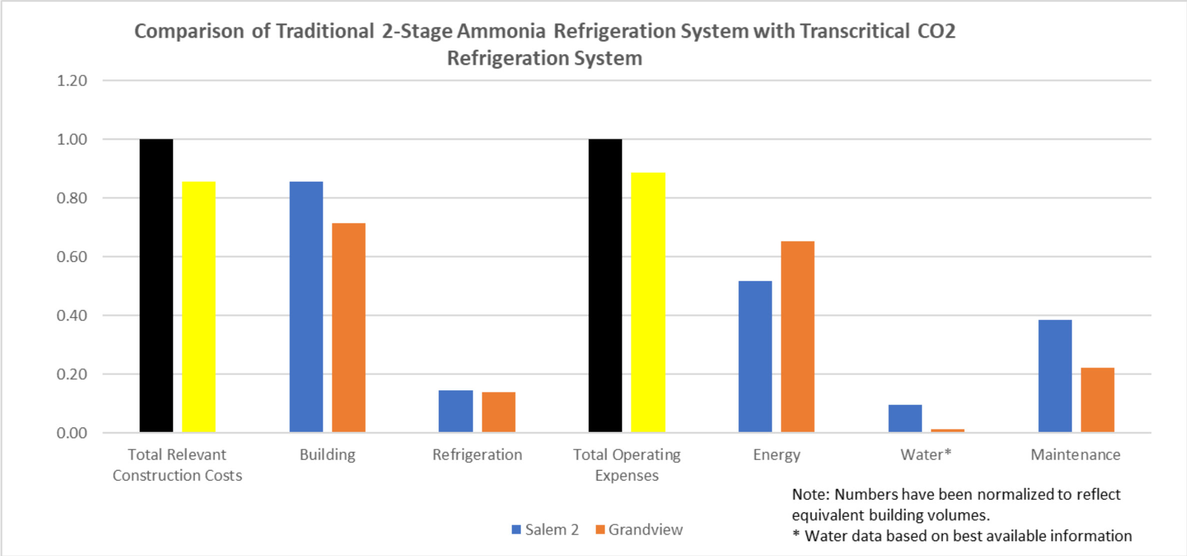


Figure 17: Comparison of First Costs and Operating Costs for Two Similar Cold Storage Facilities

A couple of points should be noted with regard to the information in Figure 17. With the exception of the water, sewer, and chemical treatment data, all operations data spans an entire calendar year. Having said that, however, it is important to note that the control system was not commissioned until October 2018. As a result, the engineering staff members at Henningsen are confident that energy performance was far from optimized in July, August, and September 2018 (which also happened to be three of the most energy intensive months of operation). The conclusion is that, if the same data is taken for 12 months through 2020, the energy comparison will show marked improvement over what is shown today. Water consumption was also higher than anticipated and only later discovered that the spray system was not being controlled properly. All told, a year from now, this picture should be even more compelling with respect to Henningsen's decision to move to transcritical CO_2 refrigeration.

Figure 18 characterizes the energy consumption of Henningsen's aggregate average with that of their state-of-the-art ammonia refrigeration system, the Grandview transcritical CO_2 refrigeration system and the aggregate industry average refrigeration consumption as compiled by the GCCA. The conclusion here is that, despite the small increase in energy consumption with transcritical CO_2 refrigeration over Henningsen's best facility, the transcritical CO_2 refrigeration system not only outperforms the Henningsen corporate average but far outperforms the industry average.

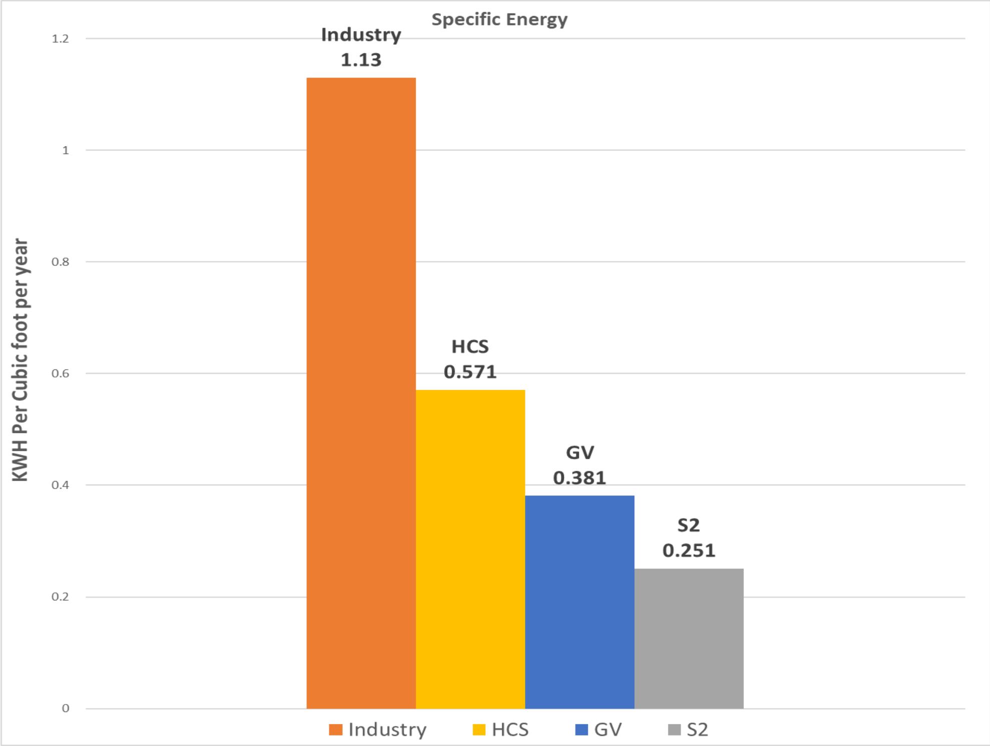


Figure 18: Comparison of Energy Usage in the Cold Storage Industry with "Best in Class" Ammonia Refrigeration System and Transcritical CO_2 Refrigeration System

Conclusions

There has been a tremendous amount of activity in the world of air conditioning and refrigeration in general and industrial refrigeration in specific. Most of the activity has been driven by regulation. This regulation has primarily focused on the safety of the operation and, to a lesser extent, environmental implications.

Over the past decade, there has been a resurgence of interest in the use of CO_2 as a refrigerant. The trend started in the automotive and commercial refrigeration markets and has since spread to the world of industrial refrigeration. Early on, there was a tremendous amount of skepticism with regard to using CO_2 for industrial applications. This was driven by concerns over energy efficiency as well as the higher pressures and available equipment. Nevertheless, early efforts at employing CO_2 in these applications were encouraging enough to spur investment into research and product development aimed specifically at the industrial refrigeration market.

What has been demonstrated, to date, is a fundamental viability of the technology into the much larger scale of industrial refrigeration. The early consensus from owners who have installed these systems into their cold storage facilities has been overwhelmingly favorable. Case studies which compare one type of system to another have been very hard to come by due to the variety of factors involved in each facility and how that facility is operated. Fortunately, there have been two highly valid comparisons that appear to indicate very favorable financial results for transcritical CO_2 refrigeration. All of this effort has continued to spur additional investment and, perhaps more importantly, competition among manufacturers to provide state of the art products for the application instead of merely “making do” with what’s available in the marketplace.

Here, we hope to present the reader with a fundamental understanding of what transcritical CO_2 refrigeration is all about, what makes it different from ammonia refrigeration, where the challenges lie, and what opportunities CO_2 refrigeration can bring to the end user. No one expects the incumbent systems to suddenly disappear only to be replaced by transcritical CO_2 refrigeration but, it should be clear, it does present a viable option to many different facility applications.

While regulation is often driven by current political climates, the strong emphasis on natural refrigerants exists in a global context and is not likely to ebb in the foreseeable future. From all appearances, transcritical CO_2 refrigeration appears to be a viable choice for the future.

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