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STUDY

CO_2 suction superheat study

Created by Future Green Now

FGN
FUTURE GREEN NOW

In collaboration with, for and on behalf of Copeland

COPELAND

Contents

This CO_2 suction superheat study — and the methodologies, data and conclusions found herein — was conducted by Future Green Now (FGN), an independent consulting firm with extensive experience designing and implementing natural refrigerant-based refrigeration solutions. Commissioned by Copeland and developed in close collaboration with the FGN team, this report documents the impacts of evaporator suction superheat on CO_2 transcritical booster system efficiencies. The findings are intended to help industry stakeholders deploy CO_2 system design strategies that deliver annualized energy savings independent of climate conditions.

Abstract

Improving the energy efficiency of refrigeration systems is an essential sustainability and operational goal for food retail operations, particularly in terms of reducing greenhouse gas (GHG) emissions from energy consumption. Although the use of natural refrigerants like CO_2 (R-744) can reduce direct emissions (Scope 1), the long-term energy efficiency of these systems — given their lifespan of 15 to 20 years — has significant lifecycle impacts on reducing Scope 2 emissions and achieving sustainability goals — while potentially lowering energy costs.

This report focuses on enhancing energy efficiency in a CO_2 booster refrigeration system, specifically concerning its low side (i.e., evaporator) suction superheat. Recently, CO_2 booster system designers have become more familiar with strategies that increase energy efficiency in high ambient conditions (i.e., warm climates and/or summer months). However, it's equally important to consider suction-side system optimizations that can unlock year-round energy savings throughout a system's lifespan.

In collaboration with Copeland and Future Green Now, researchers have conducted a study to evaluate the annualized energy savings of various low-side system technologies. It set out to address the following questions:

- What is the baseline energy profile of a system using Department of Energy (DOE)-approved evaporators with the highest available temperature differentials (TDs) and optimal superheat?
- What energy savings can be achieved with a dual-suction architecture compared to the baseline, considering both the highest and lowest evaporator coil TDs?
- How do "ultra-low to zero superheat" technologies used on medium-temperature (MT) evaporators compare to the baseline and dual suction systems?

This report highlights the impact of suction-side technologies that increase the saturated suction temperature (SST) of CO_2 booster refrigeration systems. Since the efficiency of a refrigeration system is primarily influenced by the pressure differential that compressors must overcome, increasing suction pressure should reduce the pressure differential and, consequently, lower the energy required to achieve the same cooling capacity. (See *Appendix: Evaporator operation* section for additional information.)

CO_2 booster system specifications

Modeling data and system assumptions

This study utilized modeling data that incorporated the highest, lowest and average TDs for display cases. To establish an energy efficiency baseline for North American products, a 10 °F TD was used for all unit coolers.

System assumptions:

- Typical CO_2 booster system (with no high-ambient system optimizations)
- MT load: 400,000 BTU
- Low-temperature (LT) load: 100,000 BTU
- Suction line losses: 2 °F for both MT and LT
- Software: EES (Engineering Equation Solver)
- Gas cooler standard operating conditions:
  - 59 °F minimum saturated condensing temperature (SCT)
  - 14 °F TD subcritical (SC)
  - 6 °F TD transcritical (TC)
- Dry gas cooler
- Weather data: National Renewable Energy Laboratory's (NREL) typical model year (TMY3)
- Sample cities and relative climates: Jacksonville, Fla., Chicago, and San Jose, Calif.

The study encompassed 214 display cases and 50 unit coolers from major U.S. original equipment manufacturers (OEMs), all of which met current applicable DOE and food safety standards. All unit coolers evaluated were designed with a 10 °F TD. For additional information on display cases and unit coolers in North America, please refer to *Display cases and unit coolers in North America,* provided in the appendix.

Baseline system and TDs

The baseline system was defined using the values in Table 1, including the highest TDs for display cases and unit coolers. Table 1 also details the air-off (i.e., discharge air) temperatures for each product, suction line losses and compressor SST based on various coil TDs for the lowest temperature loads.

For example, a Meat/Deli/Dairy case with an air-off temperature requirement of 30 °F and a maximum TD of 10 °F necessitates that the entire suction group operates at a compressor SST of 18 °F (394 psig). If the Meat/Deli/Dairy cases had a TD of 6 °F instead of 10 °F, the SST would increase to 22 °F (420 psig). This change would result in a 26 psig increase in pressure, leading to an approximately 1.5 percent reduction in compressor power and an 8 percent increase in compressor capacity.

Product Type	Type of Coil	Air-Off Temperature (°F) Range	Suction Line Losses (°F)	Highest Coil TD	Compressor SST (°F)	Lowest Coil TD (°F)	Compressor SST (°F)	Average Coil TD (°F)	Compressor SST (°F)
Meat/Deli/Dairy	Display Cabinets	30	2	10	18*	4	24	6	22*
Cold Room	Unit Coolers	34	2	10	22	10	22*	10	22*
Beverage/Produce	Display Cabinets	38	2	8	28	4	32	6	30
Frozen Food	Display Cabinets	-6	2	10	-18	4	-12	7	-15
Frozen Holding Room	Unit Coolers	-4	2	10	-16	10	-16	10	-16
Ice Cream/Bakery/Seafood	Display Cabinets	-13	2	10	-25*	4	-19*	7	-22*

* Indicated lowest SST of the suction group

Table 1: Establishes the assumptions used in this study concerning product types, coil types, air-off temperatures, suction line losses and SST at the compressors for the highest, lowest and average TDs

Products and their temperature requirements, as categorized in Table 1, are typical for retail applications. The SST for a refrigeration system must be set according to the lowest product temperature and the specifications of the associated unit coolers or display cases.

Figures 1a and 1b illustrate the operation of a standard CO_2 booster system with different evaporator TDs for the lowest temperature loads.

Highest, 10 °F TD for cases and unit coolers

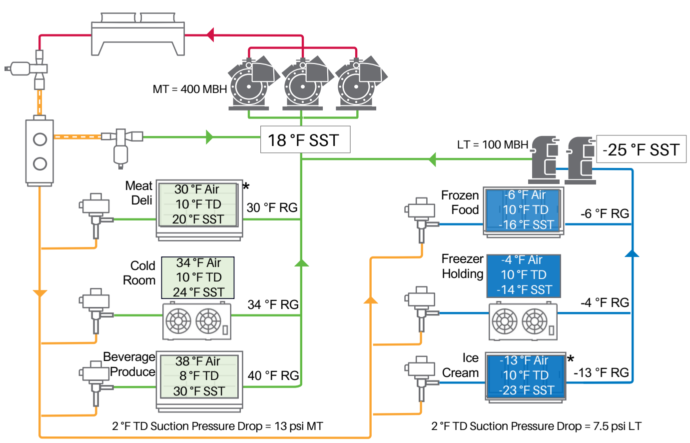


Figure 1a: This CO_2 booster schematic illustrates the common suction pressures for a system equipped with a 10 °F TD coil and 10 °F superheat used for the lowest temperature load. This configuration results in an 18 °F SST for MT and a -25 °F SST for LT.

Lowest, 4 °F TD for cases and 10 °F TD unit coolers

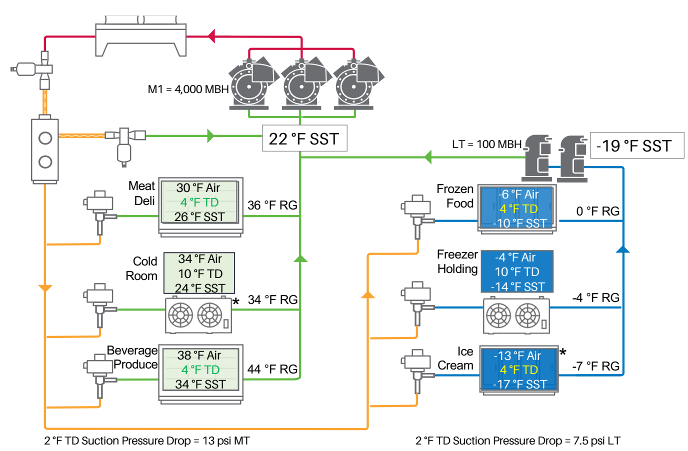


Figure 1b: This CO_2 booster schematic depicts the increased suction pressures for a system utilizing a more efficient 4 °F TD display case coil and 10 °F superheat for the lowest temperature load. This setup leads to a 22 °F SST for MT and a -19 °F SST for LT.

Note: Additional details on *Display cases and unit coolers in North America* are provided in the appendix.

Baseline CO_2 booster system

To establish a baseline refrigeration system for energy comparison, the study used a standard CO_2 booster system with internal heat exchangers, employing optimal evaporator superheat values for coils and display cases, as specified by the OEMs. *(See Figure 2a.)* By effectively optimizing internal heat exchangers, it's possible to reduce the evaporator superheat from the industry standard of 10 °F to a coil's optimal design point, thereby enhancing system efficiency while adhering to the minimum compressor recommended superheat values. A 5 °F superheat was used as the baseline for both MT and LT.

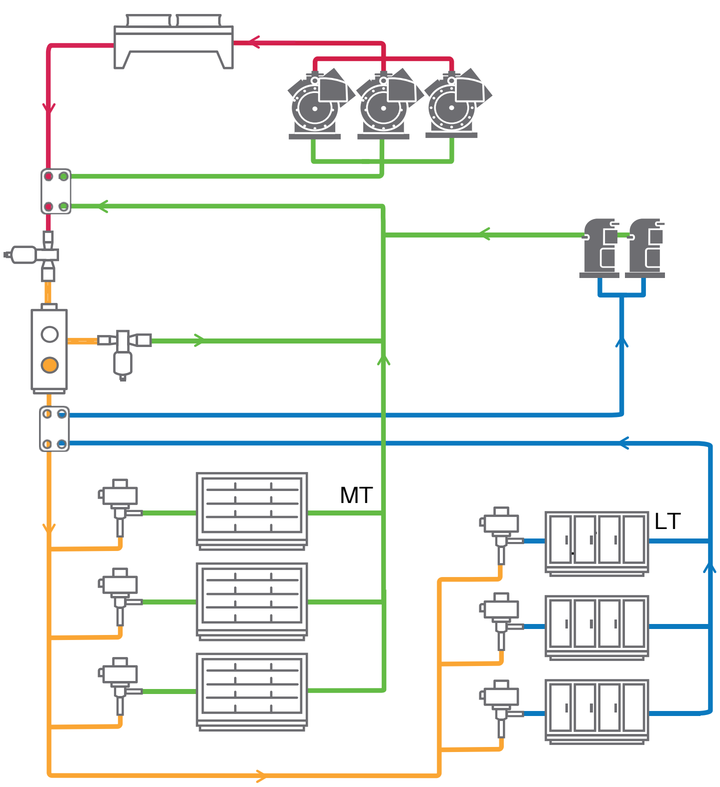
Key points:

- The TDs of unit coolers and display cases significantly affect the compressor SST of a refrigeration system.
- The TD determines the SST required to maintain the specified air temperature.
- A lower TD results in a higher SST needed to achieve the same air temperature, improving system energy efficiencies.
- The lowest required SST dictates a system's overall efficiency. Therefore, the worst combination of coil TD and lowest desired SST will set the baseline for system efficiency.
- Higher SST reduces the energy required to maintain desired air temperatures.

Note: For further details, please refer to *Evaporator operation*

Initial findings based on evaporator coil TD

Figures 2a and 2b illustrate that using the lowest available 4 °F TD evaporator coils for both MT and LT loads reduces annualized energy by 7.9 percent compared to using the highest 10 °F TD coils. Again, baseline system calculations were performed with a 5 °F superheat for MT and LT evaporators. A superheat of 5 °F was chosen to enable the baseline system to operate at the specified design TD to achieve optimum evaporator operation (i.e., temperature and humidity).



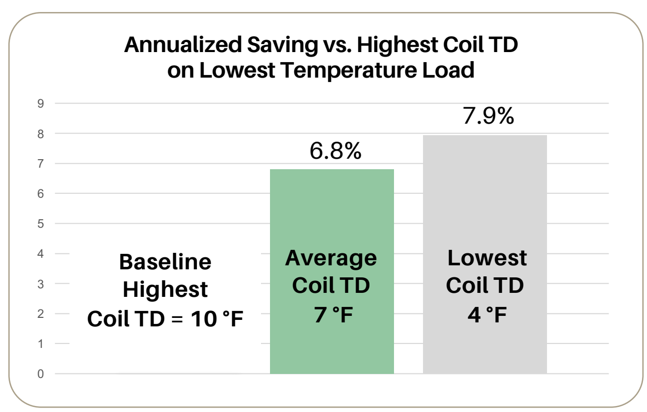


Figure 2a: Baseline CO_2 booster system featuring internal heat exchangers with a 5 °F superheat on all evaporators

Figure 2b: Annualized energy savings of average (7 °F) and lowest (4 °F) coil TDs compared to a baseline system using 5 °F superheat with 10 °F TD evaporators

Dual- vs. single-suction systems

In retail applications, where multiple temperature requirements are needed across various refrigerated cases and unit coolers, a single-suction line must accommodate the lowest temperature needs and the lowest SST based on the TD of the shared assets. Consequently, designing systems with separate suction lines could enable a store with the same case TDs to operate with higher SSTs for part of the refrigeration load.

To test this approach, the study compared the following configurations, as denoted in Table 2:

- **Single-suction systems:** MT and LT display cases have the same highest, lowest and average TDs.
- **Dual-suction systems:** MT and LT display cases are on separate suction groups, each with their highest, lowest and average TDs.

For dual-suction systems, the load requirements were grouped according to the lowest SST.

Note: A 10 °F TD (between discharge air-off and SST) was used in all calculations, as all 50 unit coolers evaluated were designed with this TD, regardless of manufacturer.

Table 2: Single- and dual-suction line capacities for highest, lowest and average TD coils

Suction Group #	Capacity (BTU)	Highest TD Coils Compressor SST (°F)	Lowest TD Coils Compressor SST (°F)	Average TD Coils Compressor SST (°F)
Single Suction				
MT	400,000	18	22	22
LT	100,000	-25	-19	-22
Dual Suction				
MT1	240,000	18	22	22
LT1	70,000	-18	-16	-16
MT2	160,000	28	32	30
LT2	30,000	-25	-19	-22

As Figure 3b demonstrates, a dual-suction design can increase system SST, even when both configurations use the highest TD coils evaluated in this study. According to Table 2, a dual-suction system with the highest TD enables 40 percent of the MT2 loads (160 of 400 MBH) to operate at 28 °F SST (462 psig), instead of 18 °F SST (394 psig). This results in a 68 psi higher suction pressure, which reduces compression ratios and enhances energy savings, while 30 percent of the LT2 loads (30 MBH) continue to operate at -25 °F SST.

For the remaining 60 percent of MT1 loads (240 MBH) in the dual-suction system, operation remains at 18 °F SST (394 psig). However, since 70 percent of LT1 loads (70 MBH) can operate at -18 °F SST (208 psig) instead of -25 °F SST (181 psig), LT1 gains 27 psig suction pressure, which contributes to lower compression ratios and an additional annual energy savings of 7.2 percent.

Single-suction highest 10 °F TD coils

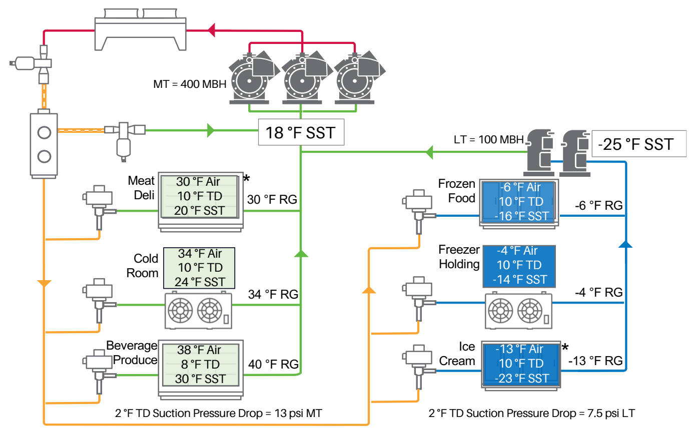


Figure 3a: Typical compressor SST for a single-suction architecture using the highest TD coil design identified in this study

Dual-suction with highest 10 °F TD coils (7.2 percent savings)

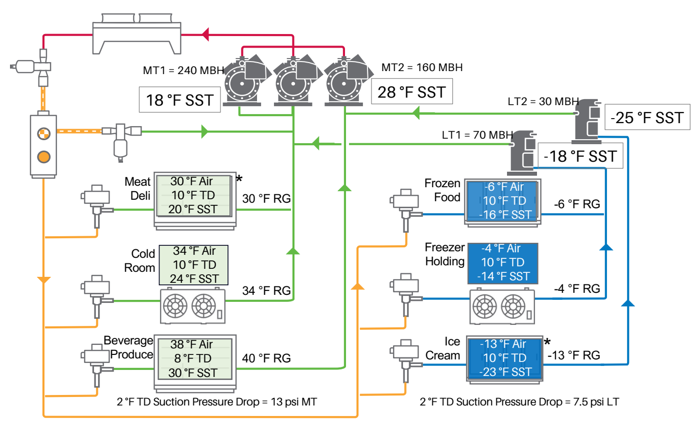


Figure 3b: Dual-suction architecture using the highest TD coil design realized an annualized energy savings potential of 7.2 percent.

Note: For additional details, please refer to *Lowest TD for cases and unit coolers* in the appendix of this document.

Evaluated technologies with highest, lowest and average evaporator coil TDs

The first aim of this research was to examine the impact of suction-side technologies on the operation of CO_2 refrigeration systems, focusing primarily on the benefits of increasing SST, coil TD optimization and dual-suction system designs.

The next key objective was to assess how reducing evaporator superheat affects SST and overall system efficiency. This strategy focuses on employing various methods to increase the suction pressure (psig), which in turn lowers compression ratios and improves energy efficiency.

Compressor minimum superheat requirements

Maintaining a minimum compressor suction superheat is vital for protecting the compressor from failure due to inadequate lubrication. Excessively low superheat can dilute the oil, reducing its ability to protect internal bearing surfaces. Most compressor manufacturers require a minimum superheat of 20 °F (11 °K), though some may specify up to 36 °F (20 °K). Roughly 50 percent of the required compressor superheat comes from the evaporators, while the remainder is achieved through the suction line's pressure drop, heat absorption from the ambient temperature, internal heat exchange or hot gas injection.

When operating with ultra-low to zero superheat, liquid is more likely to return to the suction line. To prevent this, designers often use suction accumulators (low-side receivers) with liquid drain connections to redirect captured liquid to other system parts.

Benefits of reducing or eliminating superheat:

- Increases SST
- Expands usable surface area within the evaporator
- Enables the evaporator to remove more BTUs per degree TD
- Ensures constant phase change within the evaporator for improved heat transfer

Evaluated technologies:

1. **Baseline —** Optimum coil superheat per design specification with internal heat exchangers.
    - Utilizes internal heat exchangers to increase MT compressor suction superheat while leveraging the optimal evaporator design superheat.
2. **Liquid ejectors —** No superheat.
    - Operate MT evaporators on the lowest SST loads with zero superheat, effectively using liquid ejectors.
3. **Liquid to LT —** No superheat.
    - Operates MT evaporators on the lowest SST loads with zero superheat, redirecting collected cold liquid from the low-pressure receiver to LT electronic expansion valves (EEVs) (assumed 10 percent overfeed).
4. **Dual-suction systems**
    - Use dual-suction groups for MT and LT, optimizing suction pressure with the optimal case design superheat recommended by manufacturers.

Note: For detailed descriptions of these technologies, please refer to the complete explanations in the appendix.

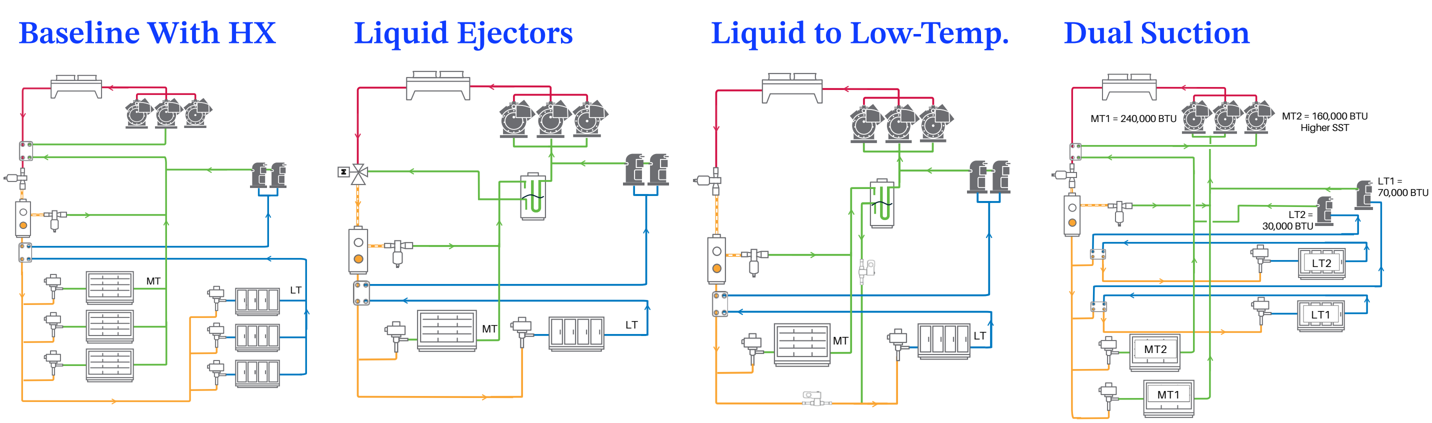


Figure 4: Depicts the four CO_2 booster architectures evaluated in this study

Energy comparison results

Figures 5a, 5b and 6 illustrate the annualized energy savings associated with the three evaluated low-side strategies. The figures compare the performance of these strategies to systems using evaporators with TDs of 10 °F (highest), 7 °F (average) and 4 °F (lowest) for the lowest temperature requirements of MT and LT loads.

Please refer to the modeling data and system assumptions section and Tables 1 and 2 for detailed assumptions and system specifications.

Liquid Ejector (No Evaporator Superheat)

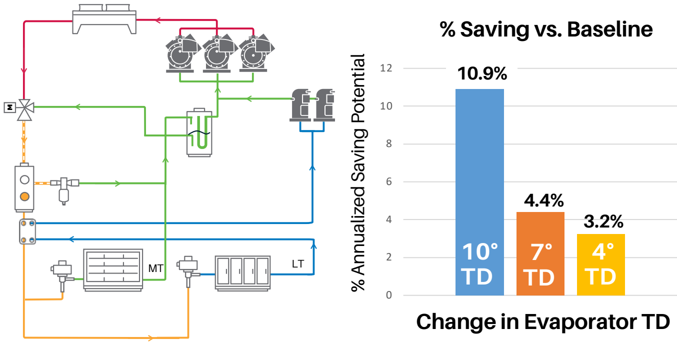


Figure 5a: Illustrates the annualized energy savings potential of liquid ejector technology applied to the lowest temperature loads using evaporators with TDs of 10, 7 and 4 °F

Liquid to Low-Temp. (No Evaporator Superheat)

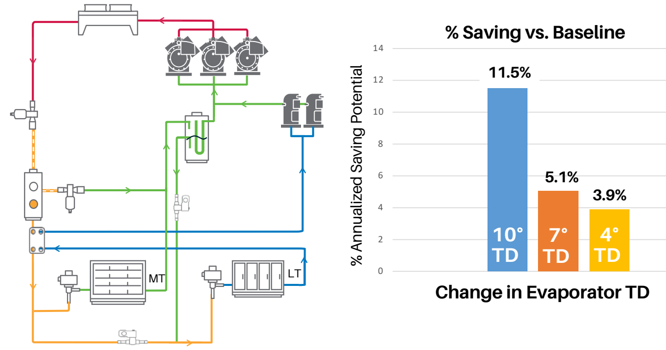


Figure 5b: Demonstrates the annualized energy savings potential of liquid to LT technology when applied to the lowest temperature loads, using evaporators with TDs of 10, 7 and 4 °F

Dual Suction (Optimal Evaporator Superheat)

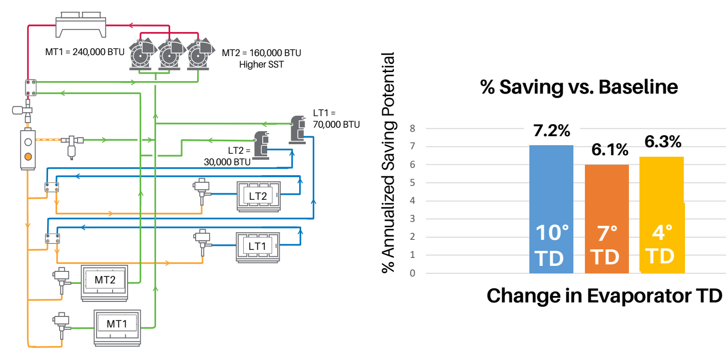


Figure 6: Demonstrates the annualized energy savings potential of dual-suction technology when applied to the lowest temperature loads using evaporators with TDs of 10, 7 and 4 °F

Note: Refer to Table 2 for a breakdown of loads.

Evaluating the energy savings potential of technology options

Comparing the impacts of highest vs. lowest TDs in display cases and unit coolers

Figures 7a and 7b compare all technologies being assessed and their cumulative annualized energy savings potential. Using this data, the study can discern the following observations:

1. **Impact of high-TD evaporators:** When employing evaporators with high TDs, ultra-low superheat strategies can help to mitigate energy losses and provide improved annualized savings compared to dual-suction systems with the same high-TD evaporators used on the lowest-temperature loads.
2. **Impact of low-TD evaporators:** Using the lowest possible evaporator TDs significantly reduces the incremental savings of the same ultra-low superheat strategy. However, by combining the lowest coil TDs with ultra-low superheat, systems can achieve a higher potential for annualized energy savings.
3. **Efficiency of dual-suction systems:** Among systems utilizing this combined technological approach, lowest coil TDs paired with a less complex dual-suction system — as opposed to liquid ejectors and liquid-to-LT technologies — offer the highest overall annualized energy savings of 14.2 percent.

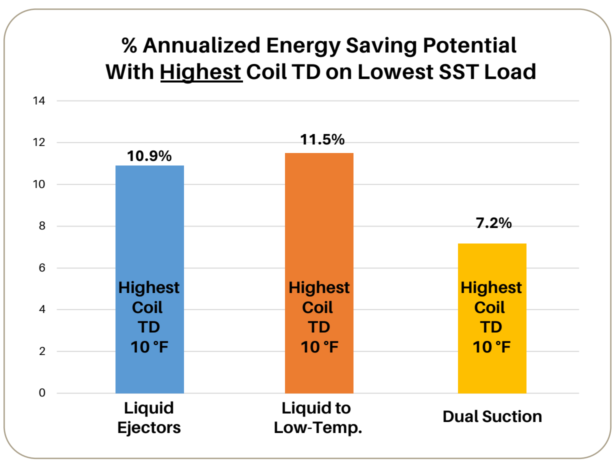


Figure 7a: Compares the annualized energy savings for three low-side strategies using 10 °F TD evaporators on the lowest temperature loads

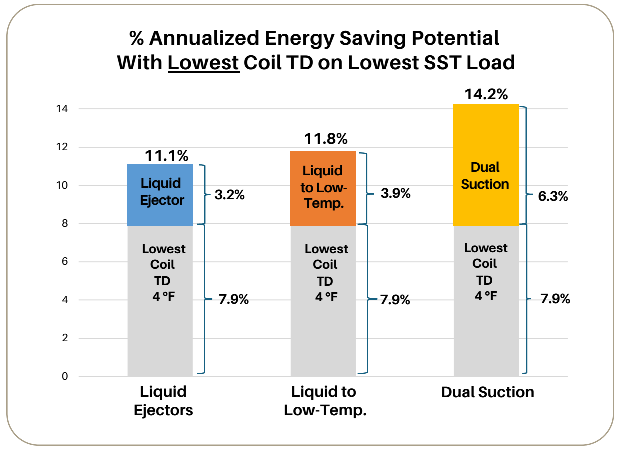


Figure 7b: Compares the annualized energy savings of three low-side strategies using 4 °F TD evaporators on the lowest temperature loads to those using 10 °F TD coils

Conclusion/ recommendations

As established in the abstract of this report, the energy efficiency of a refrigeration system is critical to ensuring sustainable operation throughout its 15- to 20-year lifespan. To maximize the efficiency of CO_2 booster and MT systems — and support their long-term adoption — energy-savings strategies like high-ambient optimizations and low-side annualized strategies outlined herein can help to establish CO_2 architectures as regulatory-compliant and energy-efficient alternatives.

This study demonstrated that compared to a single-suction system with the highest TD coil (10 °F) for the lowest-temperature loads, a dual-suction system provides an annualized energy savings potential of 7.2 percent. Regarding the use of ultra-low superheat technologies, liquid ejectors delivered an annualized energy savings potential of 10.9 percent, while a liquid-to-LT strategy delivered 11.5 percent savings. The additional savings from a liquid-to-LT strategy is due to the higher liquid enthalpy feeding the LT cases from the suction accumulator during ~10 percent of the year.

Additionally, the study demonstrated that compared to a 10 °F TD coil for the lowest-temperature loads, simply by using the lowest TD evaporators available (4 °F), systems could achieve 7.9 percent annualized energy savings without introducing unnecessary design complexities.

Among the three low-side technologies presented in this study, the dual-suction architecture — which is believed to be the least complex — provided the greatest annualized energy savings of 14.2 percent (7.9 percent from using a 4 °F TD coil, plus 6.3 percent from the dual-suction configuration).

Appendices

Evaporator operation

This report highlights the impact of suction-side technologies that enhance the operation of a CO_2 refrigeration system. These technologies primarily focus on increasing the SST of a system.

To understand the benefits of these technologies, it's crucial to grasp what determines the suction requirements of a refrigeration system. The main driver for achieving the desired product temperature in a refrigeration system is the coil's air-off temperature. Typically, supermarket refrigeration systems have LT and MT requirements to keep products either frozen or chilled. In such cases, the lowest temperature for both frozen and chilled products sets the common or lowest SST for their respective suction groups. Additionally, the type of unit coolers and display cases will further determine the required SST according to their specifications, which dictates the appropriate air-off temperature needed.

A single, dedicated LT and MT suction group must operate to satisfy each product temperature requirement. If an LT load is added to the existing suction group and requires a lower product temperature, the entire suction group must now operate at a lower SST to satisfy the lowest temperature requirement. One way to overcome this and optimize efficiency is by designing for separate suction groups. However, there are limits to the number of suction groups a system can have in a single store due to cost and complexity constraints. This study includes the addition of dual-suction groups to manage various temperature requirements as a means of comparing other energy-savings technologies. The target SST is then compared by the type of display case or unit cooler (due to varying specifications). Results will show that models with the lowest TD yield the highest SST and, therefore, the highest energy efficiency.

Each unit cooler or display case design can provide a stable product temperature via an air supply temperature directly related to its SST. A good evaporator will allow for a small TD between the air supply temperature and the SST or evaporating temperature. The higher the TD between the air supply and refrigerant temperature, the lower the SST or evaporation temperature. Both examples can achieve the desired stable product temperature.

The efficiency of a refrigeration system is mainly driven by the pressure differential that a compressor must overcome. This pressure differential is the difference between the suction pressure and the discharge pressure, where the discharge pressure is generally influenced by the ambient temperature, and the suction pressure is determined by the evaporation temperature or SST at the compressor inlet. Therefore, the higher the suction pressure, the lower the pressure differential for the compressor to overcome, resulting in less energy usage by the system to obtain the same required cooling capacity.

To further explain the above-mentioned operations of an evaporator, the following schematic can be used as a guideline to show the impact of superheat and differential temperature between air-off and SST, and its impact on system efficiency.

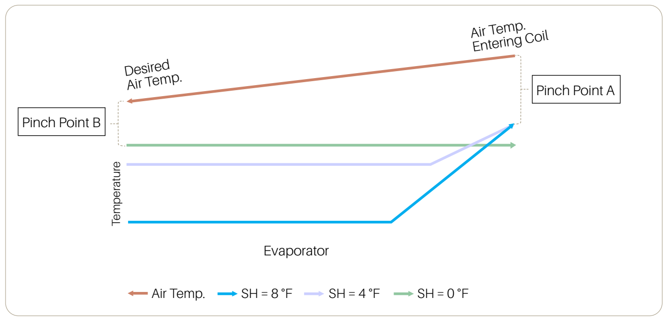


Figure 8: Relationship between air temperature and evaporator

The air entering an evaporator coil arrives at a specific temperature and must exit at the desired or required temperature. The air temperature sets the boundary for the necessary refrigerant temperature. There are two potential *pinch points* — the point where the refrigerant temperature is at its lowest in the evaporator — either at the air inlet side with the refrigerant outlet (pinch point A) or the air outlet side with the refrigerant inlet (pinch point B). A pinch point exists because these two temperatures can't overlap; the air cannot be made to be colder than the refrigerant temperature.

A system with high evaporator superheat has a pinch point at the air inlet side, while a system with no or low superheat has its pinch point at the air outlet side. From Figure 8, it can be noted that an evaporator with an 8 °F superheat must have a lower SST to achieve the desired pinch point. The lower the superheat, the higher the SST can be until it reaches a desired pinch point with the air outlet temperature. As mentioned, higher SST results in less compressor power and improved energy efficiency.

To determine the system SST, it's important to understand the specifications and requirements of various unit coolers and display case manufacturers used within the North American market. For this study, the design specifications of various evaporators were considered to understand the energy implications of high, medium and ultra-low superheat and their impacts on SST and ultimately system energy efficiency.

Display cases and unit coolers in North America

To understand how a refrigeration system operates at a given evaporator SST, it's important to evaluate how unit coolers and display cases perform at their highest possible suction pressures. In North America, unit coolers and display cases must adhere to a variety of energy and food safety standards:

- DOE (display cases)
- DOE AWEF (unit coolers)
- NRCan
- ENERGY STAR®
- NSF

These standards have parameters that must be met by each unit cooler and display case sold in North America. Stringent testing and energy ratings ensure that unit coolers and display cases operate as efficiently as possible based on a specified superheat requirement. For the purposes of this study, these standards serve as an energy baseline when comparing different evaporating conditions.

This study includes hundreds of display cases and unit coolers from multiple North American manufacturers to establish a credible industry baseline. All units are DX types; however, researchers have observed that the same standards apply to the same unit coolers or display cases for flooded evaporator types.

Unit coolers evaluated in this study:

- 50 unit cooler models were considered.
- All unit coolers were specified by suppliers to have a 10 °F TD between the suction temperature and air-off temperature.
- All unit coolers (coolers and freezers) were rated with a 6.5 °F superheat, per the annual walk-in efficiency factor (AWEF) standard.
- The median superheat range during commissioning for MT coolers was 6 to 8 °F.
- The median superheat range during commissioning for LT freezers was 4 to 6 °F.

It can be concluded that unit coolers available in North America are similar in operational superheat. For this study, a 10 °F differential between the SST and air-off temperature was used as a baseline in comparing unit cooler superheat requirements.

Display cases evaluated in this study:

- 214 display cases were evaluated from all the leading North American case manufacturers.
- The lowest superheat requirement for a display case was found to be 3 °F.
- The highest superheat requirement for a display case was found to be 8 °F.
- The median specified superheat requirement for MT was 6 to 8 °F.
- The median specified superheat requirement for LT was 4 to 6 °F.

Due to the varying design case TDs specified from manufacturer to manufacturer, this study focused on the highest, lowest and average TDs, and compared the impact of low superheat technologies on overall system energy use. Manufacturers design for optimal superheat values to enhance case performance, but these values are often ignored in the field. In practice, a 10 °F evaporator superheat for MT and LT cases is generally used to assure adequate superheat back at the compressors.

Main product categories used in this study for display cases:

- Ice Cream/Bakery/Seafood (LT): Air-off temperatures from -13 to -7 °F
- Frozen Food (LT): Air-off temperatures from -6 °F and up
- Beverage/Produce (MT) Air-off temperatures from 38 °F and up
- Meat/Deli/Dairy (MT): Air-off temperatures from 30 to 37 °F

TDs used for all the display cases:

- Ice Cream/Bakery/Seafood (LT): 10 °F TD (highest), 4 °F TD (lowest), 7 °F TD (average)
- Frozen Food (LT): 10 °F TD (highest), 4 °F TD (lowest), 7 °F TD (average)
- Beverage/Produce (MT): 8 °F TD (highest), 4 °F TD (lowest), 6 °F TD (average)
- Meat/Deli/Dairy (MT): 10 °F TD (highest), 4 °F TD (lowest), 6 °F TD (average)

This study referenced these display case categories as a baseline from which to compare the impact of low superheat technologies. The TD between display case models and manufacturers varies greatly, even though they meet DOE efficiency standards. This study demonstrated that TD is directly correlative to case efficiency. A higher case TD results in lower suction pressure and increased compression ratio, while a lower case TD results in higher suction pressure and reduced compression ratio, thereby reducing electrical energy consumption.

In the example of a single-suction lineup with multiple case designs — all operating at the same air-off temperature and having varying TDs — the common suction pressure going back to the compressor is the result of the lowest suction pressure dictated by the case with the highest TD.

Lowest TD for cases and unit coolers

Repeating the same exercise as shown in Figures 2a and 2b, using the most efficient display cases with the lowest design TD and unit coolers with a fixed 10 °F TD (from Table 2) for both single- and dual-suction system designs yielded an annualized savings with dual-suction of 6.3 percent.

The positive impact of a lower evaporator TD, as previously outlined, results in the highest possible compressor SST. In the above MT examples, a cold room requiring 34 °F air-off and 10 °F TD (plus 2 °F TD in line loss to the compressor rack) results in an MT suction SST of 22 °F, assuming one common suction line.

Single-suction lowest display case TD 4 °F

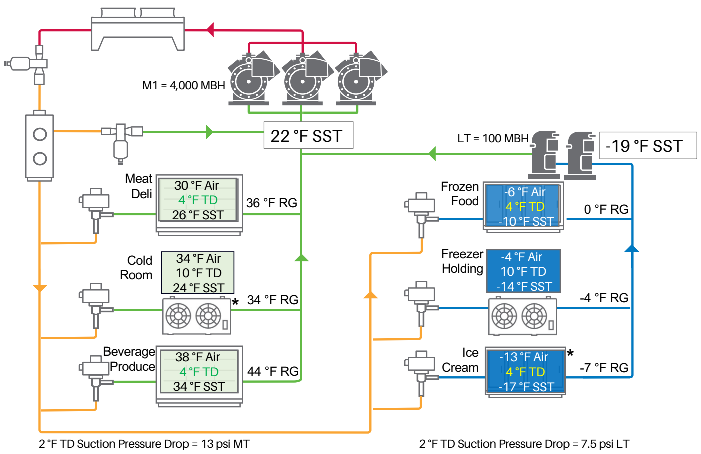


Figure 9a: Typical compressor suction pressures with single-suction architecture using the lowest display case TD found in this study

Dual-suction with lowest display case TD 4 °F

6 percent annualized energy savings

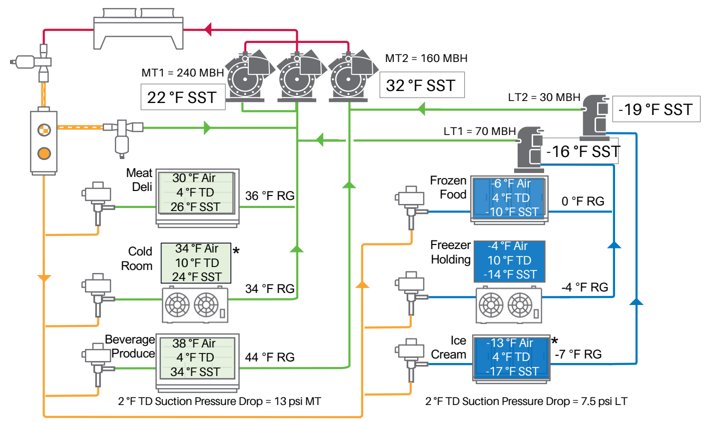


Figure 9b: Dual-suction architecture also using the lowest display case TD found in this study yielded an annualized energy savings potential of 6.3 percent

Table 2 illustrates how a dual-suction system design can improve the system efficiency of evaporators with the lowest TD based on the results of our study. A dual-suction design with the lowest TD would allow 40 percent (MT2) loads to operate at 32 °F SST (491 psig), rather than 22 °F SST (420 psig), a 71 psig higher suction pressure, thereby reducing compression ratios and increasing energy savings. The 30 percent (LT2) load would still operate at -19 °F SST. For the remaining 60 percent (MT1) load, it will still operate at 22 °F SST, while 70 percent (LT1) will be able to operate at -16 °F SST (217 psig) instead of -19 °F SST (204 psig), a 13 psi higher suction pressure, contributing to lower compression ratios and additional energy savings.

Lower superheat — internal heat exchangers

For a CO_2 booster system, maintaining a constant flash tank pressure and corresponding liquid line temperature means that all the display cases and unit cooler EEVs are supplied with constant liquid quality and pressure, making it easier to maintain a constant superheat. With the effective use of internal heat exchangers, it's possible to lower evaporator superheat from the industry standard of 10 °F down to the coil's optimal design point (as highlighted in the *Display cases and unit coolers in North America* section) to gain higher system efficiencies while respecting the minimum compressor superheat values recommended by compressor manufacturers.

Types of internal heat exchangers (HX):

1. MT suction to gas cooler outlet heat exchanger:
   a. This HX may be required if the LT discharge is not providing enough MT suction superheat based on recommended minimum values, or it's designed into systems where the MT evaporator superheats are reduced to 5 °F to ensure the highest SST possible.

2. LT suction to liquid heat exchanger:
   a. This HX provides superheat management for the LT compressors. Typical LT compressor minimum superheats are 36 °F (20 °K).

By ensuring the required minimum superheat at the compressors with the use of heat exchangers, the evaporator superheat can be controlled to as low as 5 °F to ensure higher SST.

Benefits of internal heat exchangers:

- No additional technology is required.
- Heat exchangers have no moving parts, making them simple solutions.
- Evaporators can operate with lower superheat and optimal design efficiency.
- Heat exchangers can be used to lower superheat on both LT and MT evaporators.
- Heat exchanger benefits can be gained throughout the year.

Potential challenges of internal heat exchangers:

- Cannot operate with zero superheat.
- Must allow for reasonable minimum superheat, leaving evaporators to ensure no liquid returns to the compressor.
- Unit cooler and display case specifications still apply and are dependent on the designs of the evaporators.

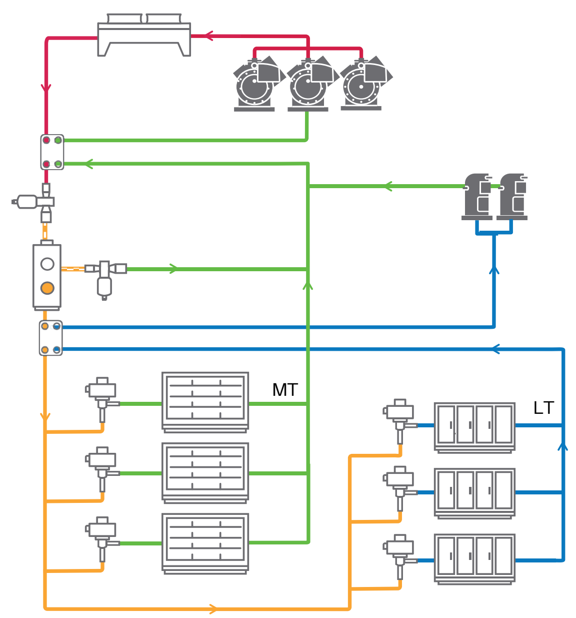


Figure 10a: Baseline architecture utilizing standard design superheat with internal heat exchangers for minimum compressor superheat management

- **214 Display Cases, MT and LT**
  — All DOE/AHRI1200 Certified
  — Operating Condition @ Rating Point
    - MT With 6-8 °F SH
    - LT With 4-6 °F SH or 3-5 °F SH
  — Coil Temperature Difference (TD)
    - High TD = 10°; Low TD = 4°; Avg. TD = 6°
- **51 Unit Coolers, MT and LT**
  — All DOE/AWEF Certified
  — All Rated at 6.5 °F SH
  — Coil TD
    - All 10 °F TD

Figure 10b: Listing of design specifications for display cases and unit coolers used in this study

Liquid ejectors — no evaporator superheat

Both liquid and high-pressure gas ejectors operate similarly yet are used to increase energy efficiency in different parts of a CO_2 booster system. Liquid ejectors drive annualized savings on the low side, while gas ejectors are used on the high side during high ambient temperatures.

In a CO_2 booster system with parallel compression, a high-pressure gas ejector is placed next to the high-pressure valve — or may replace it altogether — at the outlet of the gas cooler and inlet of the flash tank or receiver. It functions similarly to the high-pressure valve, controlling the discharge pressure of a CO_2 system and reducing it to the receiver pressure. The ejector has three basic connections: 1) the inlet receives mass flow directly from the gas cooler; 2) the side port receives mass flow from MT suction; and 3) the outlet connection is piped directly to the top of the flash tank. As the gas cooler pressure rises during high ambient temperatures, the high motive force entering the gas ejector creates a high-pressure differential across an internal venturi, causing a siphoning effect and drawing MT suction vapor into the ejector throat. The MT suction vapor mixes with the gas cooler outlet's mass flow and returns to the flash tank (receiver). The excess flash tank vapor generated by this process is compressed by the parallel compressors at a higher suction pressure, producing an energy-savings benefit.

Similarly, liquid ejectors can be applied to low superheat technology systems where the liquid present in the outlet of the evaporators is accumulated in a vessel (sometimes referred to as a *suction accumulator* or *low-pressure receiver*); from there, it's lifted (i.e., drawn into the ejector from the gas cooler out) to the receiver to be used again for cooling. For a liquid ejector setup, a parallel compressor (or intermediate compressor) is not required.

By applying liquid ejectors to the low side of a CO_2 refrigeration system, the system can operate with low or no superheat, eliminating the threat of liquid returning to the compressor suction due to the suction accumulator.

Liquid ejector design criteria:

- Ensure proper control of evaporators to manage the amount of liquid returning effectively.
- Correctly size the low-pressure receiver/accumulator vessel to hold the returning liquid.
- Correctly size liquid ejectors to ensure year-round functionality at maximum and minimum loads and pressure drops.
- Ensure control logic is sound to gain maximum energy-savings benefits from liquid ejectors and zero superheat functionality.
- Require case controls capable of shifting superheat setpoints from normal to zero superheat when needed.

Note: This study assumed continuous zero superheat operation for MT evaporators.

Adhering to the above recommendations will allow a relatively simple means to reduce superheat at the evaporators while driving SST and system efficiency increases.

Benefits of liquid ejectors:

- Can operate evaporators with very low to no superheat, resulting in an increased MT SST.
- Can help overcome some inefficiencies of evaporator coils with high coil TDs.
- Provides energy benefits year-round.

Potential challenges of liquid ejectors:

- Only used on the MT evaporators.
- Add system complexity.
- Proper means of oil return from suction accumulator to compressors must be considered.
- Additional components, piping, costs and controls integration are required.

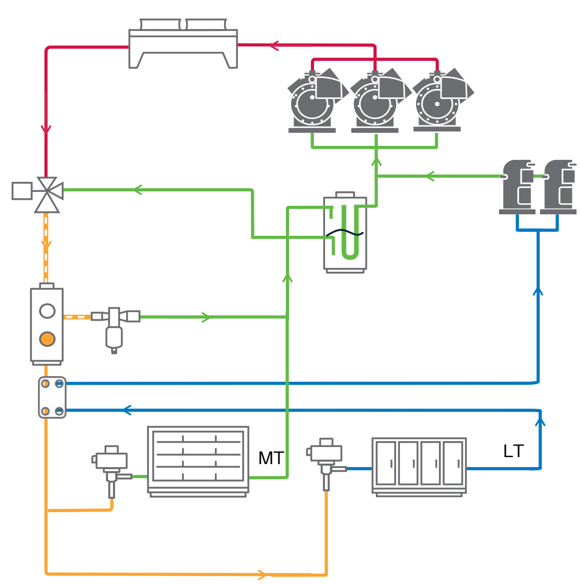


Figure 11: Simplified system schematic of a liquid ejector

Liquid to LT — no evaporator superheat

In liquid to LT technology, any liquid leaving the MT evaporators is collected in a low-pressure vessel or accumulator and transferred to LT evaporators when the receiving vessel is full, instead of going to the flash tank. This strategy for MT evaporators allows operation with no superheat without the threat of liquid returning to the compressor.

Liquid to LT design criteria:

- Correct sizing of the low-pressure liquid receiver/accumulator is required to ensure adequate operation.
    - When the collected liquid in the low-pressure receiver reaches a preset level, a solenoid valve in the main LT liquid branch closes and a liquid line solenoid valve at the outlet of the suction accumulator opens. This allows the flow of accumulated cold liquid from the MT low-pressure receiver/accumulator to feed the LT loads with high-enthalpy liquid until the low-pressure receiver is drained. Once drained, the solenoid valve from the accumulator feeding the LT cases closes and the main liquid line solenoid valves re-energizes, resuming the flow from the flash tank to the LT loads. This process of filling and draining the MT low-pressure receiver repeats continuously.
- Control logic and integration between different operating requirements must be established.
- Ensure that minimum and maximum compressor superheat is always maintained.
- Requires case controls capable of shifting setpoints from normal to zero superheat when needed.

Study assumptions:

- Continuous zero superheat operation for MT evaporators.
- 10 percent MT liquid overfeed to provide subcooled liquid to LT loads.

Although liquid to LT technology is not significantly complex, it adds moving parts that need to be understood and controlled properly to avoid putting the compressors or system at risk.

Liquid to LT benefits:

- Can operate evaporators with very low to no superheat, resulting in increased MT SST.
- Can help overcome some inefficiencies of evaporator coils with high TDs.
- Provides energy benefits year-round.
- Enables higher-enthalpy liquid feed to LT evaporators when the accumulator is full.

Liquid to LT potential challenges:

- Adds system complexity.
- Requires additional components, piping and controls integration.
- Proper means of oil return from suction accumulator to compressors must be considered.
- Low-pressure receiver sizing and switching back and forth from the flash tank.

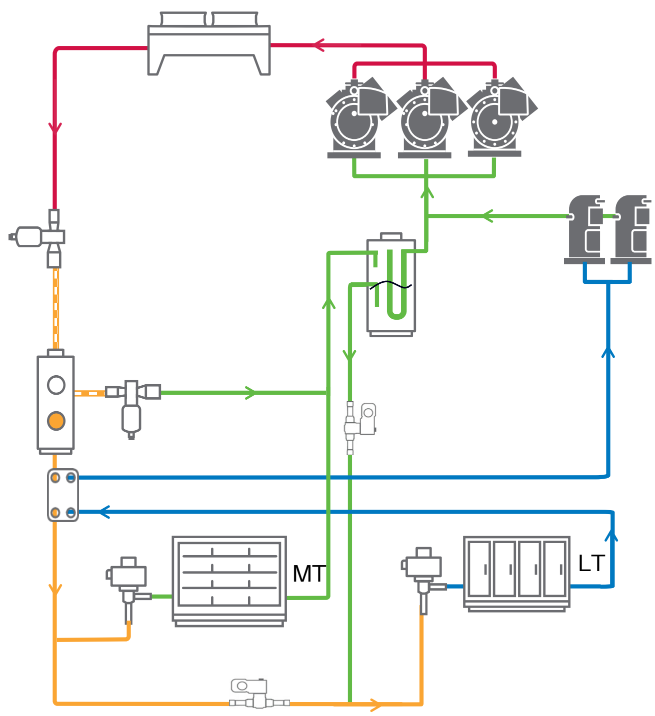


Figure 12: Simplified system schematic of liquid to LT

Dual-suction systems for MT and LT

Dividing the MT and LT loads into separate suction groups allows for optimized management of the SST in each circuit, which enhances overall energy efficiency. This study assumes that the capacity breakdown provided in Table 2 represents a typical setup for most retail food stores in North America.

For detailed comparisons of energy savings between dual-suction and single-suction systems at different coil TDs, refer to Figures 3, 6, 7a and 7b.

Methods for implementing dual-suction groups

System designers can take several approaches to add suction groups without overly complicating the setup:

- **Single centralized rack:** A large, centralized rack can be divided into separate suction groups for MT and LT loads. In a CO_2 booster setup, the liquid line for both MT and LT loads remains common, i.e., the extra costs are mainly from adding suction pipe runs and compressor drives to support the new suction groups. Depending on a store's capacity needs, additional compressors may be necessary for system redundancy and stability.
- **Distributed racks:** Smaller, strategically placed racks can be selected and distributed to match capacity needs — each with optimized SSTs for better overall store energy efficiency.
- **Condensing units:** Distributed condensing units can manage specific sections of the store, handling outlier loads and SSTs to improve the efficiency of a larger centralized rack.
- **Self-contained units:** For low-volume display cases that require a lower SST due to specific product types, self-contained units (preferably using a hydrocarbon [HC]) can be used to avoid affecting the efficiency of the main refrigeration system.

This study utilized the first approach: equipping a single rack with dual-suction groups for MT and LT.

Dual-suction system benefits:

- Increased energy savings — provides greater energy savings compared to liquid ejectors and liquid to LT strategies when using 7 °F or 4 °F TD evaporators.
- Simplicity — maintains the system's existing structure without the need for additional technologies.
- Efficiency gains — improves energy efficiency for both LT and MT groups.
- Year-round efficiency — delivers consistent energy efficiency improvements throughout the year.

Dual-suction system potential challenges:

- Additional costs — requires added investments for suction piping and compressor drives.
- Design dependencies — unit cooler and display case specifications must align with the designs of the evaporators.

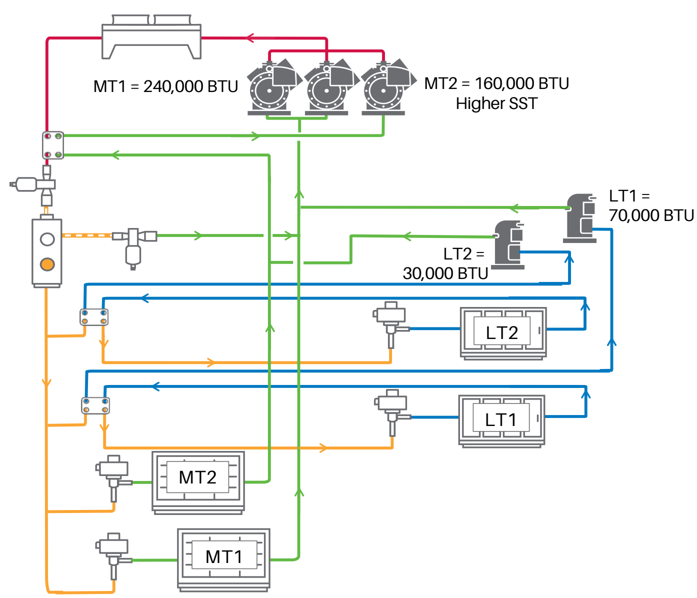


Figure 13: System schematic of dual-suction for MT and LT

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