Commercial Refrigeration: Heat Transfer Optimization and Energy Reduction

Measurement and Verification of a Liquid Refrigerant Pump System Retrofit

Chris Gaul and Michael Sheppy
National Renewable Energy Laboratory

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National Renewable Energy Laboratory
15013 Denver West Parkway
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Executive Summary

Objective

This study describes the test results of a Refrigerant Pump System integrated into a commercial supermarket direct expansion (DX) vapor compression refrigeration system. The Liquid Refrigerant Pump System retrofit (patent-pending; application number 13/964,198) was introduced to NREL in August 2014 by CTA Architects Engineers.

A DX refrigeration system uses a vapor compressor to move both vapor and liquid refrigerant. Liquid refrigerant is moved indirectly by heat energy added to the vapor stream. A Refrigerant Pump System inserts a liquid pump between the condenser outlet and expansion valve inlet to move liquid refrigerant directly by adding kinetic energy to the liquid stream. In a dimensionless and theoretical system, the net effect of exchanging high entropy vapor compressor work for low entropy liquid pump work is higher system exergy.

NREL's interest in the technology includes the potential energy and greenhouse gas emission reductions for existing and new supermarkets and other building types. After examining the Refrigerant Pump System design, available energy measurement data, reliability, maintenance, and food case temperature stability in commercial operation, the product was accepted into the NREL Commercialization Assistance Program for evaluation and analysis.

The refrigeration system was tested in a supermarket located in Freehold, New Jersey from April 6 to June 19, 2015, to measure energy use, review parameters, and observe performance. Based on the results, this report proposes additional system enhancements, along with recommendations for continued study and testing.

Conclusions

NREL measured the energy performance of the Refrigerant Pump System technology in a supermarket hydro-fluorocarbon system operation. The system solves the problems of previous attempts to use a pump to move liquid refrigerant in DX systems. It uses a patented method to provide sufficient net positive suction head (NPSH) to the liquid pump at all times.

The Refrigerant Pump System operated continuously without failure under all weather and refrigeration demand conditions during the testing period. The system was turned on and off to measure performance under similar conditions. Conventional system operation resumed with no further action than switching the unit off.

In summary, the following conclusions were reached:

- **The Refrigerant Pump System provided a regulated liquid refrigerant flow to refrigeration cases in all outdoor temperatures without head (compressor discharge) pressure controls.** A sensor signaled a variable-frequency drive to control pump speed and match refrigerant flow demand. A refrigerant tank provided the required net positive suction head for reliable pump operation. Tank levels were maintained by a sensor to ensure the pump never cavitated.

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- **The refrigerant tank is a key feature.** The tank solves the NPSH issue that caused previous attempts to add liquid pumps to DX systems to be unsuccessful. Liquid line flash gas bubbles and insufficient NPSH would cause pump cavitation and subsequent loss of pressure rise. This led to poor refrigeration system performance and dissatisfied users. The refrigerant tank supplies bubble-free liquid at sufficient head under all conditions to the pump suction for reliable operation.

  Using a tank to provide pump suction head is standard practice in large built-up liquid overfeed industrial refrigeration systems. The concept has been successfully adapted for supermarket DX systems using an eductor venturi device to keep liquid in and vapor out of the tank

- **Reliable pressure boost and energy savings.** The Refrigerant Pump System maintained liquid pressure at 30 pounds per square inch (psi) above compressor discharge pressure. Technical specifications from an expansion valve manufacturer were used to select the 30 psi set-point for highest average expansion valve capacity during all outdoor air temperature and food case load conditions.

  Refrigeration system discharge pressure operated at 125 pounds per square inch gage (psig) and was floated down to the compressor manufacturer's low limit of 70 psig. Refrigeration system suction pressure operated initially at 13 psig and was raised to 17 psig. Energy reductions during a 10-week testing period with an average outdoor temperature of 62.6° Fahrenheit (F) were recorded.

	% Savings: Compressors	% Savings: Total
Ambient Temp. 39.3-50.8°F	25%	11%
Ambient Temp. 50.8-58.9°F	23%	6%
Ambient Temp. 59.3-82.0°F	16%	6%

  Note: lower compressor manufacturer pressure setting limits may be utilized with the Refrigerant Pump System as noted in the *Additional Applications Recommended for Field Testing* section of this paper.

- **Refrigeration system operated using condenser sub-cool fan control while maintaining optimal liquid pressure**. An additional 4.3% energy reduction was recorded compared to energy used during a similar range of outdoor temperatures with the Refrigerant Pump System in operation.

- **Stable system operation in floating head pressure mode**:
  - Food case temperatures were stabilized in cold weather by delivering liquid refrigerant without bubbles/flash gas/vapor and maintaining an optimal pressure drop across expansion valves. This is expected to improve food freshness and safety.
  - The elimination of split condensers, flooding valves, and other minimum discharge pressure measures; no seasonal configuration changes were performed

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when using the Refrigerant Pump System. For the testing period, minimum discharge pressure controls were not needed to maintain stable operation. This indicates maintenance could be reduced by eliminating minimum discharge pressure controls such as split condensers, flooding valves, and dampers.

- **The Refrigerant Pump System is a passive conduit when it is not operating**. The system reverts to conventional DX operation when the Refrigerant Pump System is turned off. If the system fails, liquid refrigerant automatically bypasses it.
  - o This was deemed an important feature for risk-adverse supermarket managers.

The Refrigerant Pump System testing showed energy savings in a commercial supermarket system operation. This report identifies realistic areas for further optimization. More thorough testing is warranted and recommended to determine potential energy savings offered by integration of a Refrigerant Pump System into conventional DX refrigeration systems. Testing should be carried out for a year to have a sufficient sample size covering seasonal weather and shopping patterns.

Measurement and Verification Results

Refrigerant Pump System field testing revealed two major findings:

- Lower energy use over a range of outdoor temperatures

- Condenser fan power needed to maximize refrigerant sub-cooling can exceed energy saved at the compressor and reduce overall system coefficient of performance.

Parasitic condenser fan energy use increased by an average of 71% over the entire test period using conventional floating head pressure/liquid temperature condenser fan control during Refrigerant Pump System operation.

Conventional floating head pressure/liquid temperature control schemes try to maximize sub-cooling. This was found to increase fan energy by 71% over that needed to maintain stable system operation using the Refrigerant Pump System. Average total energy use was reduced by 4.3% when condenser drain leg sub-cooling-based fan control was used during average outdoor temperatures of 73ºF. Recorded savings were from a small sample size at the end of the test period.

An operational mode was designed to control condenser fans without excessive energy use to sub-cool liquid. Testing concluded before this mode could be optimized. Limited data showed the condenser would adequately reject refrigeration system heat with fans off in 60°F overcast weather. The median temperature at the test location is 56°F indicating condenser fan energy saving opportunities much of the year.

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1 System Description

In a direct expansion (DX) supermarket refrigeration system:

- One or more compressors move high pressure refrigerant vapor through a condenser that rejects heat to outside air, causing vapor to phase change into liquid
- Expansion valve(s) meters high pressure liquid into one or more low pressure evaporators
- Low pressure evaporators phase change liquid to vapor, which absorbs heat
- Low pressure vapor flows to the compressor and the cycle repeats

Vapor leaving the compressor is at high pressure and temperature; it is superheated above its saturated pressure due to the added work of the compressor. Compressors at one time were all reciprocating pistons in cylinders capped with cylinder heads. The term head pressure is synonymous with discharge pressure.

Vapor leaving the evaporator is at low pressure and temperature. It is also superheated to ensure the refrigerant has done all its useful work and to prevent damaging liquid droplets from entering the vapor compressor. Suction pressure describes the condition in the conduit between the evaporator and compressor.

Refrigerants in a saturated state are at their highest heat transfer capacity. Saturated vapor is 100% gas at a temperature where it is ready to condense into liquid. Saturated liquid is ready to evaporate into vapor. Vapor above saturation temperature is superheated. Liquid below saturated temperature is sub-cooled. Sub-cooled liquid is bubble-free.

Refrigeration heat exchangers are most effective when operating at saturation temperatures. In practice, pressure losses cause saturated liquid refrigerant to form flash gas bubbles that impede fluid flow through expansion valves. Superheated vapor exiting the compressor must lose sensible heat before it can change phase in the condenser. These conditions reduce heat transfer effectiveness.

1.1 Refrigerant Pump System Operation: Floating Head Pressure

The heart of a DX refrigeration system is the compressor, a machine that converts electricity into heat in the form of gas pressure. It supplies the motive force to move refrigerant through the cooling system. A compressor pumps vapor directly, and through vapor pressure, indirectly causes liquid refrigerant to flow. The Gas Laws show that in a conventional vapor compression system vapor pressure increases are accompanied by liquid refrigerant temperature increases.

From a purely thermodynamic point of view DX supermarket refrigeration systems should be the most energy efficient with the highest coefficient of performance (COP) in cold weather because they have to perform less work moving heat from a cold food case to the cold outdoors. Head pressure should be able to float downward to take advantage of cooler condensing temperature. In practice, a conventional DX system cannot take full advantage of low outdoor temperatures. Since the compressor is the only means of moving liquid through the system and it does so by applying vapor pressure to liquid there is a lower limit to reducing compressor work before there is not enough motive force to move refrigerant through the system.

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Refrigerated case cooling takes place in evaporators fed by expansion valves. Expansion valve mass flow is affected by pressure differential and bubbles in the liquid refrigerant. If differential pressure across the expansion valve is low and bubbles are present, refrigerant mass flow and, in turn, food case cooling is reduced. When a lower limit is reached and food cases no longer maintain temperature set points, the store calls a service technician for help. The technician will attempt to remedy the problem by adjusting various parameters to raise condensing pressure. If these efforts are unsuccessful the technician will force compressors to run longer to keep food cases cold. This increases pressure differential across the expansion valve while lowering suction pressure and evaporating refrigerant temperature. Case temperatures are restored at the expense of using more energy to cool the load.

In practice, DX systems are unable to full advantage of floating head pressure to raise COP.

1.2 Refrigerant Pump System Operation: Liquid Pumping

The Refrigerant Pump System separates the tasks of pumping vapor and liquid: compressors move vapor and a pump moves liquid. Gas Laws therefore do not apply because the fluid streams are decoupled and partitioned. A liquid pump increases pressure directly by adding kinetic energy to the fluid stream. A pump is on the order of 100 times more efficient than a compressor in converting electricity into liquid pressure. The tested Refrigeration Pump System uses a variable speed drive 1 HP canned motor centrifugal pump (smallest size available) on a 30 HP refrigeration system.

The Refrigerant Pump System increases liquid above saturation pressure causing it to become sub-cooled and bubble-free without lowering temperature. The Refrigerant Pump System provides sub-cooled liquid with less energy input than running condenser fans.

 Liquid sub-cooled by increased pressure has a saturation temperature higher than indoor air temperature. It will not form flash gas bubbles between the refrigeration machine room and loads on the store sales floor. This system can be expected to provide bubble-free liquid refrigerant to expansion valves under all weather conditions.

Figure 1 illustrates Refrigerant Pump System integration in a supermarket refrigeration system. The tested Refrigerant Pump System has a footprint of 2 X 2 feet and can be retrofitted into an existing DX refrigeration system by a qualified contractor.
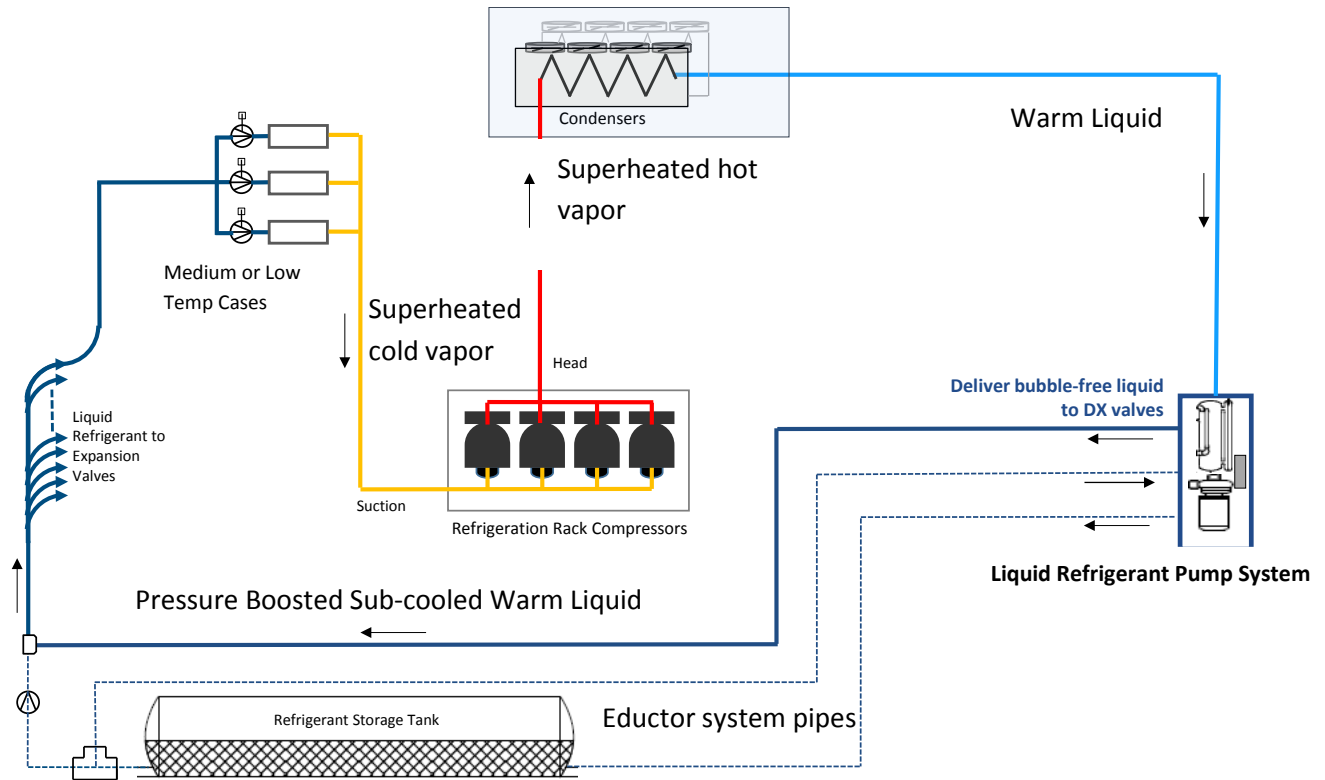
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Figure 1. Refrigerant Pump integration into Supermarket DX System

1.3 Refrigerant Pump System Operation: Cold Weather

Supermarket DX refrigeration systems must operate in all weather. A properly sized condensing unit will perform satisfactorily during the hottest outdoor temperatures. However, systems generally operate at below design dry bulb temperature most of the year. It is during cold weather when satisfactory conventional DX operation becomes complex.

In conventional DX refrigeration systems as condensing pressure/temperature floats downward with outdoor temperature bubbles/flash gas/vapor can form in the liquid refrigerant line. Bubbles coupled with low pressure differential across the expansion valves reduces refrigerant flow which adversely affects case temperatures. Evaporators starved for refrigerant can get very cold from low suction pressure leading to excessive frost buildup, insufficient heat transfer, and poor food case temperatures. It is often necessary reduce suction pressure by running more compressor capacity to overcome this problem.

The conventional cold weather solution to provide adequate liquid pressure to expansion valves is to restrict liquid flow from the condenser to the receiver and divert compressor discharge hot gas to the inlet of the receiver. This backs liquid refrigerant up into the condenser, reducing its heat rejection capacity, which increases the condensing pressure. At the same time the hot gas raises liquid pressure and temperature in the receiver, allowing the system to satisfactorily cool food cases.

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A Refrigerant Pump System functions as a mechanical sub-cooler. It adds pressure instead of lowering temperature to sub-cool liquid. This allows it to sub-cool liquid independent of outdoor temperature. The theoretical advantage of improved COP in cold weather can be achieved in actual operation.

1.4 Refrigerant Pump System Operation: Expansion Valves

Expansion valves control the flow of liquid refrigerant entering the evaporator by maintaining a constant superheat in refrigerant vapor at the evaporator outlet. Superheated suction vapor is necessary to ensure the refrigerant has performed all useful work and that no damaging liquid droplets reach the vapor compressor.

Expansion valves work best when supplied with bubble-free liquid. Even slightly sub-cooled liquid has no bubbles. Conventional DX systems sub-cool liquid refrigerant by removing sensible heat, generally by running condenser fans such that liquid refrigerant approaches outdoor air temperature. Liquid refrigerant sub-cooled by reducing its temperature with cold outside air can warm up while passing through store spaces and lose its sub-cooling on its way to refrigeration loads. Bubbles may form in liquid feeding expansion valves, reducing refrigerant mass flow and evaporator cooling capacity.

Liquid line flash gas problems have been addressed by adopting electric expansion valves. Thermostatic and electric expansion valves of the same port size have identical capacities for all operating conditions. Electric expansion valves adjust more quickly and accurately than mechanical thermostatic expansion valves. Electric expansion valves mitigate, but do not solve, liquid refrigerant delivery problems created in low outdoor temperature operation and during dynamic changes in cooling and defrost loads.

A Refrigerant Pump System supplies expansion valves with bubble-free liquid at sufficient pressure to provide full cooling capacity and stable operation independent of head pressure.

2 Test Set Up

The refrigeration rack controller recorded pressures, temperatures, and numbers of compressors and condenser fans operating. Compressor and condenser fan energy use was recorded in Volt-Amperes using current transformers on three phases. Data was automatically uploaded through a wireless modem to a Cloud-based data acquisition system. Testing compared the Refrigeration Pump System on vs. off in varying outdoor temperatures. Condenser fans were constant speed and not equipped with variable-frequency drives.

Table 1. Test Overview and Parameters

Test Overview	Tested Load and Static Parameters
Test period: **April 6-June 19, 2015**	Design comp. load (Btu/hr.): **247,500**
Location: **Freehold, New Jersey**	Refrigerant: **R-134A**
Equipment tested: **Liquid Refrigerant Pump System retrofit (patent-pending; application number 13/964,198)**	Dew point cond. temperature: **110°F**
	Dew point evap. temperature: **15°F**
Total testing days: **63**	Evap. superheat.: **10°F**
Average outdoor temperature: **62.6°F**	Condenser-outdoor ΔT: **13°F**
Average outdoor daily temperature range: **39-82°F**	Return gas temperature: **65°F**

Test Scenarios and Variable Parameters

- Refrigerant Pump System OFF (baseline measurements)
    - Condensing temperature set-point: 100°F
    - Saturated suction pressure set-point: 13 psig (12°F)

- Refrigerant Pump System ON
    - Condensing temperature set-point: 70°F
    - Saturated suction pressure set-point: 17 psig (18°F)
    (As stated above, suction pressure is increased when using the Refrigerant Pump System because a pure column of pressurized liquid is delivered to evaporator expansion valves).
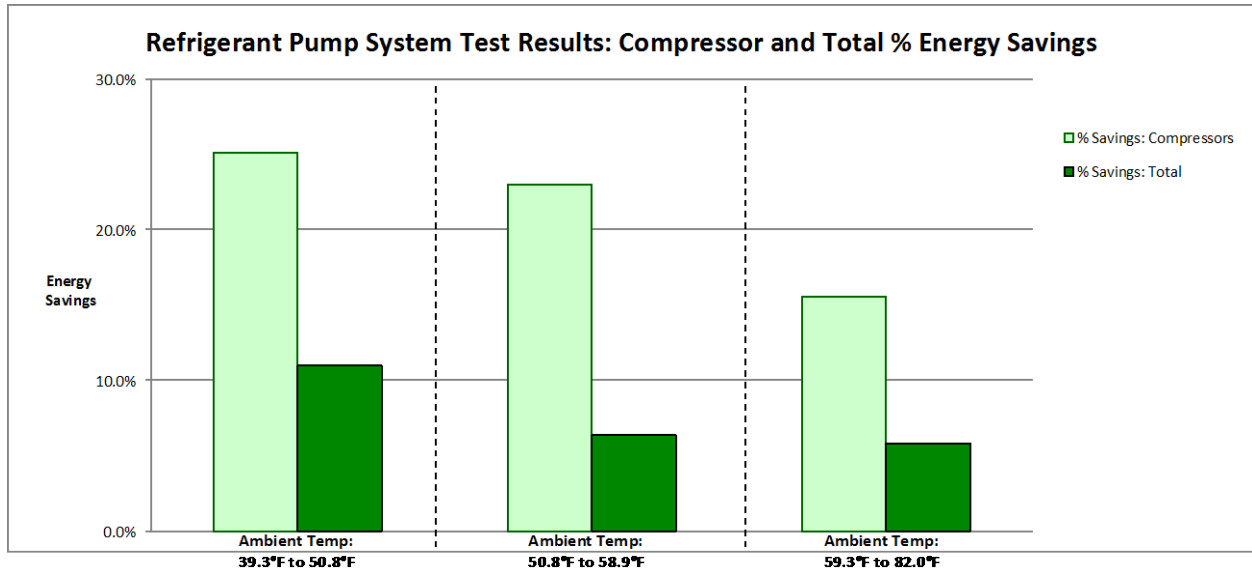
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Test Results Data

Figure 2. Compressors and total energy savings percent by outdoor temperature range with Refrigerant Pump System ON, Condenser fans providing excessive sub-cooling.
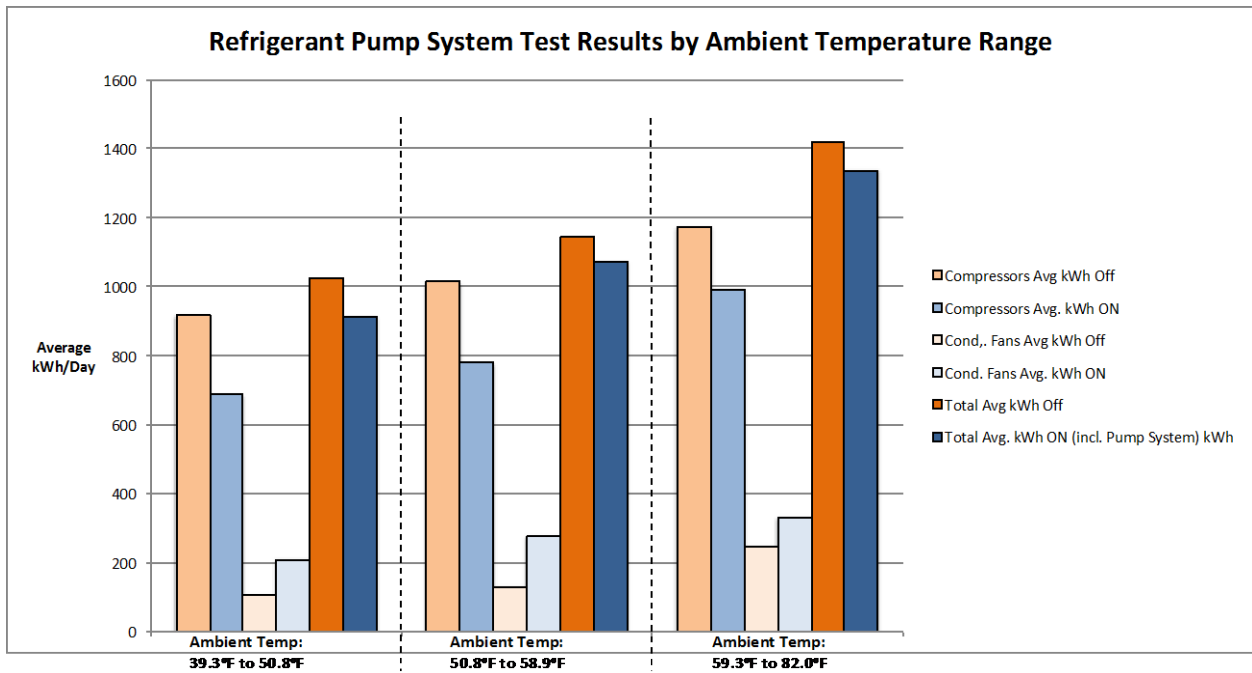

Figure 3. Compressors, condenser fans, total energy use by outdoor temperature range for Refrigerant Pump System ON vs. OFF.

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Analysis:

Energy savings with Liquid Refrigerant Pump on and head pressure allowed to float down with cool outdoor temperature yielded less than anticipated energy savings. Condenser fans were set to achieve 70 psig head pressure which equates to 69°F condensing temperature.

It was ascertained that with a 13°F condenser temperature differential outside air would have to be below 56°F for condensed liquid to reach 69°F. Operators often regard the extra fan power expended trying to reach 70 psig as providing useful liquid sub-cooling that in theory increases refrigeration effect and reduces compressor load. Tests show that compressor energy savings were offset by high fan power. Sub-cooling performance gains did not justify the fan energy expended.

A test scheme was devised using the refrigeration rack controller to balance head pressure with condensed liquid temperature. Fans were staged to provide slight but not excessive sub-cooling. This idea came late in testing with limited data collected. In a fully developed control scheme the rack controller would optimize compressor energy and variable speed condenser fans to achieve the highest system COP.

3 Future Work: Additional Applications Recommended for Field Testing

The Refrigerant Pump System offers potential applications for further energy reduction and efficiency improvements. In summary:

- The technology allows for stable operation at condensing temperatures of 40ºF and below while maintaining bubble-free liquid to expansion valves. Unlike other floating head pressure techniques, split condensers, flooding valves, and other minimum discharge pressure measures are not needed and consequently do not negatively impact exergy (eliminating head pressure controls would partly offset the Refrigerant Pump System added cost).

- The Refrigerant Pump System can be configured to inject liquid refrigerant into the compressor discharge vapor stream to remove superheat. Saturated vapor entering the condenser is expected to improve its heat exchange effectiveness.

- Liquid injection de-superheating and controlling sub-cooling by varying condenser fan air flow opens the possibly to increase COP by coupling the refrigeration system to the supermarket air conditioning system (Figure 6):

    - During lower outdoor temperatures refrigerant flows to the outdoor condenser in the normal manner.

    - During higher outdoor temperatures refrigerant is diverted from the outdoor condenser to a heat exchanger cooled by the supermarket air conditioning to become a cascade cooling system.

- Successful testing of a cascade using common hydro-fluorocarbon refrigerant opens a path to developing a sub-critical carbon dioxide (CO_2) system suitable for warm climates.

3.1 De-Superheating Discharge Vapor

Head pressure is the highest pressure in a conventional DX refrigeration system. A Refrigerant Pump System increases liquid refrigerant to 30 psi above head pressure. This allows a means of improving condenser heat exchange effectiveness.

It is expected that all other things being equal, refrigerant phase changing on a conduit surface provides more effective heat transfer than conduction.

In conventional DX refrigeration systems the compressor discharge line carries superheated vapor to the condenser. The condenser rejects heat by blowing outdoor air over tubes carrying refrigerant. The condenser removes heat by cooling superheated vapor to saturation temperature through conduction, phase changing (condensing) vapor into liquid, and finally sub-cooling liquid by conduction. The fraction of heat exchange surface needed to cool superheated vapor into saturated, ready to condense vapor varies depending on vapor and outdoor air temperatures.

In a Refrigerant Pump System, liquid is available at higher than head pressure. Liquid refrigerant can be injected in a controlled manner into the superheated vapor compressor discharge line to the condenser. The liquid refrigerant absorbs sensible heat by changing state and giving up its

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latent heat. It flashes from liquid to vapor and cools superheated discharge gas. Injecting sufficient liquid reduces discharge vapor to saturated temperature. The saturated vapor stream enters the condenser ready to phase change into liquid. No portion of the condenser heat exchange surface is needed for de-superheating by conduction.

Liquid injection to de-superheat discharge gas is theorized to improve condenser heat transfer effectiveness by using the entire surface area for phase change. It is further expected to improve effectiveness by increasing refrigerant mass flow through the condenser. A Refrigerant Pump System separates vapor and liquid refrigerant streams making it possible to flow more refrigerant through the condenser than the evaporator. This is not feasible with a conventional DX system. It is important to note that using refrigerant for de-superheating would not reduce refrigerant available to evaporators.

Liquid injected for de-superheating would be metered through an electric stepper valve connected to the rack controller. The controller would adjust injection rate based on compressor discharge vapor and condensed liquid temperatures and pressures.

Improved condenser heat exchanger effectiveness means less airflow is needed to reject refrigerant heat to outdoor air which would save fan power. The refrigeration system controller would measure compressor and fan power to provide optimum airflow for best COP.

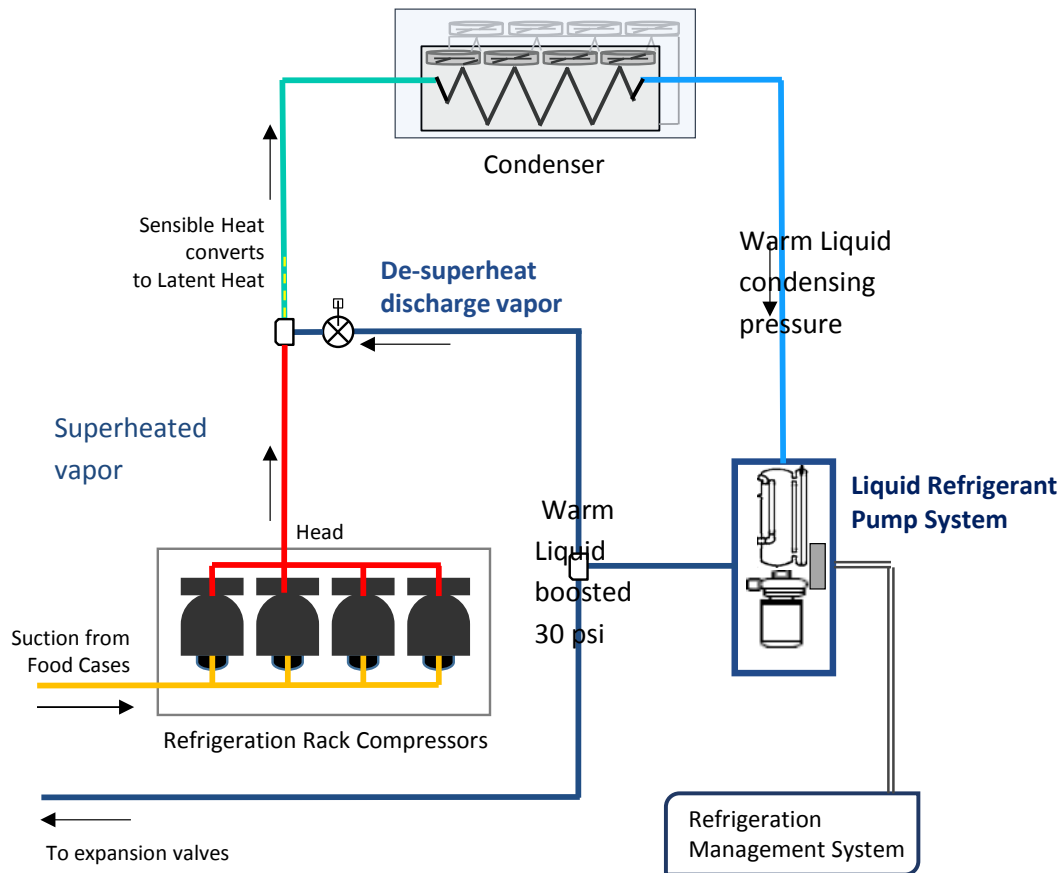Figure 4 shows the Refrigerant Pump System configured for de-superheating.

Figure 4. Refrigerant Pump System with discharge gas de-superheating.

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There are potential energy savings due to reduced condenser fan operation using de-superheating and sub-cooling-based fan control, as well as the addition of variable-frequency drives. Field testing measurement and verification is recommended. Figure 5 illustrates the de-superheating process on a pressure-enthalpy chart.
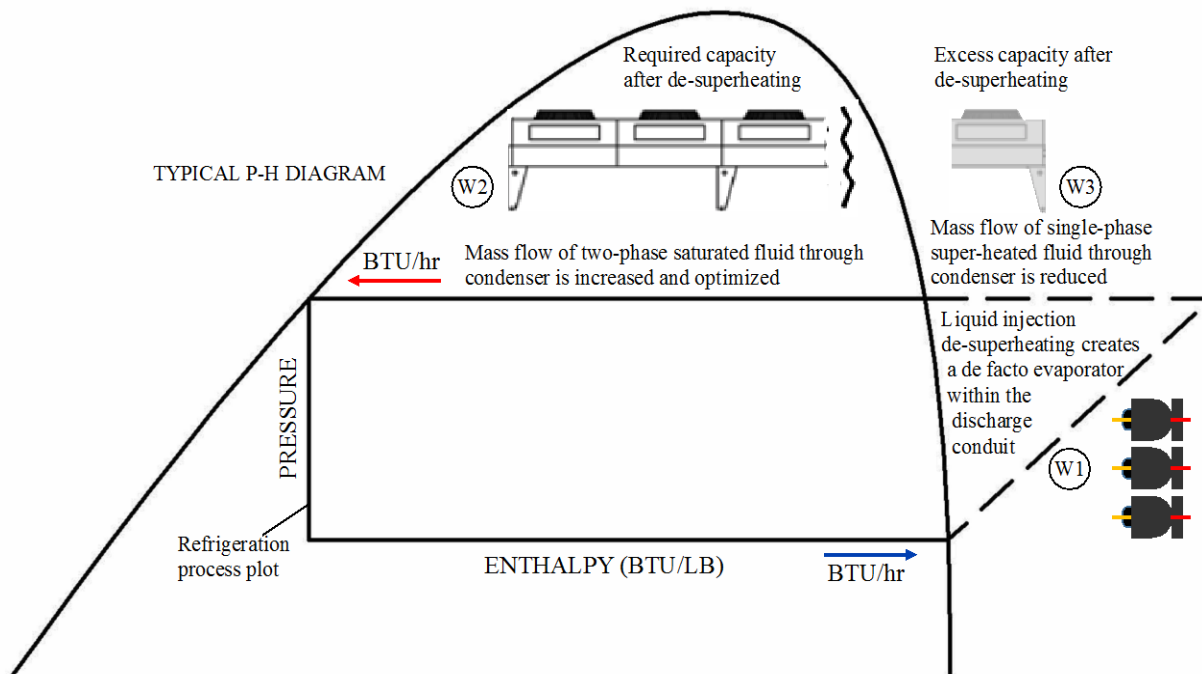

Figure 5. Typical pressure-enthalpy diagram using de-superheating.

Field testing indicates that sub-cooling liquid refrigerant by more than necessary for stable system operation is counterproductive. More fan power is used than is saved at the compressor.

Reducing vapor temperature entering the condenser reduces thermal stress and condenser surface degradation. This will reduce refrigerant leaks. In water-cooled equipment, lower refrigerant temperature reduces mineral scaling on heat exchange surfaces.

Field testing is required to optimize liquid injection de-superheating.

3.2 Cascade Refrigeration

Nearly all U.S. supermarkets have air conditioning. A Refrigerant Pump System opens the possibility of using the supermarket air conditioning system instead of outside air as a condensing medium. In hot weather the refrigeration system would work as a cascade condenser which is expected to improve refrigeration system COP. Research is needed to determine if overall refrigeration and air conditioning energy use would benefit from this arrangement.

Figure 6 illustrates the Refrigerant Pump System theoretical application of de-superheating discharge vapor and use of a high-COP cascade condenser enabling refrigeration system operation at reduced condensing temperatures year-round.
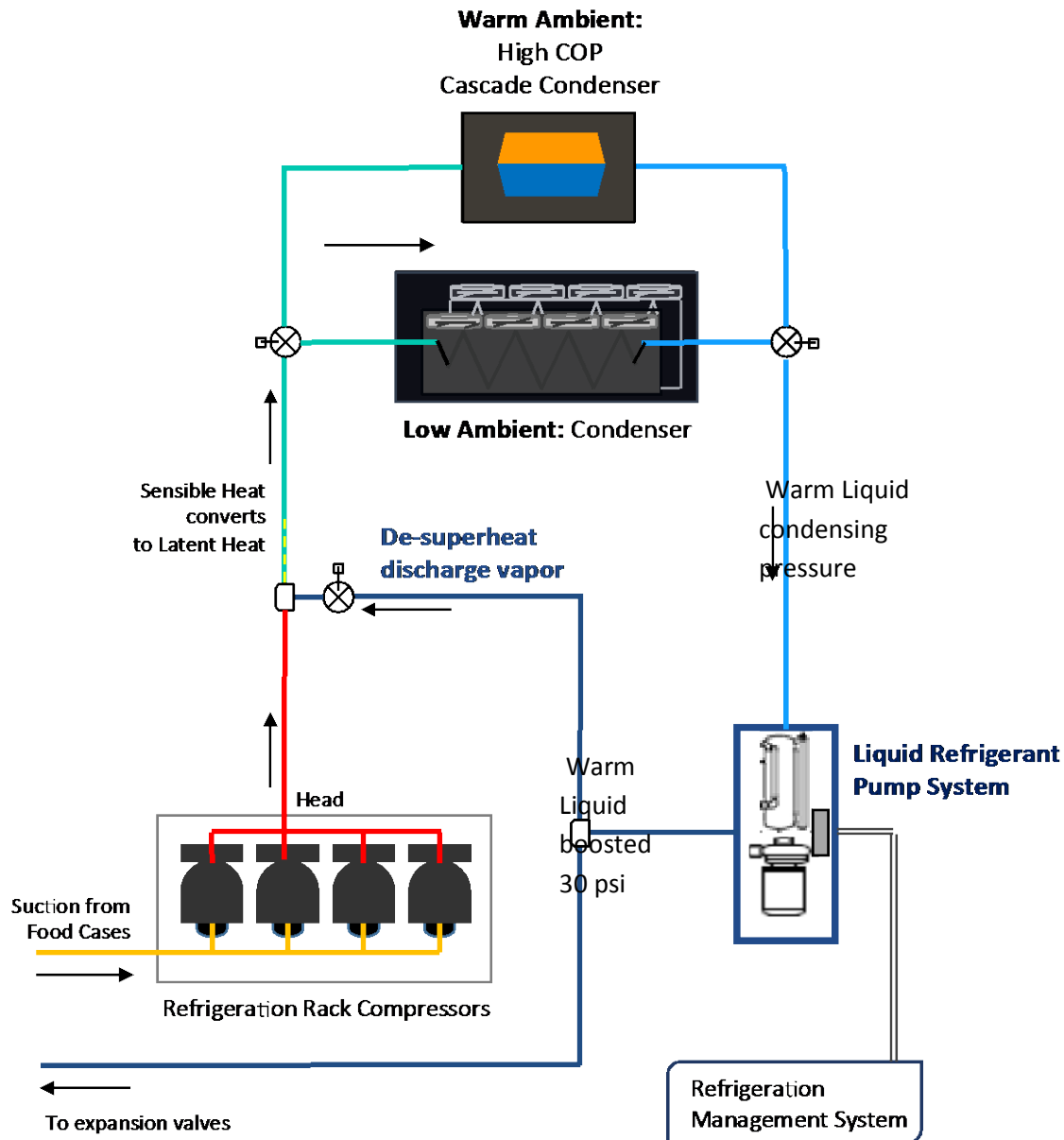
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Figure 6. De-superheating and use of a high-COP cascade condenser.

3.3 Enabling Efficient CO_2 DX Refrigeration Systems

Supermarket refrigeration system designers are interested in CO_2 refrigerant because it is plentiful and will never face phase-out as has happened with popular synthetic refrigerants. CO_2 has a critical pressure of 1,055 psig at 87.7°F. Above these conditions, transcritical CO_2 is neither liquid nor vapor. Since most climates experience outdoor air temperatures above 87°F, some means other than a condenser is required to reject heat.

When a transcritical CO_2 refrigeration cycle is plotted on pressure enthalpy and temperature entropy diagrams, it becomes apparent that the physical and thermodynamic properties of CO_2

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make it a poor choice for refrigeration condensing units operating in high outdoor temperatures. CO_2 is a better choice for refrigeration condensing units operating in cool climates.

Figure 7 illustrates the reduction in COP for CO_2 as ambient temperature rises (from Emerson Climate Technologies TEG124-0910/E Study).
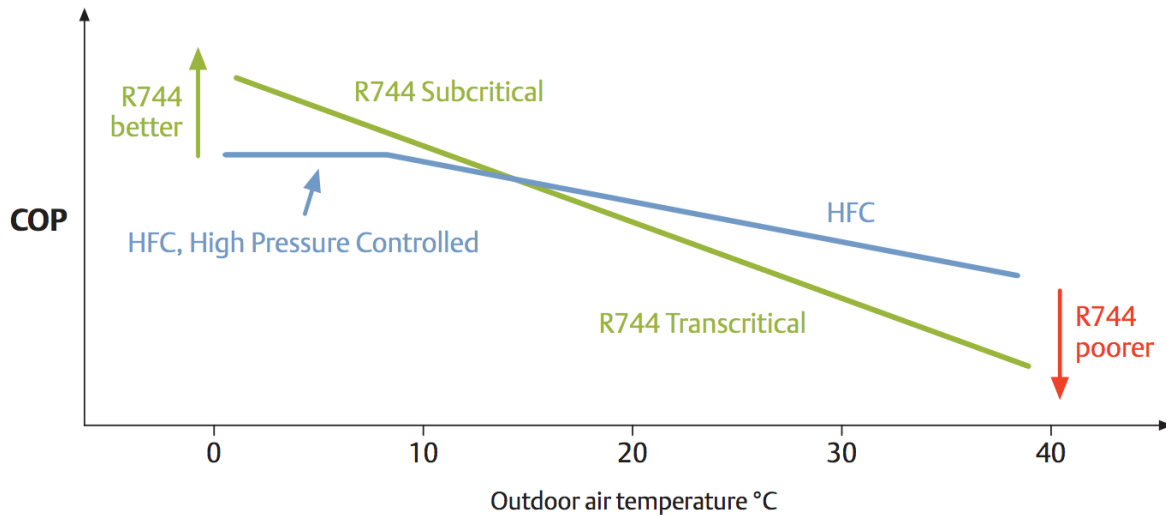

Figure 7. Comparison of CO₂ (R744) COP vs. hydro-fluorocarbon refrigerant.

During moderate to high outdoor temperatures, the high-pressure throttle valve and flash gas bypass valve combination have been adopted to transfer heat energy and pressure from the transcritical CO_2 to the condensing unit in order to return it to its liquid state. The high-pressure throttle valve and flash gas bypass valve combination do not utilize an efficient change of state refrigeration effect to accomplish heat rejection for changing discharge fluid to liquid. This energy efficiency tradeoff should be recommended when designing a refrigeration system using only CO2.

In transcritical mode CO_2 system COPs are lower than conventional vapor compression systems. In warmer climates this penalizes CO_2. Other refrigerants such as R410a have higher COPs in warmer climates.

As previously described for a hydro-fluorocarbon system, a CO_2 system with Refrigerant Pump System can utilize discharge fluid heat transfer optimization to make subcritical operation possible year-round when paired with a high-COP cascade condenser as shown in Figure 8.
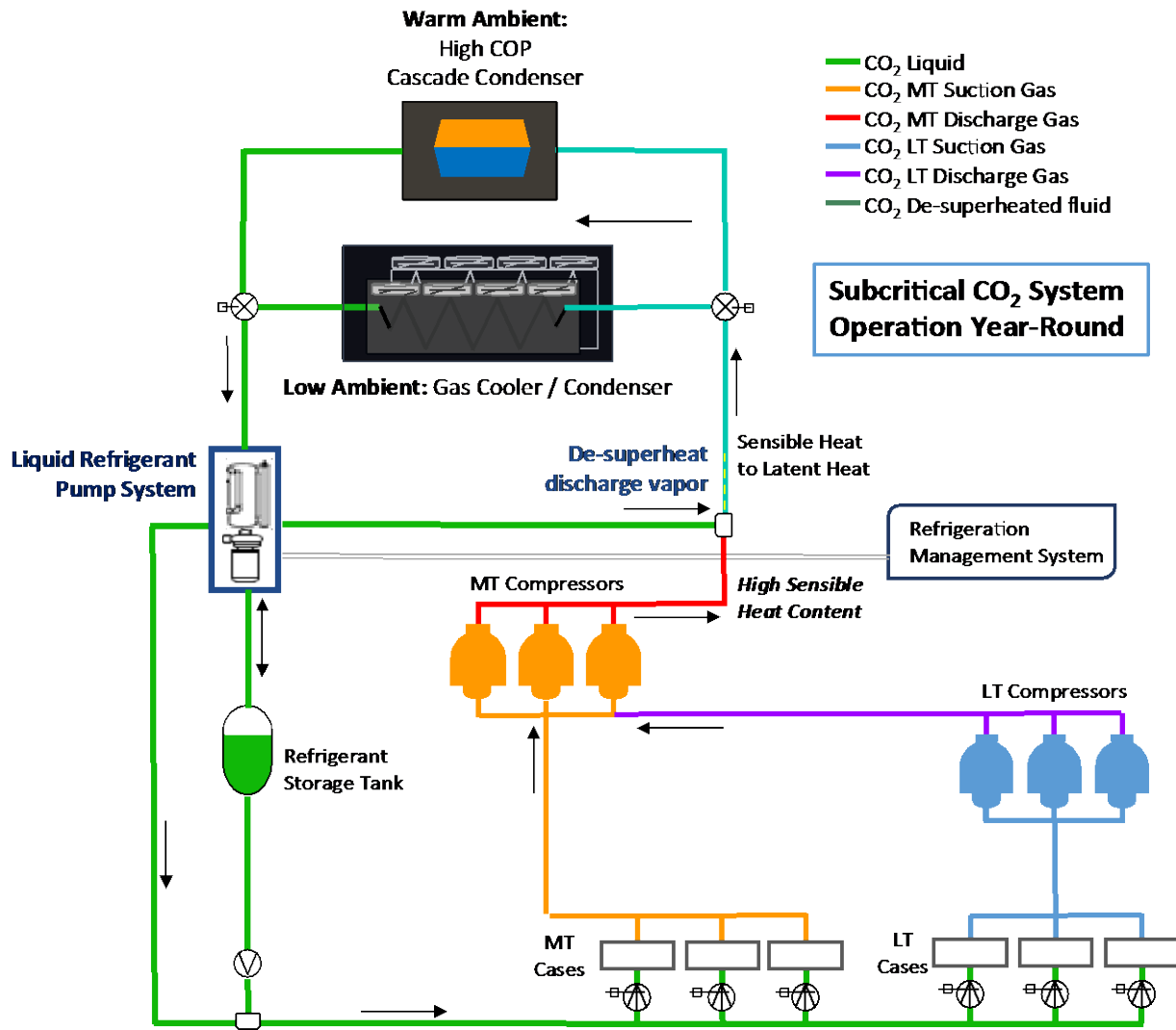
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Figure 8. De-superheating in a CO_2 system.

The liquid to vapor change of state results in a subcritical fluid mixture with a higher heat transfer coefficient and a lower temperature. The lower temperature subcritical fluid will divert from the gas cooler/condenser. The lower temperature fluid will instead be sent to a high-COP cascade condenser for further heat removal and condensation.

The result of utilizing the Refrigerant Pump System de-superheating application is an increase in total system COP, subcritical CO_2 refrigeration operation year-round, and a technically viable CO_2 refrigeration option for warm climates.

A natural refrigerant such as R-717 (ammonia) may be desired in such a cascade system, as is done in industrial practice. However heating, ventilating, air conditioning, and refrigeration systems using R-410A or other synthetic refrigerant will continue to be used in supermarkets for the foreseeable future.

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Appendix

TEV Capacity Calculations: Without and With Refrigerant Pump System Retrofit

Information Courtesy of Sporlan Division – Parker Hannifin Corporation, Sporlan Division bulletin 10-10 / 411_Thermostatic Expansion Valves with Selective Thermostatic Charges

Pressure Drop Across TEV (psig)		EVAP Temp °F	COND Temp °F	TEV Capacity without Refrigerant Pump System Based on Nominal 1 Ton Valve Types F-EF-G-EG	TEV Capacity with Refrigerant Pump System	% TEV Capacity Increase with Refrigerant Pump System
without Refrigerant Pump System	+30psi with Refrigerant Pump System					
Medium Temp						
15.00	45.00	20	50	Valve inoperable	1.01	Valve operable
35.70	65.70	20	60	0.83	1.12	36.0%
59.00	89.00	20	70	1.00	1.23	22.7%
85.10	115.10	20	80	1.10	1.28	16.9%
114.20	144.20	20	90	1.17	1.32	13.0%
146.50	176.50	20	100	1.19	1.30	9.3%
182.20	212.20	20	110	1.17	1.26	8.0%
Low Temp						
54.30	84.30	-20	50	0.88	1.09	24.4%
75.00	105.00	-20	60	0.95	1.13	18.0%
98.30	128.30	-20	70	1.03	1.16	13.2%
124.40	154.40	-20	80	1.04	1.17	11.6%
153.50	183.50	-20	90	1.06	1.16	9.1%
185.80	215.80	-20	100	1.04	1.12	7.6%
221.50	251.50	-20	110	1.01	1.08	7.0%

Test Equipment Utilized

Panoramic Power® Cloud based energy data acquisition and analysis tool
Current Transformer amperage transducers
Wireless Bridge