TECHNICAL FEATURE

Transcritical CO_2 Supermarket Refrigeration

BY COLLIN WEBER, ASSOCIATE MEMBER ASHRAE; HARRISON HORNING, P.E.

Hannaford Supermarkets opened a store in Turner, Maine, featuring the first transcritical (TC) carbon dioxide supermarket refrigeration system in the United States. The two-year-old, 35,000 ft^2 (3252 m^2) new-construction supermarket includes conditioned and refrigerated merchandising space, as well as food preparation areas and offices. The TC CO_2 refrigeration system serves a total of 740 kBtu/h (217 kW) of combined low- and medium-temperature loads, while providing high-quality waste heat that meets much of the store's space heating needs.

From Fall 2013 through Summer 2014, Hannaford partnered with the U.S. Department of Energy's Better Buildings Alliance (http://tinyurl.com/qbxucjf) to conduct a study comparing the site to a legacy store in Bradford, Vermont, that uses a hydrofluorocarbon (HFC) refrigeration system. During the one-year data collection period, the TC CO_2 system achieved approximate energy parity with the HFC system, while reducing storewide carbon equivalent emissions by 12%. The full report, Case Study: Transcritical Carbon Dioxide Supermarket Refrigeration Systems, is available at http://tinyurl.com/qbrx4hs.

Installation Overview and Study Background

TC CO_2 systems, unlike carbon dioxide cascade systems, use carbon dioxide as the sole working fluid. The TC cycle, as the name suggests, involves cycling of the refrigerant between the subcritical and supercritical phases. When a refrigeration system is operating transcritically, heat rejection occurs above the critical pressure, while cooling takes place below the critical pressure. The use of carbon dioxide as the sole working fluid and the inherent high working pressure arising from it is the driver of many design differences between TC CO_2 booster systems and conventional refrigeration systems.

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TABLE 1 Refrigeration system profiles.

REFRIGERATION LOAD TYPE	BRADFORD (HFC)	TURNER (TC)
Low-Temperature Reach-In Cases (Number of Doors)	102	102
Low-Temperature Island Cases (ft)	28	28
Medium-Temperature Open Cases (ft)	318	314
Medium-Temperature Reach-In Cases (Number of Doors)	49	49
Walk-In Coolers	4	4
Walk-In Freezers	2	2
Total Refrigeration Load (Btu/h)	750,000	740,000
Total Installed Compressor Power (hp)	181	201
Type of Expansion Valves	EEV (Pulse Type)	EEV (Stepper Type)
Defrost Scheme	Electric	Hot Gas

TABLE 2 Building HVAC specifications.

HVAC SYSTEM PARAMETER	BRADFORD (HFC)	TURNER (TC)
Air Handler Outdoor Airflow Capacity (cfm)	4,100	5,000
Air Handler Supply Airflow Capacity (cfm)	36,100	34,000
Space Cooling Capacity (MBtu/h)	950	908
Estimated Heat Reclaim Capacity (MBtu/h)(Based On Available Heat of Rejection from Refrigeration)*	Up to 900	500 – 1,000
Nominal Heat Reclaim Loop Design Temperature (°F)	100	120
Nominal Boiler Output Capacity (MBtuH)	638	638

*TC CO_2 systems differ from full condensing heat reclaim in that heat reclaim is conducted directly off the compressor discharge line. As a result, not all of the available waste heat is reclaimed. However, this configuration is better-suited to the characteristics of TC CO_2, which performs inefficiently at the high heat rejection temperatures that would be needed to obtain high quality waste heat from a full-condensing type configuration applied to the CO_2 gas cooler.

Compressor output pressure often exceeds 1,000 psia (6895 kPa).

While a mature technology in Europe and Canada, TC CO_2 refrigeration is in the early stages of deployment in the United States. Motivated by the success of the technology in other cold-weather regions, Northeastern U.S. retailer Hannaford elected to pilot a TC CO_2 refrigeration system in its new-construction supermarket in Turner, Maine. Hannaford worked with a supplier with significant experience in the sector to develop a system for its application.

The TC CO_2 system at the Hannaford store in Turner consists of a single rack for both medium- and low-temperature applications, comprising three low-temperature compressors and six medium-temperature TC compressors. The store uses an air-cooled gas cooler (the equivalent of the condenser in a conventional system) mounted on the roof for heat rejection. For heat reclaim, an array of heat exchangers is connected to the system using steel piping, which is commonly used in TC CO_2 systems due to the need to accommodate the extremely high compressor discharge pressures. The heat reclaim loop uses a propylene glycol and water mixture as the working fluid.

In addition to TC CO_2, the refrigeration system also uses hot-gas defrost and stepper type electronic expansion valves (EEVs). Hannaford estimates that the incremental cost of the TC CO_2 system (over a prototypical brand-standard HFC system) was about 40% for the refrigeration equipment alone, in addition to a 10% to 15% incremental cost for piping and display cases. Additionally, due to the unique nature of this pilot project, installation and start-up costs were elevated above those associated with a prototypical HFC system.

In Spring 2013, Hannaford and the U.S. Department of Energy's Better Buildings Alliance Refrigeration Technology Solutions Team began a collaborative study of the TC CO_2 pilot site. The study focused on a year's worth of submetered energy data collected at the pilot store, and at a comparable store in the region, to evaluate the energy, climate, and operational impacts of implementing the TC CO_2 system.

Study Site and Comparison Store

For the purposes of this study, Hannaford and DOE focused on the Turner TC CO_2 pilot store, and chose a supermarket using a conventional HFC-based system located in nearby Bradford, Vermont, as a baseline for comparison of the energy performance. Turner and Bradford (about 95 miles west of Turner) experience similar climates, and both stores are in ASHRAE Climate Zone 6A,[1] making them well-suited for comparison.

The supermarkets at the two sites have very similar layouts, refrigeration loads, and envelope characteristics. The number and configuration of the display cases and walk-in coolers/freezers is nearly identical in the two stores, and they share the same temperature setpoints. *Tables 1* and *2* provide characteristics of the stores' refrigeration and HVAC systems.

Heat Reclaim

Both stores compared in this case study use similar HVAC and heat reclaim systems. The main HVAC equipment has a direct expansion cooling coil, glycol/water heat reclaim coil, and glycol/water boiler coil, in that order. The heat reclaim system provides the primary means of space heating (i.e., the first stage of heat during the heating season) and reheat (for dehumidification of outdoor air during the cooling season). The boiler system provides auxiliary (second-stage) heat as needed.

The Bradford (HFC) system is set up for "full-condensing"[2] heat reclaim for heating in the winter, and reheat during active dehumidification in the summer. When space heating is needed, the refrigeration system operates at elevated head pressures to achieve the condensing temperature desired for heat reclaim.

PHOTO 1 Gas cooler located on the roof of the Turner store.

Maintaining an elevated head pressure during the heating season significantly increases electricity use. To mitigate this energy penalty, the Bradford store has three stages of heat reclaim, one per rack. For many hours during the heating season, one or more of the refrigeration racks are not called for heating, and they continue to operate with a very efficient "floating head" strategy.[3]

In spite of the increased electricity use, the heat reclaim system displaces a significant amount of purchased fuel. Given the high cost of propane (the heating fuel available for rural stores in the Northeastern U.S.), Hannaford finds that this makes economic sense. The cost of electricity at Bradford is around \$0.115/kWh throughout the year,[4] but the winter prices of propane can rise to upwards of \$2 per gallon. On a per-Btu basis, this is analogous to a price of \$2.19 per therm of natural gas.[5] Operators having access to low-cost natural gas might reach

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a different conclusion regarding this space-heating technology.

In contrast to Bradford, the Turner system is set up for conventional series heat reclaim, leveraging the naturally high discharge temperatures of TC CO_2. Due to the fundamental thermodynamics of a TC CO_2 process, "full-condensing" heat reclaim is not practical. However, the high discharge temperatures allow for substantial heat recovery at moderate load conditions. (Note: It is considered uneconomical to pursue heat reclaim at high load conditions due to the high electricity demand at high discharge temperatures with TC CO_2 systems.)

When a low indoor temperature is recorded at Turner, the control system calls for the first stage of heating and the racks switch over to heat-reclaim mode: hot gas from the compressor discharge is diverted through a heat exchanger on its way to the gas cooler. Heat recovery from the compressor discharge line occurs at about 120°F (49°C) in the glycol/water loop, compared to a nominal heat glycol/water design temperature of about 100°F (38°C) at the Bradford store.

The higher reclaim temperature at Turner allows for smaller coils and lower airflow than are needed in the HVAC system at Bradford. The Turner heat reclaim system also appears, nearly two years into its operation, to be more intuitive than the Bradford system and is likely to have better persistence of savings after initial commissioning.

Site Data Collection

Hannaford monitored the stores for one year, from September 2013 to August 2014, for the purposes of this case study. Hannaford collected submetered electric data at each compressor rack, as well as the gas cooler and glycol pump for the Turner TC CO_2 system, at five-minute intervals. In addition, Hannaford monitored monthly utility bills (electricity and propane) to evaluate the effect of heat reclaim from the TC CO_2 system on building heating, ventilating, and air-conditioning energy use.[6]

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FIGURE 1 Comparison of refrigeration system monthly electricity consumption.

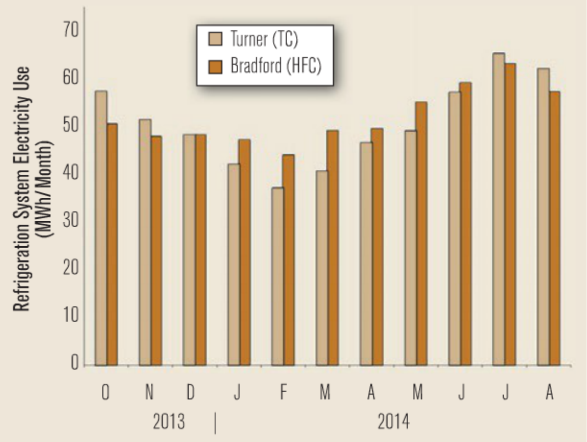
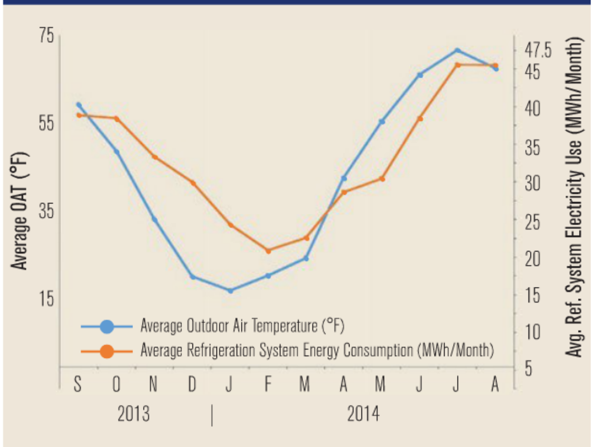


FIGURE 2 Turner store temperature and power consumption trends – monthly.



Hannaford also installed additional electric submeters to capture the energy use of systems that differed between the stores. Specifically, the Turner store featured a well and a wastewater treatment facility. Additionally, there were differences in exterior lighting between the two sites. Submetering of these disparate loads allowed the net energy consumption data to be adjusted to provide a more accurate comparison between the sites.

Measured Energy Performance

Refrigeration system energy consumption, comprising the energy use of the compressor rack and gas cooler or condenser, was captured and plotted on a monthly basis for the two stores. As can be seen in *Figure 1*, the TC CO_2 system's electricity consumption is within the same range as that of the conventional system in Bradford. The electricity consumption is higher in the hotter months (by up to 14%) and is nearly equal or lower (by up to 18%) in winter.

Figure 2 compares monthly electricity consumption of the refrigeration system in Turner with the average monthly outdoor air temperature, accounting for the combined electricity use of the compressor racks, the glycol pump, and the gas cooler. Average daily and monthly temperatures were calculated from the submetered data, where, alongside refrigeration system energy consumption, the outdoor air temperature was also recorded at five-minute intervals. As expected, the electricity consumption of the TC CO_2 booster refrigeration system correlated with outdoor temperature.

Climate Impacts

In addition to the energy profiles of the stores, the study also examined climate impacts. The main sources of climate impact are refrigerant leakage and propane use (direct impact) and electricity use (indirect impact). Chain-wide, Hannaford supermarkets average a leakage rate of about 15% annually, which is below the EPA national average leak rate estimate of 20%.[7] For the two supermarkets considered for this case study, measured annual refrigerant leakage was equal (200 lb [91 kg] of refrigerant per store over the year-long analysis period). Though the leakage masses are identical, the associated climate impacts differ tremendously due to the substantially higher global warming potential (GWP) of the HFC-407A refrigerant used in Bradford. Carbon dioxide emissions associated with burning propane at the locations were calculated using the U.S. EPA's Emission Factors for Greenhouse Gas Inventories.[8]

Indirect environmental impact was calculated from the electricity bills at both supermarkets over the course of the year using the publicly available EPA Climate Impact Calculator.[9] *Table 3* compares the climate impacts (including direct and indirect impacts) of the two stores.

The direct leakage of refrigerant at Bradford constituted about one-third of the total climate impact of the refrigeration system. This is in line with the breakdown of impacts shown in past analytical studies of supermarket refrigeration life-cycle performance.[10] For the system in Turner, the direct impact is almost negligible.

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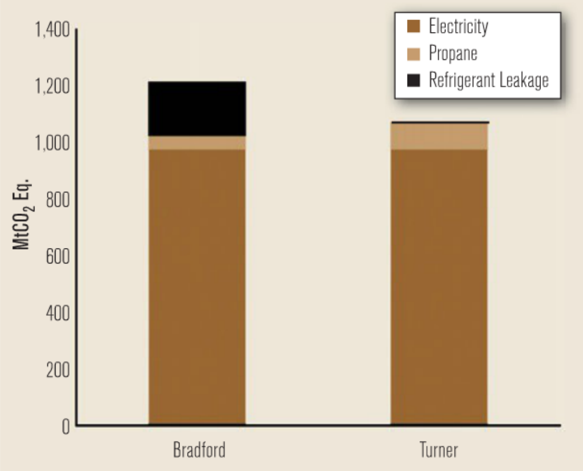
TABLE 3 Direct and indirect whole-store climate impacts – September 2013 to July 2014.

		BRADFORD (HFC)	TURNER (TC)
Electricity Use	Site (kWh)	1,414,683	1,415,920
	Source ($MtCO_2$ Eq.)	975	976
Propane Use	Site (MMBtu)	766	1,543
	Source ($MtCO_2$ Eq.)	48.2	97.0
Refrigerant GWP	–	2,100	1
Refrigerant Leakage	(lb)	200	200
	($MtCO_2$ Eq.)	191	0.1
Net Impact	($MtCO_2$ Eq.)	1,214	1,073

FIGURE 3 Net storewide climate impacts.



On a full-store basis, the data indicate that the Turner store exhibited a 12% lower overall climate impact compared to the Bradford store over the data collection period, as shown by *Figure 3*. The Bradford store achieves refrigeration leakage rates well under the national average and uses a refrigerant (HFC-407A) that has almost half the GWP compared to other conventional refrigerants (such as HFC-404A and HFC-507A). Therefore, the climate benefits achieved at the Turner store would be even more significant compared to many other conventional stores.

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PHOTO 2 Transcritical CO_2 compressors and oil separators.

Lessons Learned

During the first year of operating the TC CO_2 system at Turner, Hannaford gained valuable experience in issues specific to this technology type. For example, during commissioning, pressure testing is critical due to the high working pressures of TC CO_2 systems. Further, strict adherence to ASHRAE Standards 15 and 34 (*Safety Standard for Refrigeration Systems* and *Designation and Classification of Refrigerants*, respectively) must be maintained. Even though CO_2 is not classified as toxic, it is an asphyxiant.

Additionally, careful control system operation and operator training are important, as control systems for TC CO_2 refrigeration systems differ from those used for conventional systems. The new control system installed in the Turner store (needed for the TC CO_2 booster system) also allowed store operators to more easily override lighting schedules and other controls compared to standard store formats. Steps had to be taken to mitigate operator unfamiliarity with the new configuration.

Due to the nascence of this technology, there may be concern regarding a lack of easily available components and replacement parts. To address this concern, Hannaford required the supplier to preemptively make parts available. An inventory of spares (a parts cabinet) was set up on site, and whenever a part was used, a replacement was procured. This alleviated concerns about unavailable or difficult-to-find replacement parts. Hannaford found this to be a convenient arrangement for this pilot, and benefited significantly by keeping a sustained relationship with the supplier during a pilot

project such as this, leveraging their resources and learning from their experience.

Recommendations

Colder regions such as Maine have historically been targets for cost-effective implementation of TC CO_2 systems. However, suppliers claim that new developments have extended the climate range of the technology, making installations in warmer regions increasingly attractive. Little field data are currently available to substantiate those performance claims. We recommend more pilot installations with detailed documentation across a range of climate zones and operating conditions to demonstrate the performance of the newest evolutions in these systems.

Notes and References

1. Climate Zone 6A is defined as Cold – Humid with 7200 < HDD 65°F ≤ 9000.

2. In this heat reclaim scheme, the reclaim coil is placed in parallel with the refrigerant condenser, allowing effectively 100% of the heat of rejection to be captured for heating use when the system is operating in heat reclaim mode.

3. In a floating head pressure control scheme, the condensing pressure is allowed to vary as a function of the ambient heat rejection temperature. Thus, at lower ambient temperatures, the condensing pressure is significantly reduced, and the compressor power needed decreases commensurately.

4. Based on Hannaford's utility bills for this store.

5. Based on heat content values for propane and natural gas from, respectively, DOE Alternative Fuels Data Center (http://www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf) and EIA NG Monthly, 2014 Average (http://www.eia.gov/todayinenergy/detail.cfm?id=18371).

6. Due to the time frame constraints on this study, utility bill data was only available through July 2014 at the conclusion of the study period, so whole-store impacts were evaluated from September 2013 through July 2014.

7. Estimate per EPA GreenChill Partnership; http://www2.epa.gov/greenchill.

8. Available at: http://www.epa.gov/climateleadership/documents/emission-factors.pdf.

9. The calculator is available at: http://www.epa.gov/cleanenergy/energy-resources/calculator.html.

10. Fricke, Brian A., Pradeep Bansal, and Shitong Zha. 2013. "Energy Efficiency and Environmental Impact Analyses of Supermarket Refrigeration Systems," ASHRAE Annual Meeting Conference Paper Session 7. ■