Energy efficiency and sustainability converge in natural refrigerants

New hydrocarbon-based self-contained food retail refrigeration technologies are significantly improving energy efficiencies compared to conventional systems.

By James Knudsen
Images courtesy of Danfoss.

Food retail stores are among the most energy intensive buildings. They are also a significant contributor of greenhouse gases through refrigerant release. Worldwide, there has been a push to address these issues. Recent technological developments focusing on natural refrigerants hold promise to solve these issues. In a variety of CO₂ systems or hydrocarbon-based self-contained units, new technologies can improve energy efficiencies compared to conventional systems.

Added to this is the potential of reclaiming the waste heat to further reduce food retail energy demands. We are approaching a time when waiting for a regulatory push to explore new technology may be a costly alternative. This article will look at advances in energy-saving technologies for natural refrigerant systems in food retail.

Energy comparison
Comparing energy efficiency of different systems and refrigerants can be difficult. The inherent efficiency of a particular cycle can be optimized through equipment and techniques, but there are some fundamentals that are inherent in the refrigerant properties and can be judged fairly independent of specific details. In addition, many techniques can be (and probably should be) used independent of refrigerant choice, including the use of case controllers with electronic expansion valves, sub-cooling and variable speed drives for compressor capacity control, and condenser fans.

This article uses data published by OEMs or component manufacturers, which is generally calculated based on available models. Much of this data has been verified through field case studies. For more information, one should discuss this in detail with equipment suppliers. They can provide a wealth of information gained from years of applications on many different systems.

CO₂ systems
Carbon dioxide has been around as a refrigerant from the beginning. While it is non-toxic and non-flammable, it was replaced as a popular refrigerant due to physical properties that make it more complicated to use as a refrigerant. CO₂ operates at relatively high pressure and its low critical point leads to inefficiencies in operation in warm ambient temperatures.

CO₂ has returned to the marketplace recently because of environmental concerns with chemical refrigerants and with the toxicity and flammability of some of the other natural refrigerants. In some markets—Europe and Japan particularly—CO₂ is the accepted standard for new food retail systems.

While this movement started in response to environmental concerns, technologies have been developed that make this choice a cost-effective investment as well. It has been reported that in European markets, CO₂ system are at first cost parity with chemical refrigerant systems and are more energy efficient as well. It should be noted that in Europe benchmark systems employ electronic case controls, which are a requirement for CO₂ systems.

In general, CO₂ systems can be divided into two types: 1) sub-critical, cascade systems, and 2) transcritical CO₂ systems.

Sub-critical cascade systems utilize a second (sometimes called a top side) refrigeration system to condense the CO₂ used in the primary system. The use of cascade systems maintains the CO₂ below its critical temperature where the system operates more efficiently. This also has the effect of lowering the highest pressures seen in the cycle. Cascade systems are among the most energy efficient ways to use CO₂ as a refrigerant and eliminate any concerns about the climate for application of the system. The downside is that the second, top side refrigeration system adds cost and requires another refrigerant decision be made for this part of the system.
In a transcritical CO₂ system, the CO₂ can go beyond its critical point where it will no longer be condensed into a simple liquid. While this type of system leads to some inefficiencies and higher pressures, new technologies allow it to still operate more efficiently than chemical refrigeration systems, even in the warmest climates. Due to the elimination of the top side refrigeration system, transcritical CO₂ systems can be less costly than cascade systems.

**Cascade CO₂ systems**

One of the most energy efficient large centralized refrigeration systems for food retail applications is a CO₂ cascade system with a low-charge ammonia top side system. This system combines the benefits of CO₂ as a refrigerant with the efficiencies of an ammonia system to condense the CO₂. Ammonia, although both toxic and flammable, has been used in large cold storage applications for many years. Very good standards and practices exist to use ammonia safely and effectively. In addition, due to its excellent properties as a refrigerant, very little ammonia is actually required for food retail sized systems. In fact, it has been demonstrated that a typical food retail system can use less than 50 lb of ammonia, compared to around 2,000 lb of chemical refrigerant in a conventional system. With such a low-charge system—which can be located outside of the building envelope, many of the ammonia operating requirements for safety are greatly reduced.

In another variation of the cascade CO₂ system, hydrocarbons (specifically propane) are used as the refrigerant on the top side chiller. In the few systems that have been tested, this is typically in the form of several propane-based chillers. The systems combined contain around 265 lb of propane. Propane system designs are very similar to traditional HFC systems, with both similar pressures and temperatures, and provide substantially better energy efficiency. The high flammability of propane does require special electrical enclosures, leak detectors, and safety equipment and procedures.

**Transcritical CO₂ systems**

Transcritical CO₂ systems are by far the most popular choice for natural refrigerant systems in large centralized food retail applications worldwide. The proliferation of these systems has led to substantial investments in R&D to increase their efficiency. This is an issue in warm climates because, at temperatures above 88°F, CO₂ is operating above its critical point, which means that, when releasing the heat absorbed during evaporation, the CO₂ does not condense to a liquid but remains a high-pressure saturated gas. Following the release of this heat through the gas cooler, the high pressure is dropped through a transcritical valve, allowing some of the fluid to condense. Dropping the pressure also results in some lost work that was put into the system at the compressors. These particular characteristics of CO₂ lead to low thermodynamic Carnot Efficiency (maximum achievable cycle efficiency) compared to other refrigerants. In addition, the required high pressures add cost to components like compressors, piping, gas cooler (condenser), and transcritical valve.

**Booster systems**

New system designs are available that can reduce these inefficiencies and utilize lost work in the system to improve this situation. The basic transcritical CO₂ system design today is called a booster system—a name it gets from the fact that the discharge from the low-temperature compressors “boosts” the suction pressure of the medium-temperature compressors. While this is a fine system that will run effectively in all climates, it loses efficiency the warmer the outdoor temperature is, creating a concept called the transcritical equator. This “equator” defines the northern climate zone where, based on average annual temperatures, a transcritical system is on average more efficient than a conventional HFC system.

**Parallel compression**

Parallel compression is a current technology for transcritical CO₂ systems that improves efficiency over a booster system and moves the transcritical equator south. This broadens the range of climates in which CO₂ systems can be used efficiently. A parallel system splits the medium temperature compressors into two groups. One group continues to draw suction from the medium temp evaporators and the low-temp compressors (booster system). The parallel compressors are applied to the flash gas only which is at a higher pressure than the medium-temperature suction. This portion of the compressor load does less work and therefore uses less energy. In all but the warmest climates a parallel compressor transcritical CO₂ system will be more efficient than comparable HFC systems.
The most recent development in the design of transcritical CO₂ systems uses a device called an ejector. This is a mechanical device that can utilize the work lost in dropping the pressure to condense the CO₂ after the gas cooler. Ejectors convert the high pressure of the supercritical gas to velocity. This lowers the pressure and draws in medium temperature suction gas. The high velocity combined gas streams are then expanded and slowed down to recover the pressure, resulting in condensing the CO₂ and lifting a portion of the medium-temperature suction to reduce the work required to compress it. This saves energy and eliminates entirely the so-called transcritical equator. A system equipped with gas ejectors is more efficient than comparable HFC systems in all climates.

Liquid ejectors
One of the next steps in future system design is to utilize the ejector device in another way to even further reduce energy use. This technique utilizes a liquid ejector and allows the medium-temperature evaporators to operate flooded. Flooded evaporators are set so that the entire coil is used to evaporate liquid and thereby operate more efficiently. Running flooded evaporators is not normally done due to the risk of returning liquid refrigerant to the compressors and damaging them.

While this technique has been tested with other refrigerant systems, the advantage with a transcritical CO₂ system is it allows the use of a liquid ejector that acts as a free pump. Since it utilizes work that would have otherwise been lost, it can move the excess liquid from the evaporators back to the receiver—protecting the compressors—with no additional energy usage. In addition, the more efficient evaporators provide other system benefits, including, for example, shorter, less frequent defrosts.

Heat reclaim
Heat reclaim has been used for a long time on all types of systems. It means simply finding ways to utilize the waste heat generated in a refrigeration cycle elsewhere in the store—most commonly for heating water. HFC systems provide relatively low-grade heat and thereby can generally only supplement the heating of water. CO₂ systems, on the other hand, provide very high-grade heat that can not only heat water but also provide for comfort heating and be used in dehumidification systems. In some locations with district heating grids, these systems can even be a source of heat that can be sold back to the utility.

Propane (hydrocarbon) systems
It is well known that propane and other hydrocarbons are flammable—a characteristic that has allowed these substances to fuel many backyard barbecues. However, propane and other hydrocarbons also make excellent refrigerants. Propane operates very similarly to conventional chemical refrigerants and is very efficient. Plus, when used in limited quantities, propane has been shown to be safe and effective. The limits on the charge size (currently 150 g in most cases) generally restrict the use of this natural refrigerant to self-contained units. Self-contained units are refrigerated cases or cabinets that contain a small refrigeration system within the device (as opposed to piping the refrigerant from a remote central system).

There are two ways to use these self-contained units in food retail applications: 1) air-cooled, or plug-in, units, and 2) water cooled, or semi-plug-in, systems.

Air-cooled
Air-cooled units are the simplest to deploy since they only need to be plugged in where they are going to be used. These units are very common in many different applications. The use of propane as a refrigerant in these units has been growing steadily and today there are more than 100,000 units in operation in North America. Most manufacturers of self-contained units offer a propane version of their units and at least one supplier has committed to standardizing on propane for all of its products. It has been reported that propane-based units can be more than 25% more energy efficient than self-contained units with conventional refrigerants.

Semi-plug-in
The only problem with air-cooled, self-contained units is that they typically discharge the waste heat from the refrigeration cycle into the surrounding air-conditioned space. This issue can be mitigated by using a water-cooled unit that is connected to a cooling loop to discharge the heat outside of the conditioned space. Since the self-contained units need to be both connected to the water loop and plugged in, they are called semi-plug-in units.

The energy benefits of these units are a little complicated. The units themselves run more efficiently since the condensing temperatures are typically lower and the air conditioning load is less. However, they require pumps for the cooling loop and chiller that use additional energy, and there can also be losses in the heat exchanges between the systems. The primary benefit provided by these somewhat more expensive systems, particularly for small retail stores, is that they can be deployed in spaces not designed to handle the additional heat load of multiple self-contained systems. They have also been tested in large food retail venues where water piping and multiple small systems may benefit installation costs and flexibility, compared to large centralized systems with refrigerant piping. While the author is not aware of definitive data showing an energy comparison of larger semi-plug-in systems to HFC and CO₂ systems, with the efficient propane refrigerant, this is a concept with interest.
Conclusion
Technical advances in climate-friendly natural refrigerant systems are reducing up-front costs, as well as improving energy efficiency to the point that investment in these systems is becoming a financial imperative as well as a sustainability project. In food retail, CO₂, ammonia, and hydrocarbons bring a wide range of advantages to the end user. Regardless of the current regulatory environment, there is an undeniable trend worldwide toward natural refrigerants. Whether from the federal government or individual states, there will be continued pressure to reduce greenhouse gas emissions in North America. We expect that the continuing advances in the capabilities and efficiency of natural refrigerant systems will provide an economic incentive at least as strong as the regulatory push. Food retail is energy intensive and a significant contributor of greenhouse gas emissions. But, natural refrigerants hold promise to significantly contribute toward the resolution of both issues, while at the same time increasing operational performance.

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