CO2 TRANSCRITICAL BOOSTER SYSTEMS

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Refrigeration systems for supermarkets and other applications have been evolving toward the use of environmentally friendly natural refrigerants over the past couple of decades. In recent years, this advancement has led to the installation of numerous systems that use carbon dioxide (CO_2) as a refrigerant. The first of these systems only used CO_2 as either a secondary coolant or as a direct expansion (DX) gas in the low-temperature portion of a cascade-type system. Both of these approaches continued to rely on the use of some synthetic, environmentally harmful hydrofluorocarbon (HFC) refrigerants in either the primary side of the former systems, or the medium-temperature portion of the latter. Now a type of DX system that runs entirely off of CO_2 has begun to see increasing use in North America.

CO_2 transcritical booster systems rely on the same vapor-compression refrigeration cycle as do traditional DX systems. In fact, they use the same main components that traditional systems do: compressors, evaporators, condensers and expansion valves. The operation of a booster system, consequently, will seem familiar to anyone who knows how a traditional system works. The difference in how the two types of systems operate has to do with the nature of the refrigerants they use.


Figure 1 - Booster System Rack

Traditional DX systems that use HFC refrigerants, such as R-410A, typically operate at pressures of around 400 pounds per square inch (psig). Due to the material characteristics of CO_2 (R-744), systems that use it must be engineered to operate at higher pressures — as much as 1450 psig depending on ambient conditions. This means, for instance, that on the high side of the system a type of copper pipe especially designed for the higher operating pressures of CO_2 can be used.[1] Other components specifically designed for the higher operating pressures of R-744 are also needed for the system. These components are described further on in this paper.

The energy consumption of the first transcritical CO_2 booster systems depended on the ambient conditions where they are used (see the description of adiabatic condensers below). As the ambient temperature drops, a CO_2 booster system works in the subcritical range, allowing it to potentially deliver better energy performance than other types of systems. That, combined with the system's complete elimination of HFCs, makes it an effective option for customers looking to achieve sustainability and lower operating costs. This combination of benefits provides the greatest rationale for the use of a CO_2 booster system.

In addition, the CO_2 booster incorporates both medium-temperature and low-temperature capability in a single, compact unit. The compressors in the unit can be sized to accommodate a wide range of loads. Instead of separate systems for a store's medium- and low-temp loads, only one system is needed for both. In about the same amount of space that would have been needed for just one portion of a traditional system, a booster system can meet all of the store's refrigeration needs. By reducing the equipment needed to run an entire store to a single system,

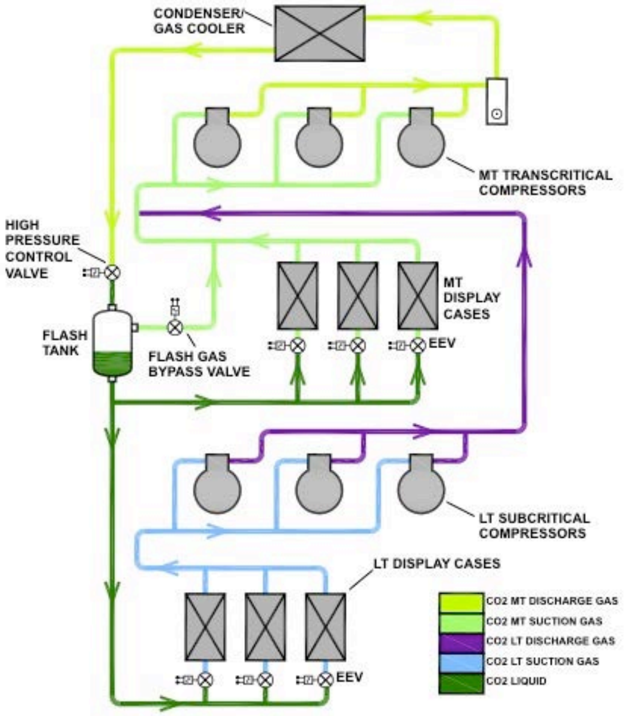

Figure 2 - Simplified system piping

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[1] Copper-iron alloy tubing became available in late 2015.

supermarkets can save space and simplify their operation.

How the System Works

Certain aspects of CO_2 booster systems will be familiar to anyone who knows how traditional DX systems work. Like those, booster systems have four main components that include compressors and evaporators. But in addition to using a condenser and expansion valves, booster systems also use a high-pressure control valve and a special type of condenser that works as a gas cooler under higher ambient conditions.

Another key difference from traditional systems is that booster systems work with the same refrigerant moving between the low- and medium-temperature compressors. The low-temperature compressors discharge to the suction of the medium-temperature compressors. In other words, the low-temperature compressors serve as a booster to the medium-temperature compressors.

Suction gas from the low-temperature display case and freezer evaporators enters the low-temperature subcritical compressors at around 200 psig, well below the critical point for CO_2. The low-temperature compressors discharge that gas at about 425 psig then combine it with the medium-temperature suction gas from the medium-temperature display cases and walk-in cooler evaporators before entering the medium-temperature transcritical compressors. The medium-temperature discharge gas leaves the compressors, depending on ambient conditions, anywhere from 560 psig to as much as 1450 psig, which is above the critical point. Under warmer conditions in which the pressure rises above 1055 psig, the system operates in the transcritical range.

Under all conditions, however, the discharge gas from the medium-temperature compressors feeds to the condenser, where the heat it carries is rejected to the outside environment. This heat rejection process is standard in any refrigeration system.

Sizing of the compressors on the low-temperature and medium-temperature stages of the system is carefully determined to assure optimal capacity control during partial load operation. The condenser design is optimized for high-performance, even at high ambient temperatures when the system is operating in the transcritical range.

The CO_2 leaving the condenser feeds to a high-pressure control valve that expands the CO_2 into an intermediate pressure receiver called a flash tank. The gas enters the valve from 560 to 1450 psig, depending on ambient conditions, and exits the valve at 540 psig. The valve is designed to work somewhat like a hold-back valve in order to maintain optimum pressure through the gas cooler for the most efficient operational performance of the system.

The flash tank (or tanks on larger systems) works the same way, in principle, as a conventional receiver and can usually contain all of the refrigerant charge during pump-down and shutoff. Some systems, however, utilize capacity in the gas cooler during pump-down in order to employ a smaller flash tank. The pressure in the tank is held at a constant level that is sufficient to maintain differential pressure throughout the system.

From the flash tank, both liquid and gas refrigerant is fed back to the system. Liquid refrigerant is supplied to the medium- and low-temperature evaporators controlled by conventional electronic expansion valves. Vapor from the flash tank is fed through a flash gas bypass valve back to the medium-temperature compressors. The flash gas bypass valve maintains a constant pressure in the flash tank.

Apart from some of the unique components just described, the system works in a similar way to other types of DX systems. The main differences are related to the two-stage design of the system and the fact that all evaporators in the system are supplied with liquid from the same source. For most experienced technicians, the system will not seem overly complicated.

Major Components

As previously stated, CO_2 booster systems use many components that are common to other types of DX systems, along with some that are specifically designed for the CO_2 application.

CO_2 Compressors

Like any other type of DX system, compressors are used to move refrigerant through booster systems. Unlike most other types of DX systems, however, booster systems use two sets of compressors — one set for the medium-temperature stage and the other for the low-temperature stage. Semi-hermetic, reciprocating compressors are typically used for both stages. Scroll compressors can be used for the low-temperature stage on systems for customers who prefer them. Both types of compressors are available from a variety of manufacturers.

Compressors operate with either polyolester (POE) or polyalkylene glycol (PAG) oils specially selected for use in this application, so an oil-management system is required. The components of the oil-management system are the same as for conventional DX systems, but they are designed to accommodate the higher operating pressures associated with CO_2 and include oil-level regulators (either electronic or mechanical), a separator, a reservoir and a filter. CO_2 compressors also require crankcase heaters to warm the oil whenever the compressor is not running. Some CO_2 compressors contain relief valves to ambient. A sight glass on the front of the compressor allows visual monitoring of the oil system during operation.

When viewed on the pressure-enthalpy diagram (next page), the medium-temperature compression cycle can be seen starting at around 400 psig where the gas enters the compressors. From there, depending on ambient conditions, the gas may reach up to 1385 psig as it discharges from the compressors and enters the condenser. Of course, for the gas to reach that range, the ambient conditions must exceed 80°F.

Typically smaller than the medium-temperature compressors (though depending on application their size may vary), the low-temperature compressors operate well below the critical point in much the same way as the CO_2 compressors on a cascade system. Like those compressors, the ones on the booster system receive suction gas from the low-temperature evaporators. On booster systems, suction gas enters the compressors at 200 psig and discharge gas leaves them at 400 psig. From there, it is combined with gas from the medium-temperature evaporators to become the suction gas for the medium-temperature compressors.

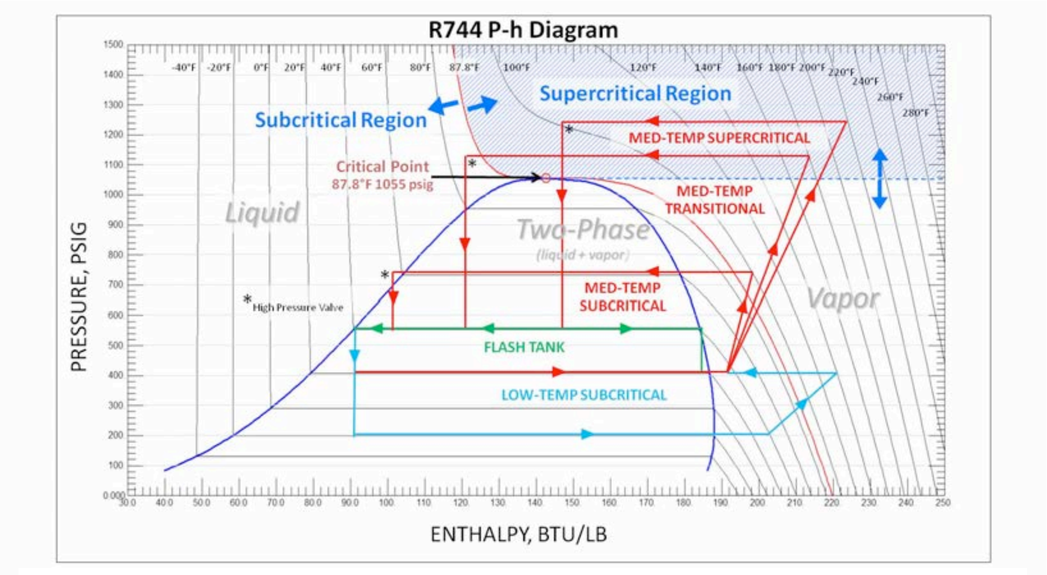

Figure 3 - Enthalpy diagram showing how changes in condensing pressure affect the amount of energy used or released (enthalpy) by the system.

A key feature of the system is the use of a variable frequency drive on the lead medium-temperature compressor for better capacity control and on the low-temperature compressors for even greater energy savings.

Oil Separator

Once the medium-temperature discharge gas leaves the medium-temperature compressors, it passes through an oil separator. Oil separators are a common component on DX systems. Booster systems, like the lower section of cascade systems, use synthetic POE oil. Booster systems are equipped with a highly efficient mechanical oil separator that uses coalescing filters to remove contaminants from the oil system. The separator can be used with or without an external oil reservoir.

Condenser/Gas Cooler

This component typically works the same way a condenser does in a conventional DX system. At ambient conditions below 80°F, medium-temperature discharge gas enters the condenser/gas cooler and rejects heat to the outside air as it passes through the coils of the unit. The main difference between a booster system condenser and a conventional condenser is that when the ambient temperature rises above 80°F, the booster system begins operating in the transcritical range. Then the discharge gas passing through the system is unable to undergo any further state change, but remains a supercritical gas, or fluid, as it is otherwise known. This last point is a key distinction. Under transcritical conditions, the discharge gas enters the gas cooler as a supercritical fluid and stays that way all the way through the gas cooler to the high-pressure control valve (below). No subcooling of the gas takes place as in a regular condenser. Under 80°F, however, the unit then works just like a condenser in a typical DX system.

In the same way that efficiency gains are made on the compressors through the use of variable speed drives, so, too, are the fans on the condenser controlled. Also, the condenser is equipped with a shut-off valve for maintenance or other needs.

In order to extend the efficiencies of the system to warmer climates, an adiabatic condenser can be used. This type of condenser allows the system to continue condensing at lower wet-bulb temperature than the ambient dry-bulb temperature.

Adiabatic condensers use the evaporation process to lower the temperature of the ambient air as it flows through a set of water-moistened pads before reaching the condenser's coils. This cooler air then absorbs heat from the dry coils. Customers have found that in warmer climates this approach actually operates at greater energy efficiency than air-cooled systems.

High-Pressure Control Valve

Like the condenser, the high-pressure control valve works under two modes of operation. It usually controls subcooling in the condenser when that unit operates as a condenser. Under conditions during which the unit is working as a gas cooler (above 80°F ambient), the valve controls pressure in the unit.

Flash Tank

The expanded gas from the high-pressure control valve flows into the flash tank at around 540 psig. The flash tank performs the same function as that of a receiver on a conventional DX system. At 1300 psig it is capable of holding the entire charge of the system if necessary, such as during pump-down or an outage. Conventional receivers, however, only return liquid to the evaporators. The flash tank, on the other hand, is equipped with a flash gas bypass valve that sends vapor from the tank to the medium-temperature suction lines, where it joins the gas from the medium-temperature evaporators returning to the medium-temperature compressors.

Other Components

Piping

One of the benefits of CO_2, as pointed out earlier, is its high volumetric capacity. This allows for smaller diameter piping to be used than would otherwise be needed for a HFC system of similar capacity. In fact, smaller diameters add to the overall advantages of the system since they decrease the refrigerant charge and handle higher pressures. In some cases, ¼-inch pipe (6 x 1 mm) is adequate. On systems with hot gas defrost, however, 3/8-inch (8 x 1 mm) to ½-inch (10 x 1 mm) pipe is necessary.

Piping and elbows to and from the condenser/gas cooler for installations currently in the field have used schedule 80 carbon or stainless steel. The piping is welded, and where damp conditions or exposure to weather might occur, coated with primer and varnish. Recent developments from suppliers, however, have led to the availability of a type of copper piping especially designed for use with CO_2. Producers of this material obtained National Science Foundation (NSF) certification at the end of 2015.

Controllers

As with other types of systems, controllers for booster systems are available from a number of manufacturers. On booster systems, the controller maintains the optimal pressure in the gas cooler when the system is operating in the transcritical range so as to maximize the system's performance. This method of control provides an optimum coefficient of performance (COP). Heat reclaim with a 0-10 volt signal is also available through this approach.

The system makes use of compressor capacity control through pack controllers that can handle up to either four or eight compressors. The pack controllers work on suction pressure and are a standard means for controlling suction groups in any refrigeration system. The pack controllers are capable of regulating variable speeds for two compressors combined with one-step compressors of the same or different sizes, depending on the choice of coupling pattern.

For most people familiar with the challenges facing commercial refrigeration, the rationale for moving to environmentally friendly natural refrigerants is well known. Foremost among the approaches that are available, CO_2 booster systems offer the greatest advantages. The design of these systems allows them to work most of the time in the same way that traditional DX systems do and makes their installation and operation fairly straightforward. The complete elimination of HFC refrigerants that booster systems provide moves users of these systems toward a more sustainable basis of operation than other alternatives currently available.