

8. Refrigeration

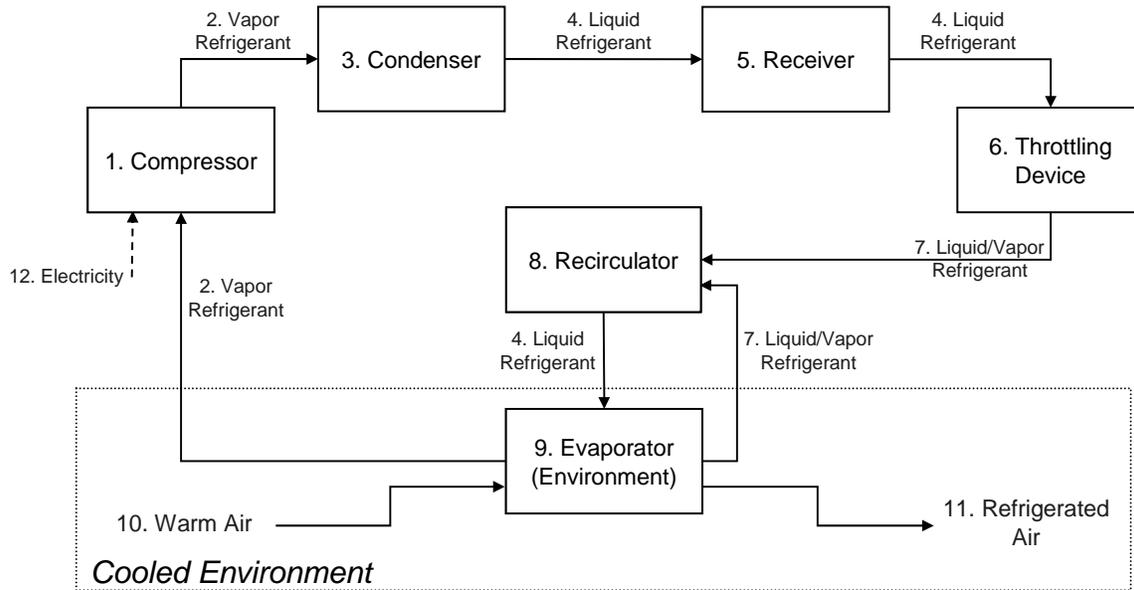


Figure 8.1 – Refrigeration system layout (single stage)

The food industry has benefited greatly from the development of mechanical refrigeration systems. Perishable products can be kept safe for longer periods of time when processing and storage environments can be maintained at constant temperatures. Refrigeration systems and their applications continue to evolve into more reliable, safer, and less expensive operations. A general description of a refrigeration system follows.

REFRIGERATION SYSTEM OVERVIEW (REFER TO FIGURE 8.1 ABOVE)

The basic refrigeration cycle used by most food processors consists of four major components: compressor (1), condenser (3), throttling device (6), and evaporator (11). Most systems also use a receiver (5) to provide a buffer for refrigerant as demand varies and a recirculator (8) to pump the refrigerant to multiple evaporator units.

Refrigerants

Different fluids can be used in a refrigeration system as the medium for heat transfer. To create good system performance, the ideal refrigerant should have a high evaporative pressure and a low condensing pressure. For more than 100 years, ammonia has been the refrigerant most widely used by the food processing industry; approximately 90% of food processors rely on it.

Compressor (1)

The compressor keeps the refrigerant flowing so it can absorb energy from a cold region and transfer it to a hot region. Compressors change the refrigerant from a low-pressure vapor to a high-pressure vapor and move it through the system. Very low temperatures

are required (e.g., -40°F) to freeze a product. Therefore, in order to operate efficiently, freezing operations generally use a two-stage system with a low-pressure or booster compressor and a high-pressure compressor.

Compressors can be classified as open or hermetically sealed. Open compressors, which are mostly used for large applications, have an external drive like an electric motor or gas engine. The drive motor and compressor of hermetically sealed equipment are enclosed within a frame. Refrigeration compressors, like air compressors, are often categorized as:

- Dynamic
 - Centrifugal
- Positive displacement
 - Reciprocating
 - Rotary Screw
 - Scroll

Centrifugal compressors are very efficient if they are working at full capacity. They pressurize the refrigerant vapor by centrifugal force from a single or series of impellers. This type of compressor is used in large water chilling applications.

Reciprocating and rotary-screw compressors are common in food manufacturing operations that use ammonia refrigeration. Reciprocating compressors generate pressure from pistons that compress the refrigerant within a cylinder. Rotary-screw compressors may have single or twin screws. The rotary-screw compressors trap the refrigeration within the helical treads of the rotor, moving it forward and decreasing the space between the treads as it rotates. Oil injected into a compressor not only provides lubrication, but also seals the compressor and helps cool it.

In scroll compressors, the refrigerant is compressed by a scroll-shaped vane that rotates within a fixed vane, decreasing the space available for gas as it rotates.

Capacity control for the refrigeration system plays an important role in saving energy. Not all types of compressors can be controlled the same way. Some capacity control methods are listed below:

- on-off
- suction valve unloading
- speed control
- hot gas bypass
- slide valves
- variable pitch inlet guide vanes
- suction dampers

The on-off control is the simplest. A thermostat indicates when the environment has reached a predetermined temperature, and the compressor shuts off. The compressor is turned back on if the temperature rises above a set limit. This type of control is most suitable for small capacity systems.

The suction valve unloading method works by lifting the suction valves of some cylinders to the open position. The gas cannot be compressed within the open cylinders, which results in an efficient reduction of refrigeration capacity.

Installing a variable speed drive or a multi-speed motor on the compressor allows the equipment to reduce capacity by reducing motor speed. Compressor rotational speed can then be varied to match the system's changing requirement for refrigeration capacity.

The capacity of reciprocating and centrifugal compressors can also be controlled by bypassing hot gas from the discharge port to the suction port of the compressor, creating an artificial load on the system. This is very inefficient.

Reciprocating compressors can take advantage of the first five control methods. The capacity of screw compressors is commonly controlled by a slide valve or speed control.

Rotary-screw compressors use slide valves to adjust the necessary refrigeration capacity at partial loads by permitting the equipment to reduce the total volume of refrigerant compressed within the housing.

There are three ways to control the capacity of centrifugal compressors:

- speed control
- variable pitch inlet guide vanes
- suction dampers

The first method, speed control, is achieved by using variable speed drives or multi-speed motors, as discussed earlier. The second method, variable pitch inlet guide vanes, uses adjustable vanes that prepare the refrigerant vapor as it enters the rotating impeller by sending the vapor in the same direction as blade rotation. The compressor remains at a constant rotational speed, but the refrigeration capacity is altered. The third method, suction dampers, alters inlet pressure to the compressor, therefore altering the volumetric flow of refrigerant into the compressor. Suction damper capacity control is inefficient.

Condenser (3)

The condenser transfers the heat from the refrigerant to a coolant medium, usually ambient air. Inside the condenser the refrigerant changes from a vapor to a liquid. There are three basic types of condensers:

- air-cooled
- water-cooled
- evaporative

With air-cooled condensers, fans force air through a bank of coils containing the refrigerant vapor. The air absorbs the heat as it passes by the coils and cools the refrigerant. The condensing capacity of a system can be increased by forcing more air through the coils or by providing more heat transfer surface area. Cooling capacity is directly related to the difference of the condensing temperature of the refrigerant and the air temperature (dry bulb).

Water-cooled condensers use water as the medium that absorbs heat. A shell-and-tube heat exchanger, for example, has water flowing through the tubes and refrigerant in the shell. The water source is normally a cooling tower, and the water is circulated to continuously absorb heat from the refrigerant. This type of condenser is used most commonly with large chillers and sometimes in large refrigeration systems.

An evaporative condenser is a combination of an air-cooled and a water-cooled condenser. As the hot refrigerant vapor flows through the bank of tubes, water is sprayed over the tubes and evaporates. As the water evaporates, it absorbs heat from the refrigerant, which increases the efficiency of the condensation. Because of the increased efficiency, evaporative condensers can be smaller than air-cooled units.

Evaporative condensers are wet-bulb temperature sensitive and they condense refrigerant to within 10 to 15°F of the wet-bulb temperature. As a result, these condensers are the most efficient of all types.

Receiver (5)

The receiver serves as a buffer for liquid refrigerant to be stored for use by the system. The liquid refrigerant is taken from the receiver to the evaporators as needed to satisfy the load. A receiver is needed when the system refrigeration load varies greatly.

Throttling Device (6)

The throttling device separates the high-pressure and low-pressure sides of the system. It reduces the refrigerant pressure and controls the flow rate of refrigerant to the recirculator—or directly to the evaporator in systems that do not have a recirculator. The following are types of throttling devices:

- thermostatic expansion valve
- constant pressure expansion valve
- float valves
- modulating valves

The thermostatic expansion valve automatically adjusts the flow rate of refrigerant needed to satisfy the refrigeration load based on the temperature of the refrigerant vapor leaving the evaporator.

The constant pressure expansion valves are basically pressure regulating valves that control the pressure at the evaporator. Because these valves only adjust to the pressure, they are limited to constant cooling loads.

Float valves are divided in two categories: high-side and low-side. The high-side float valve controls flooded liquid chillers systems with a single compressor, condenser, and evaporator. The high-side valve is installed on the high-pressure side of the throttling device and adjusts the flow of liquid refrigerant to the evaporator. Low-side float valves can be used in systems with multiple evaporators and are placed on the low-pressure side of the throttling device.

Modulating valves are normally operated electrically (electronically), but pneumatic modulating valves are also available. The modulating valve gradually feeds the liquid from the receiver to the recirculator in response to a liquid level sensor in the recirculator vessel. This type of feed valve keeps the flow of refrigerant in direct response to the refrigeration load requirements, which more effectively limits the amount of flash gas that makes it to the compressors. This system replaces the old solenoid valve, hand expansion valve, and level sensor, all of which tended to feed erratically and kept the compressors' capacity reduction systems working overtime.

Recirculator (8)

Liquid recirculation systems are designed to recirculate three to four times the amount of evaporated refrigerant. This guarantees total wetting of the evaporator tube surface and also ensures the return of any lubricant that may be in the circulated refrigerant. Compared to flooded evaporators, recirculation minimizes the amount of refrigerant in the system. The return piping from the evaporators will contain both vapor and liquid refrigerant.

The re-circulation of the refrigerant is done in two ways:

- gas pressure pumping
- mechanical pumping

The gas pressure pumping system (not shown in Figure 8.1) utilizes the high pressure of the hot vapor to push the cold liquid, which is at a lower pressure, to the evaporators. This is an inefficient system but is sometimes used when electrical power, which is required for mechanical pumping, is not available or could not be safely used.

Mechanical pumping normally uses electric motor-driven pumps to distribute the liquid refrigerant to the evaporators. Pumps used for this function can be semi-hermetic (canned) or open type.

Evaporator (11)

Inside the evaporator heat from the cooled region or medium is absorbed into the refrigerant, and, as a result, the refrigerant changes from a liquid to a vapor. The evaporator can be of the following types:

- liquid coolers
- air and gas (unit) coolers

Liquid coolers use shell-and-tube heat exchangers to chill process liquids (e.g., water and milk) or fluids used on air conditioning coils. Shell-and-tube heat exchangers are limited to 38°F water to prevent freezing.

Another type of liquid cooler is the 33°F boudelot water chiller, which circulates water over refrigerated plates. This permits water to be chilled to 33°F without the possibility of freezing, which may occur in a shell-and-tube heat exchanger.

Air and gas coolers, also known as unit coolers, can be either flooded or dry. Dry types of air and gas coolers are preferred due to their minimal need for refrigerant. Frost will occur on the coils of unit coolers when the temperature of the coil falls below 32°F. Frost acts as an insulator, which reduces the efficiency of the system. Common defrosting techniques are

- isolation of the coils
- water defrost
- hot gas defrost

Isolating coils was one of the first techniques used to defrost coils in rooms above 38°F. Careful design of the room allows the coils to be separated from the cold region so warm air can be circulated over them without increasing the total refrigeration load. Another method of defrosting isolated coils is the use of electric heat.

Water defrosting is done by applying water over the coils to remove the frost. However, careful consideration to the flow and temperature of the water must be taken to make sure that it does not freeze on the coil or on the return from the cold room. This is the most efficient defrosting method.

Hot gas defrost is the most commonly used method of defrosting in large-scale applications. During the defrost cycle, hot refrigerant gas from the discharge of the compressors is sent through the coils to melt the frost. This method can be efficient and inexpensive to install, but control valves must be used for safe and reliable defrosting.

Air Infiltration

Air sometimes can enter the system and mix with the refrigerant, greatly reducing overall efficiency. Air can enter the system

- when it's open for repair
- when it's being filled with refrigerant or oil
- through seals and valves if the suction pressure is below the atmospheric pressure

Air can be purged in two basic ways: manually or automatically. Manual removal of air is accomplished using a strategically positioned valve that is opened by hand as required. Automatic purgers can be mechanical or electronic.

ENERGY SAVINGS OPPORTUNITIES AND RELATED BEST PRACTICES

Refrigeration plays an important role in food safety. For many food processors working with perishable items, refrigeration can be the most costly component of the operation, accounting for over 50% of the electric bill. Therefore, significant financial benefit can be realized by using the following best practices to improve refrigeration.

Compressor

Compressor Maintenance

Predictive maintenance of the compressor and refrigeration system will result in the following benefits:

- fewer shut-downs to conduct emergency repairs
- reduced maintenance costs (planned maintenance is always cheaper than emergency repairs)
- less overtime pay (hours can be planned, not scheduled around emergency repairs)
- extended lifespan for equipment (properly maintained equipment lasts longer)
- a safer work environment (can result in a decrease of insurance cost)

As part of the predictive maintenance program, the following should be performed:

- vibration analysis of rotating equipment
- pipes and vessels thickness testing
- infrared inspection of all equipment, piping, electrical gear, and insulation
- lubricant usage monitoring

A good vibration analysis will identify potential problems on rotating equipment. Anticipating and repairing potential problems before they develop can minimize larger problems. Certain types of insulation retain humidity and can promote the formation of rust on the encapsulated pipe or vessel. It is recommended that an insulation inspection and vessel thickness testing be performed regularly on pipes and vessels, such as the recirculator.

An ultrasonic gauge is a relatively inexpensive and accurate tool for this type of thickness (gauge) measurement. Insulation technology has evolved over time, bringing new products for rust resistance and better efficiency. Apply a rust inhibitor on pipes and vessels before re-insulating them.

Compressor lubricant should be tested regularly for impurities. A coalescent separator can be installed on the system to decrease oil carryover into the refrigerant. Large amounts of oil in the refrigerant (ammonia) can cause foaming, which can damage compressors. An oil analysis should be performed about every six months to identify possible problems with the system.

Lubricant leakage and carryover into the refrigerant can be identified by closely tracking the amount of oil put into and removed from the system. These two quantities should be essentially the same.

Thermosyphon Lubricant Cooling

The lubricant in a compressor is also responsible for cooling the compressor and keeping it sealed. Lubricants absorb heat, so to keep a compressor running effectively, the lubricant must be cooled. This can be done in different ways.

One method of cooling the lubricant is direct injection of refrigerant in the compressor housing. This method is inefficient and can also damage the compressor. Direct injection cooling can decrease overall efficiency of a screw compressor by as much as 10% for systems with a high compression ratio and 5% for systems with a low compression ratio. A pump can be added to the system to inject a high-pressure refrigerant, thereby reducing

efficiency losses. However, this may lead to over-injection of refrigerant and may severely damage the compressor.

A good solution for lubricating screw compressors is to add an indirect cooling system. This system can use a heat exchanger (plate-and-frame or shell-and-tube) with cooling tower water, a section of an evaporative condenser, or a thermosyphon system (using refrigerant) to exchange heat between the hot lubricant and refrigerant. Since the oil needs to be decreased by only a few degrees, a high-pressure refrigerant can be used to accept heat from the lubricant. The thermosyphon cooling system eliminates the need for a pump and can save a large percentage of motor horsepower. Condenser water can also be used for the thermosyphon, although it tends to collect more impurities, so the system will need to be periodically cleaned.

Thermosyphon Cooled Desuperheater

A thermosyphon cooled desuperheater can be added to keep the refrigerant at a lower temperature. Making this addition to the system's low-stage compressors can remove approximately 60°F (41.5 Btu/lb of ammonia) from the discharge refrigerant, which, in turn, removes the same amount of work from the high-stage compressors, saving a significant amount of energy.

Raise System Suction Pressure

As ambient temperature decreases, the load on the refrigeration system usually decreases as well. When this occurs in two-stage systems, a simple way to save energy is to slowly increase the suction pressure/temperature of the low-stage compressors. It is estimated that energy savings of about 8% can be realized with two-stage systems when the suction temperature (and therefore pressure) is raised from -30°F to -20°F. For a system with blast freezers, savings can be even greater (12%) if the temperature/pressure is increased from -40°F to -30°F. A slow step increase in pressure/temperature is recommended in this case. It is estimated that high-stage compressors can save approximately 8% of motor break horsepower for a rise of 10°F in suction temperature.

Older two-stage systems have rotary booster compressors with limited compression ratios, and, therefore, the intermediate pressure cannot exceed approximately 20 psig. Many of these old compressors have been replaced with rotary-screw compressors that can tolerate higher compression ratios, but the intermediate pressure has been left at 20 psig. In such cases, the intermediate pressure should be adjusted upward. This will decrease the energy usage per ton of refrigeration. The optimum intermediate pressure equalizes the absolute compression ratio between the two stages.

High Efficiency Motors

Installing premium efficiency motors and variable frequency drives (VFD) on compressors and condensers may significantly reduce energy consumption. The use of a VFD is most beneficial for air-cooled and evaporative condensing systems with large differences between required and installed condenser capacities. Refer to the motors appendix of this document for more details.

Condenser

Operate Condenser at Lowest Possible Pressure

To save energy when compressing refrigerant, the condensing temperature/pressure should be set as low as possible. Many operators complain that their system cannot operate at low pressures. However, the true cause of most of the complaints can be linked to a problem that's unrelated to lower condensing pressure. For example, a common complaint is that hot gas defrost cannot be operated at pressures below 150 psig. However, in most cases, the insufficient amount of hot gas for effective defrosting is explained by undersized piping rather than lower pressure.

Microprocessor controllers can be installed on the condensing system to ensure that minimal condensing pressure is used and to efficiently sequence the use of fans and water on the condenser. The processor should take into consideration temperatures and pressures of the system as well as ambient wet-bulb temperature. The pressure/temperature of the system should be at about 10°F above wet-bulb temperature, the temperature at which water will evaporate on a given day (which is greatly affected by the amount of humidity in the air).

Significant energy savings can result from installing a microprocessor controller on the condensing system. Installing such a system typically has a very short pay-back period.

Use Axial Fans on Condenser

Because air-cooled or evaporative condensers do not need high-pressure air, axial fans are well suited to this application. Axial fans use approximately 50% less energy than centrifugal fans and adequately do the job required by the condenser.

Heat Recovery from Refrigeration System

Heat should be recovered from as many industrial processes as possible. Of course, it is important to compare the capital investment for such systems to potential energy savings before making a decision or an investment. Heat recovered from the refrigeration system is commonly used to preheat boiler feedwater or to heat water that is used for equipment cleanup. This is done using a shell-and-tube heat exchanger in parallel with the condenser. During warm months, water temperature may be increased up to 45°F by the heat reclaimed from the condenser. This saves money by significantly reducing the amount of energy needed to heat the water. During cold weather, the refrigeration system has to do less work, and, therefore, it is possible to reduce the pressure at which the compressors operate. A positive result is a significant reduction in the energy needed to power the compressor; on the negative side, there is also a significant reduction in the amount of heat that can be recovered at the condenser. In most cases the energy savings from operating compressors at a lower pressure during cold months is greater than the savings from heat recovered at the condenser.

Throttling Device

Sizing and Operation of Throttling Devices

When the thermostatic expansion valve is working properly, the temperature difference from the inlet and the outlet of the valve is very noticeable. A smaller than normal temperature difference between the inlet and the outlet of the throttling device means that the pressure drop inside the valve is less than it should be. This can be caused by a clogged (dirty) or damaged valve seat.

If the throttling device is undersized, the condenser must be kept at high pressures to force enough refrigerant through the system. Therefore, if the supply of refrigerant is insufficient for the cooling load, the throttling device should be inspected as a possible reason. The day-after-day savings of running at a lower system pressure will quickly repay the one-time expense of a larger throttling device (and, possibly, larger piping).

Evaporator

Demand Defrost

The concept behind demand defrost is to defrost the system when, and only when, necessary. This differs from timed systems that defrost at a set interval, regardless of need. Demand defrost should be used for refrigeration areas below freezing point. The defrost cycle starts based on pressure readings from sensors located across the coils. An increase in pressure drop indicates the presence of frost over the coils and activates the defrosting system. The liquid refrigerant formed during defrost should be drained and piped to the high-temperature recirculator or intercooler.

Correct Size of Pipe for Defrost

In most cases, when reducing condensing pressure doesn't initiate defrost, the problem is incorrect sizing of the defrost piping. Piping should be redesigned to allow for sufficient hot gas flow.

Dedicate Compressor for Defrost

If reducing the pressure on the condenser will cause insufficient hot gas for defrosting and correcting the pipe size is not feasible, significant energy savings may still be realized. One compressor of a large system can be dedicated to running at the pressure needed for the defrost cycle, while the other equipment can be dedicated to lower-system pressure. Savings from reducing the condensing pressure are generally greater than the cost of dedicating a compressor.

Air Purging

Air must be purged from the system. An automatic purger should be installed to decrease refrigerant loss during the process and reduce the possibility of operator error.

Recirculator

Use Mechanical Pump for Recirculation System

Studies have proven that mechanical pumping of liquid refrigerant on recirculation systems is more efficient than hot gas pumping. An electric liquid refrigerant pump can be installed on the recirculation system to push the needed refrigerant to the evaporators. A hot gas pumping system operating at 15 psig with a condensing pressure of 185 psig and capacity of 500 tons of refrigeration can waste approximately 30 hp. A 5 hp electric pump can be substituted, resulting in significant energy savings.

RESOURCES

Printed Material

- ASHRAE Standard 15-1992, Safety Code for Mechanical Refrigeration.
- ASHRAE Standard 34-1992, Number Designation and Safety Classification of Refrigerants.
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- Stoecker, W.F., Industrial Refrigeration Handbook, 1998.
- Wulfinghoff, D.R., Energy Efficiency Manual, Energy Institute, MD, 1999.

On-Line Tools

- U.S. Department of Energy
Best Practices: www.oit.doe.gov/bestpractices
Fact Sheets: www.oit.doe.gov/factsheets/fact_other.shtml#bp
- Energy Information Bridge: www.osti.gov/bridge

Energy Matters: www.oit.doe.gov/bestpractices/energymatters/energy_matters.shtml

Gartner Refrigeration and Manufacturing: www.gartner-refrig.com

Tips and Tools: www.gartner-refrig.com/resources/tips.asp

The Industrial Refrigeration Consortium: www.irc.wisc.edu.

Downloads: www.irc.wisc.edu/software/downloads.php

Publications: <http://www.irc.wisc.edu/publications/>

Organizations

American Society of Heating, Refrigerating, and Air-Conditioning Engineers
(ASHRAE): www.ashrae.org

The Industrial Refrigeration Consortium: www.irc.wisc.edu

International Institute of Ammonia Refrigeration: www.iiar.org

Iowa State University Industrial Assessment Center (IAC): (515) 294-3080 or
www.me.iastate.edu/iac