energydesignresources

design brief

Energy Efficiency Practices in Industrial Refrigeration

Summary

Energy costs are a significant expense for facilities that operate industrial refrigeration systems. In new construction projects, significant energy savings can be achieved by incorporating energy efficiency technologies in the project design. For facilities being expanded or upgraded, ensuring the efficiency of the refrigeration systems can lead to significant energy savings without compromising productivity.

Efficient industrial refrigeration systems are developed through proper design, the use of premium efficiency equipment, and the installation of appropriate system controls, as well as regular maintenance. This design brief is intended to provide building owners, facility managers, architects, and consulting engineers with the latest information on energy efficiency technologies in refrigeration systems required in the agriculture, food processing, manufacturing and fabrication, medical, high-tech, and biotechnology industries. It highlights design considerations and provides an overview of common energy efficiency measures, specifically:

- Optimized compressor sequencing
- Moderately oversized condensers
- Floating head pressure control
- Increased suction pressure
- Variable frequency drives

CONTENTS

Summary 1

Introduction 2

Industrial Refrigeration Systems 3

Design Considerations for New Construction and Retrofits 12

Frequently Practiced Energy Efficiency Measures 21

Example of Energy Efficient Refrigeration System for New Construction 30

Additional Information Resources 32

References 33

- Premium efficiency motors
- Liquid overfeed evaporators
- Demand-based defrosting
- Purgers
- Insulation
- High-efficiency lighting fixtures and controls
- Rapid-closing doors

Introduction

Industrial refrigeration systems play a critical role in the business operations of many commercial sectors in California, including food processing, cold storage warehousing, and chemical processing. Energy costs are a significant expense for these businesses. For example, approximately 25% of the electricity consumed by the food processing industry is used for process cooling and refrigeration.[1] Nevertheless, despite the high energy costs associated with refrigeration and the potential savings from increased efficiency, the historical focus on designing and installing new refrigeration equipment has been to develop systems that can meet a facility's energy load at a minimum capital cost. Energy use and operating costs have had a lower priority.

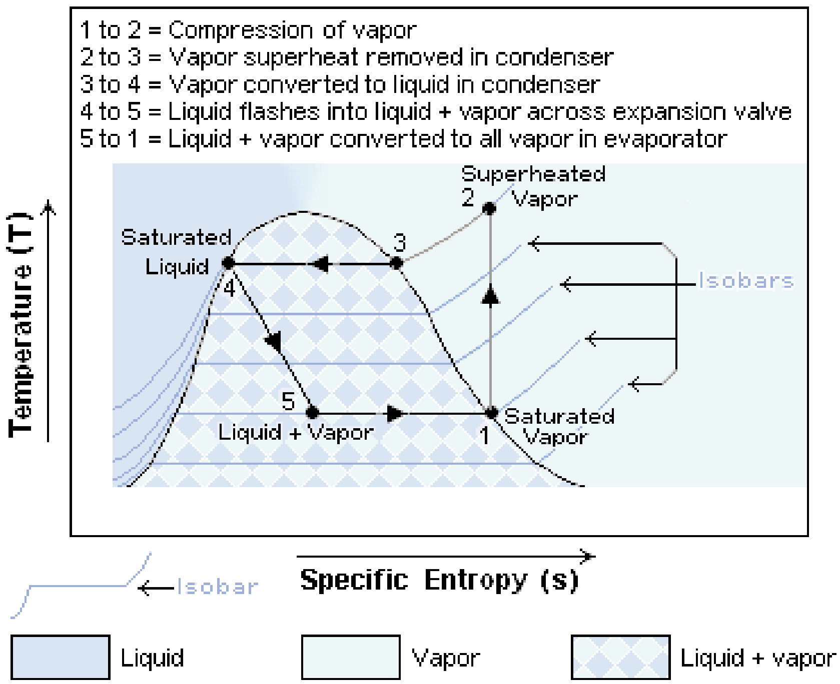
The *2006 California Energy Efficiency Potential Study* underscores the significant potential for year round electricity savings from refrigeration projects; in California, the potential savings from economically viable refrigeration projects (retrofit opportunities) at commercial and industrial facilities exceeds 3,100 GWh per year.[2] Going forward, building owners, architects, and contractors can help capture the inherent economic and environmental benefits from electricity savings by ensuring that a new facility or a building undergoing major renovation incorporates optimal refrigeration design techniques, efficient equipment selection, and appropriate control systems.

Utility incentive programs offer both design assistance and financial incentives based on energy savings for eligible refrigeration projects. Target markets covered by these utility programs include agriculture, food processing, industrial and fabrication, commercial, medical, high-tech, and biotechnology.

Industrial Refrigeration Systems

Cooling is accomplished using vapor cycle refrigeration, where the refrigerant absorbs and rejects heat with the help of external work. Vapor cycle refrigeration involves a phase change of the refrigerant and can be classified as either vapor compression refrigeration or vapor absorption refrigeration. The phase change cycle is shown in Figure 1.

FIGURE 1: TEMPERATURE-ENTROPY DIAGRAM OF VAPOR COMPRESSION CYCLE



Source: http://en.wikipedia.org/wiki/Vapor-compression_refrigeration

The vapor absorption cycle is similar to vapor compression, but uses an absorber to dissolve the refrigerant into liquid. A liquid pump then increases the pressure, and a heat source is used to drive off the refrigerant vapor from the high-pressure liquid. The vapor absorption cycle is typically used in locations with access to cheap heat energy sources or process waste heat. Because of its very low coefficient of performance compared to the vapor compression cycle, vapor absorption is not normally used for industrial cooling purposes.

Various types of refrigerants exist, but many of them are being phased out due to increased regulation. Refrigerants usually fall into one of the following groups:

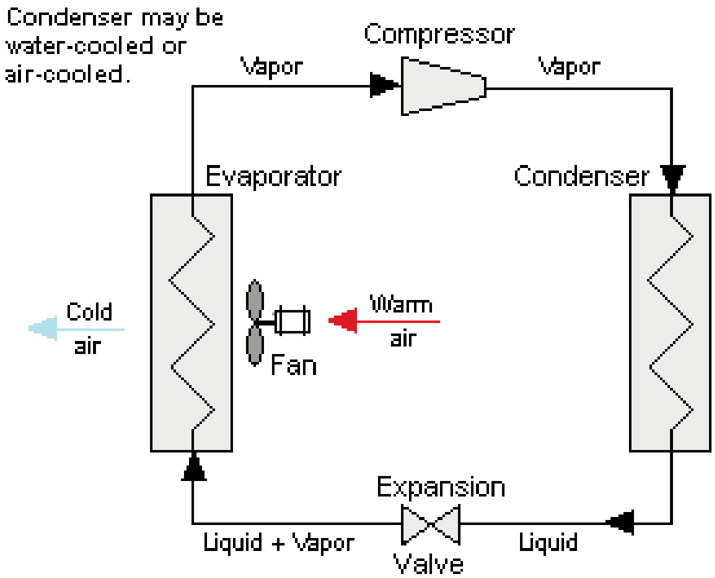
- CFCs – chlorofluorocarbons
- HCFCs – hydrochlorofluorocarbons
- HFCs – hydrofluorocarbons
- HCs – hydrocarbons
- NH_3 – ammonia

CFCs have been widely used in the past but are now phased out of production due to their high ozone-depleting potential (ODP). HCFCs also have ODP; they are strictly regulated and are in the process of being phased out. HFCs and HCs have zero ODP and are being used as replacements for refrigerants with ODP. Ammonia is toxic but has no ODP and is used extensively in industrial refrigeration systems. Several advantages of ammonia have contributed to its popularity in industry, including high latent heat and therefore less required mass flow, low pressure losses in connecting piping, and low reactivity with refrigeration lubricants.

Refrigeration systems are designed to achieve and maintain the specific required conditions of a facility's refrigerated space by producing enough cooling to overcome the heat added by external and internal loads as well as the heat generated by the product.

Refrigeration systems usually comprise four major components—compressor, condenser, expansion device, and evaporator—which are described below and shown in Figure 2. Several equipment types and technologies are available for each of the major components; in many cases, each system component comes from a different manufacturer. To maximize the overall efficiency of a refrigeration system, it is important to consider the interaction among components as well as the individual performance of each.

Figure 2: Basic Diagram of a Refrigeration System



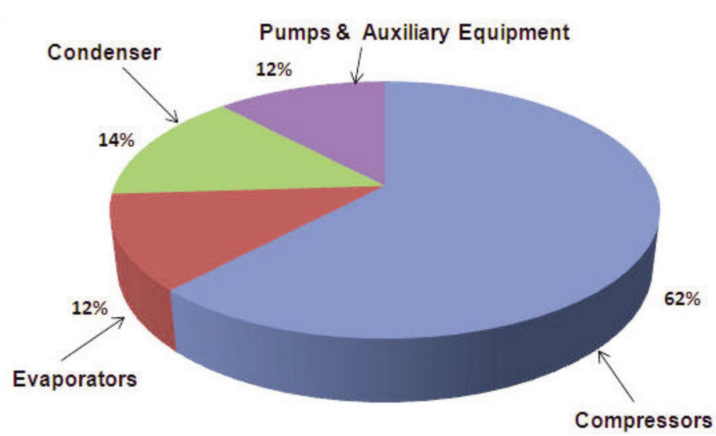
Source: http://en.wikipedia.org/wiki/Vapor-compression_refrigeration

Compressor

The compressor performs the work in the refrigeration system, and typically consumes most of the required system energy, as Figure 3 illustrates. Consequently, many of the potential efficiency measures involving refrigeration systems center on ways to reduce compressor power loads.

Compressors are usually powered by an electric motor and can use either positive-displacement or dynamic compression technology. Positive dis-

Figure 3: Power Consumption by Typical Refrigeration System Components on an Average July Day



Source: Manske, 1999 [3]

placement machines operate by trapping and reducing the volume of gas before releasing it to the discharge side of the compressor. Dynamic compressors use angular momentum to increase the velocity of the gas and then convert the momentum into an increase in pressure.

Most industrial refrigeration systems use either reciprocating or screw compressors, both of which are positive-displacement machines. Other less common compressor types include rotary vane, scroll, and centrifugal. Different compressor technologies have different control strategies for adjusting their capacity in order to meet the cooling load. Compressors are constructed as either open-drive, hermetically sealed, or semi-hermetic.

- Open-drive compressors are designed with the shaft extending out of the compressor and connected externally to the motor.
- In a hermetically sealed motor-compressor unit, the entire assembly is encapsulated. Only the refrigerant lines and electrical connections extend out of the housing.
- Semi-hermetic compressors are designed with the motor and compressor encapsulated, although the heads of the compressor can be removed to gain access to the compressor and motor for servicing.

Reciprocating compressors utilize a cylinder and piston for compression. They can consist of multiple cylinders. Capacity control is typically accomplished by the use of cylinder unloading, during which the compression cycle is disabled by keeping the suction valve open as the piston moves to the top position and the charge is routed back to the suction line. The compressor's capacity reduction is proportional to the number of cylinders unloaded. For example, if two out of six compressor cylinders are unloaded, then the compressor capacity is reduced by 33%.

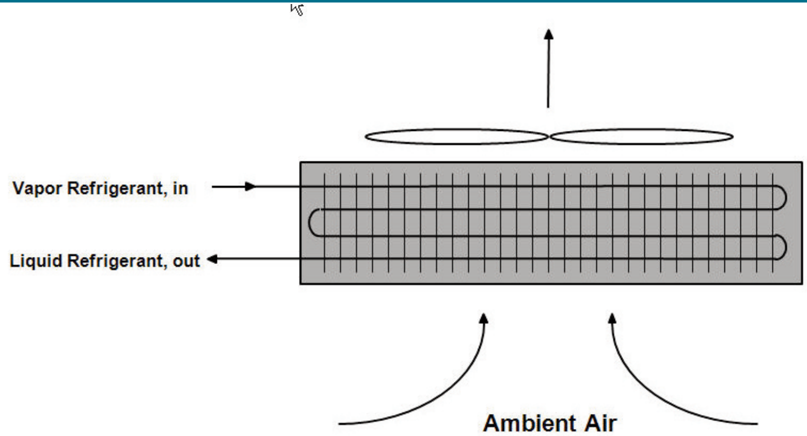
Screw compressors use interlocking rotors that trap and force the refrigerant along the axis of the compressor, compressing the gas by progressively decreasing its volume. On a screw compressor, capacity is usually controlled with a slide valve. The slide valve adjusts the location of the suction port along the rotor, which changes the volume of suction gas allowed to enter the compression chamber.

Depending on size and system characteristics, refrigeration systems may utilize single or multiple compressors. Multiple-compressor systems provide more capacity variation and more back-up capabilities for maintenance or failures.

Condenser

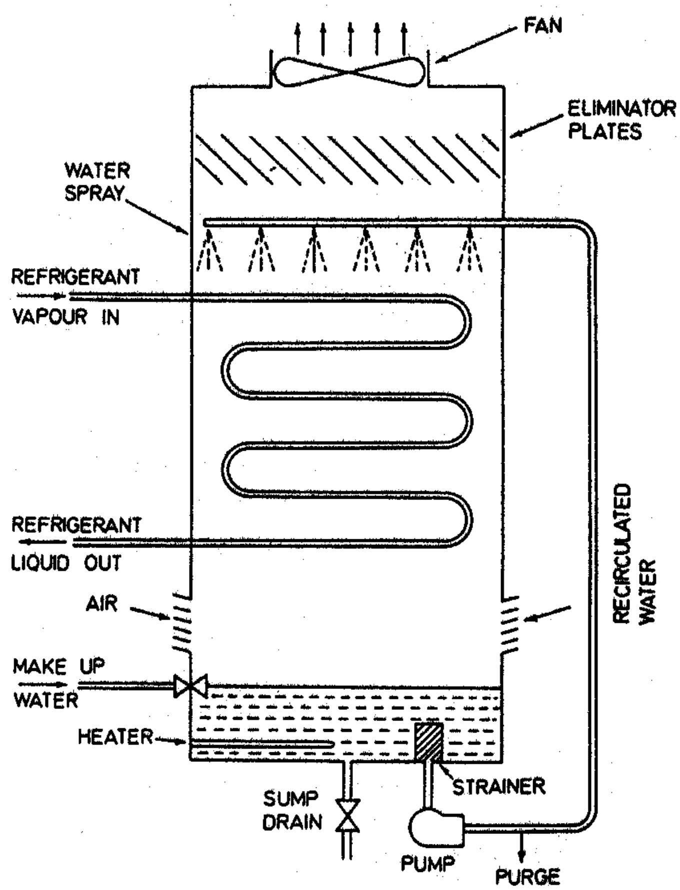
Condensers are heat exchangers used to reject the heat from the refrigeration cycle to the outside air. Three types of condensers are used in refrigeration systems: air-cooled, evaporative, and water-cooled. Air-cooled condensers, illustrated in Figure 4, reject heat directly to the outside air, much as a car radiator does. They are typically configured as finned-tube heat exchangers with a fan drawing ambient air across the heat exchanger. The cooling capacity and required condensing temperatures for this type of condenser are directly related to the ambient dry bulb temperature. Air-cooled condensers are frequently used for smaller, commercial packaged systems.

Figure 4: Air-cooled Condenser



Evaporative condensers, illustrated in Figure 5, are the most common type of condenser for industrial refrigeration systems [4]. Evaporative condensers use a recirculation pump to spray water over the condenser tube bundle. Fans move ambient air across the tubing, similar to an air-cooled condenser, transferring heat away from the heat exchanger to the outside environment. The water is evaporated by the heat of the refrigerant gas as the refrigerant condenses inside the heat exchanger. Unlike air-cooled condensers, evaporative condensers rely on lower wet bulb temperatures

Figure 5: Evaporative Condenser



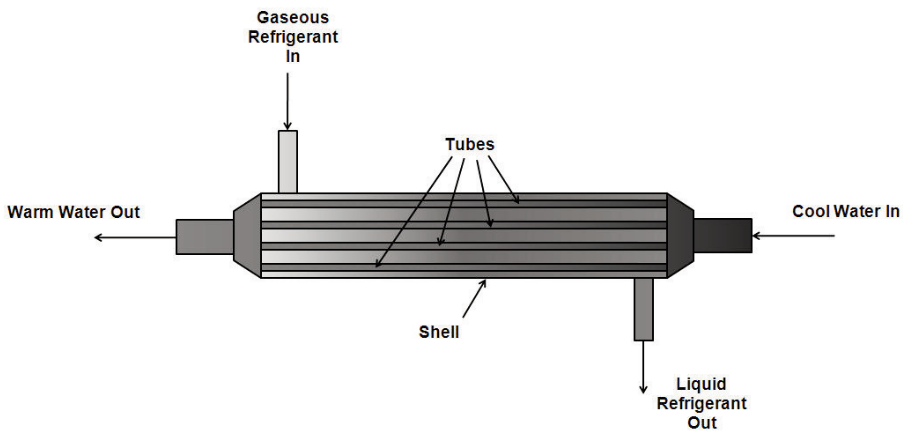
Source: http://www.fao.org/DOCREP/003/R1076E/R1076E04.HTM (Fig. 17)

to remove heat from the system, and therefore can operate at lower condensing temperatures. Evaporative condensers are ideally suited for operation in dryer climates with low wet bulb temperatures.

Water-cooled condensers, like that in Figure 6, use low-temperature water in a heat exchanger to reject heat from the refrigerant gas. This type of condenser typically works in conjunction with a cooling tower that is used to cool the water. Due to the additional cost of installing a cooling tower, water-cooled condensers are generally used only in very large refrigeration systems.

Evaporative and water-cooled condensers are typically more expensive to install and have higher operating and maintenance costs than air-cooled condensers; however, they are typically more efficient and require less space for the same amount of heat rejected.

Figure 6: Water-Cooled Condenser



Condensers and cooling towers are usually sized to meet the conditions of both the design cooling load and the coincident ambient conditions and are set to operate at a fixed condensing temperature (also known as head pressure) or within the design approach/range in the case of a cooling tower. However, most systems are usually not operating at full load, which results in the condenser being operated at a reduced capacity based on the amount of heat that needs to be rejected and the existing weather conditions. The condenser fans control the amount of heat rejected; therefore, in many industrial refrigeration systems, the standard method for controlling condenser capacity is through fan speed control or fan cycling.

Expansion Device

The expansion device releases high-pressure liquid refrigerant into a low-pressure liquid/vapor mixture that then feeds into the evaporator. The expansion device controls the refrigerant flow entering the evaporator based on the amount of superheat of the gas leaving the evaporator. The mass flow of refrigerant entering the evaporator is controlled to be equal to the rate at which it can be completely vaporized in the evaporator by the absorption of heat. The expansion device functions to keep the evaporator actively cooling while preventing liquid from returning through the suction line to the compressor.

Evaporator

The evaporator is a heat exchanger that removes heat from the refrigerated space or process and serves as the link between the cooling load and the refrigeration system. Heat may be removed from air, water, or any other intermediate fluid. Three common types of evaporators are used in industrial refrigeration systems:

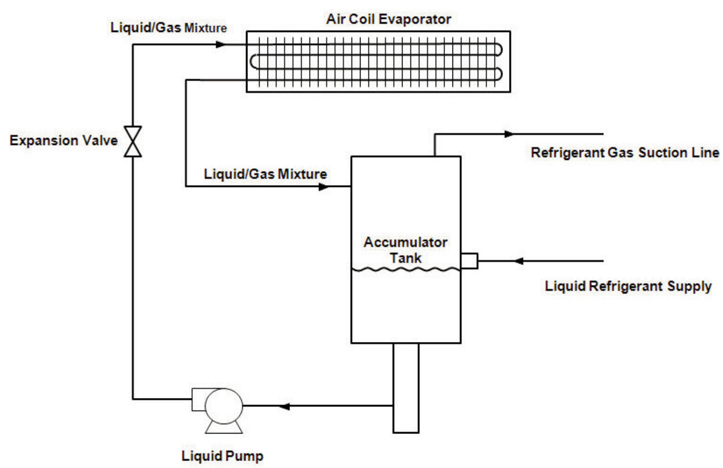
- Direct expansion (DX) evaporators, in which the liquid refrigerant expands and evaporates directly inside the heat exchanger.
- Liquid recirculation/overfeed evaporators, which use a separate vessel for the expansion process and separate the low-pressure liquid from the vapor. This method utilizes the heat transfer surface more efficiently than DX evaporators through good refrigerant distribution and completely wetted internal tube surfaces.
- Flooded evaporators, which flood the entire heat exchanger with liquid to promote latent heat transfer.

Evaporators can be further classified into three common types of heat exchangers:

- Air coil units, which use refrigerant cooled coils in an air steam for air conditioning.
- Shell-and-tube heat exchangers, which are used for chilling liquids such as water, glycol, or brine by transferring heat between a tube bundle and the surrounding shell.
- Plate-type heat exchangers, which are configured with a series of parallel plates, with alternating fluid or refrigerant on adjacent plates. Heat is transferred between the adjacent plates.

Air coil heat exchangers consist of a series of tube coils which have fins bonded to them in order to increase the surface area of heat transfer. Air coil units can be either direct expansion or liquid recirculation/overfeed. In a direct expansion system the refrigerant is released into the evaporator coils as a liquid/gas mixture and is completely evaporated inside the coils before returning in vapor state to the compressor suction line. In a liquid recirculation/overfeed system the high-pressure refrigerant is fed to a vessel at evaporator pressure where a constant liquid level is maintained. Liquid refrigerant is pumped from the vessel through the evaporator where it partially evaporates and then returns to the vessel as a two-phase mixture (see Figure 7). The refrigerant gas is separated in the vessel from which it is returned to the compressor suction line.

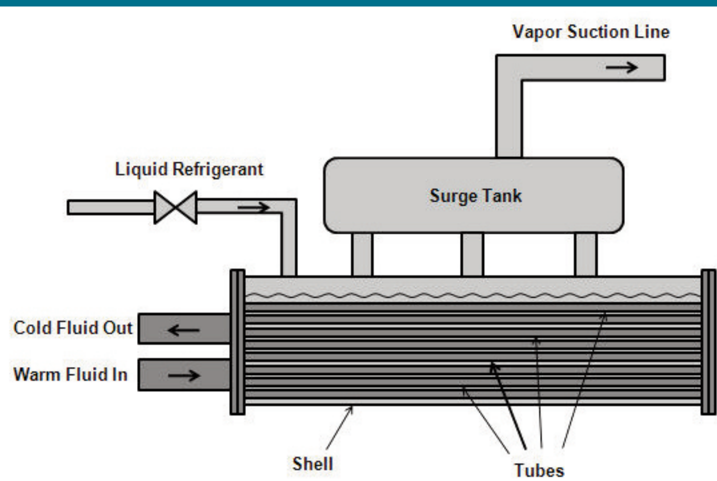
Figure 7: Liquid Overfeed System



Shell-and-tube heat exchangers can be configured as either direct expansion or flooded type (see Figure 8). In a direct expansion shell-and-tube chiller, the fluid to be chilled flows through the shell side while the refrigerant is directly expanded in the tube side. In a flooded type chiller, the fluid to be chilled circulates on the tube side while liquid refrigerant surrounds the tube bundle and evaporates on the shell side; the entire heat transfer surface is wetted with liquid refrigerant.

Plate-type heat exchangers can be configured with the refrigerant side as either flooded or liquid overfeed. The flooded type uses saturated liquid

Figure 8: Shell and Tube Flooded Evaporator



refrigerant as the cooling medium similar to a flooded shell-and-tube heat exchanger. A liquid overfeed configuration similar to that described for air coil heat exchangers can also be used with plate-type heat exchangers.

Defrosting Controls

Air coil evaporators often require some type of defrosting controls to maintain optimum heat transfer performance. In systems with suction temperatures below the freezing point of water and below the dew point temperature, condensation forms and produces frost on the coils. The frost negatively affects system performance by acting as an insulator that restricts heat transfer as well as impeding air flow through the evaporator coils. Therefore, the evaporator coils must be periodically defrosted. A number of control strategies exist for initiating defrost cycles, including time clocks, running time monitors, air pressure differential controls, air temperature differential controls, and frost sensors.

Defrosting methods used in industrial systems are:

- Hot gas defrost: This common defrost method recirculates hot refrigerant gas through the coils on an intermittent basis to warm the coils and melt accumulated frost.
- Hot water defrost: Water defrost is quick, efficient, and effective for rapid cleaning of the entire coil surface. It can be performed manually or automated. The typical application is in large units used for cooling industrial products rather than in small ceiling-suspended units.
- Air defrost: If the conditioned space has an air temperature above about 35°F, air can be used to defrost the coils by leaving the fans on to circulate air through the coils during the evaporator off cycle periods.
- Electric resistance defrost: This method utilizes electric heating elements attached to the finned coil surface to melt accumulated frost. This can be a rapid defrost method, but it also dissipates more heat into the enclosure.

Design Considerations for New Construction and Retrofits

The operation of the entire refrigeration system, including the interactive effects of individual refrigeration components, should be considered when selecting and sizing equipment and evaluating control technologies. Standard refrigeration systems are often designed based on the performance of each component, which may not always result in the optimal performance of the overall system. For example, a lower refrigerant temperature set point in the evaporator will reduce the required air flow needed to do the same amount of cooling. However, the lower temperature will also increase the required pressure lift, thereby increasing the load on the compressors. Therefore, when determining the optimal refrigerant temperature, it is important to take into account the energy requirements of both the evaporator fan motor and the compressor in order to minimize overall system energy consumption and costs.

The energy efficiency design recommendations made below are focused on a typical industrial refrigeration system. Although the particular equipment and control strategies that produce the most efficient refrigeration system design will vary by project and type of facility, key factors to consider include:

- Type and variability of load (temperature and humidity requirements for product, including entering product temperatures and product turnover)
- System size and cooling requirements (low or medium temperature system)
- Geographic location (ambient temperature, seasonal temperature changes)
- (For existing systems) Age of the system (designed date and equipment that was utilized/available)

Equipment sizing and selection is a critical step in the design of an efficient industrial refrigeration system. Described below are criteria, discussed on an individual refrigeration component basis, that should be taken into account as part of the front-end design of a new construction or retrofit refrigeration project.

Compressor Criteria

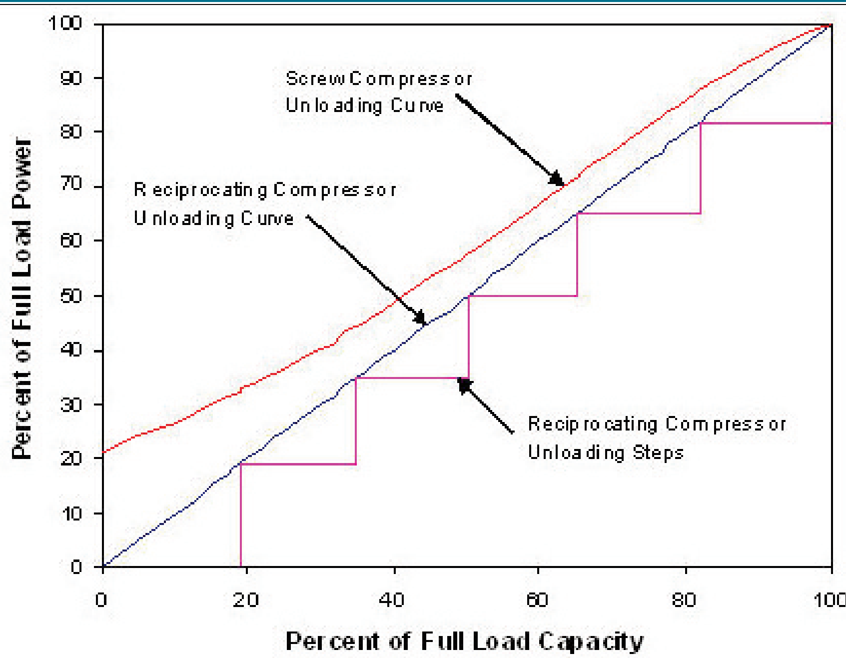
Motor Efficiency: One key element in the design of energy efficient compressors is the use of premium efficiency motors. Typically, premium efficiency motors are available for compressors at a small incremental cost over standard efficiency motors. The savings potential from utilizing premium efficiency motors is significant, however, given the high number of operating hours during which industrial refrigeration systems are in service.

The use of premium motors is highly attractive for the design of new refrigeration systems. Premium efficiency motors can easily be selected when designing built-up systems, and packaged systems can often be customized to include them as well. On their own, however, the savings from premium motors will not likely achieve enough energy savings to justify the retrofit of existing systems. Specifically, retrofitting existing systems with high efficiency motors is typically not a cost-effective measure unless the retrofit opportunity involves the replacement of old or degraded motors or compressors. In these situations, upgrading a refrigeration system to include premium efficiency motors can be an effective energy efficiency improvement. Premium efficiency motors provide an efficiency gain of approximately 3% to 10%, relative to Pre-EPAct motors, depending on the size of the motor, hours of operation, load, and other factors.[5] In the case of a retrofit of very old motors, gains may be even greater because of a lower baseline.

Compressor size. Premium efficiency compressor motors are appropriate for all refrigeration systems; however, the appropriate compressor type(s) and size(s) must be determined based on the facility load. Compressor sizing should take into account the required cooling load as well as the other equipment and controls being installed as part of the system. In addition, the compressor sizing should take into account the types, sizes, and controls on the other system components. For existing systems, when compressor replacement is required due to equipment burnout or degradation, changes in compressor loads due to other installed controls should be considered. In these situations, it is possible that the facility's load could be met with smaller compressors.

Compressor type. Once the appropriate compressor size is determined, compressor type(s) should be selected in light of the variability in loads at the facility. For facilities with significant throughput and new products frequently entering the refrigerated space, the initial pull-down load can be significantly higher than the normal load required to maintain refrigerated conditions, resulting in high variations in load. At full-load capacity, screw compressors generally perform better than reciprocating compressors. However, as shown in Figure 9, reciprocating compressors unload more linearly than screw compressors, and therefore can perform better in systems with highly variable loads.

Figure 9: Compressor Unloading Comparison



Source: Manske, 1999 [3]

It should be noted that in Figure 9 the screw and reciprocating compressors do not generally have the same rated power and full load capacity. The curves do not show the compressors' performance efficiencies; although screw compressors normally have higher efficiency near full-load capacity, reciprocating compressors have better part-load efficiencies. The reciprocating compressor has discrete steps of unloading, as shown by the unloading steps curve. The points of intersection between the linear unloading curve and the unloading steps curve indicate the actual operating points of the reciprocating compressor. In cases where the reciprocating compressor is meeting a load not corresponding to its increments of capacity, the compressor will cycle its capacity above and below to meet the load on a time-averaged basis.

Number of compressors. A characteristic of efficient refrigeration systems is the use of multiple compressors. Utilizing multiple compressors provides several benefits, including improving load optimization by increasing the variety of options available and providing redundancy in the system to avoid interruption in service due to repairs or required maintenance. Selecting compressors of unequal size allows for even more loading combinations. In addition, the compressor configuration can include both reciprocating and screw compressors, which takes advantage of the benefits of both types. As previously discussed, screw compressors typically perform slightly better at full load; however, reciprocating compressors unload more linearly. Therefore, where both types are available, screw compressors are generally used at full capacity to serve the base load, and reciprocating compressors are modulated as needed for load-following or "load-trimming."

Compressor controls. The utilization of control technologies on compressors can enhance the performance of a refrigeration system. An effective control technology with energy savings potential for compressor motors is the variable frequency drive (VFD), which controls the motor speed based on required load. Systems with variable cooling loads can benefit substantially from VFD retrofits; however the viability of this option is dependent upon equipment-specific factors, and the compressor manufacturer should be consulted.

An alternative strategy involves optimizing the sequencing of compressors when multiple compressors are included in a system. Specifically, computer control systems can be utilized to stage or sequence compressor operations so that they match variable load requirements. Proper sequencing can save energy due to the differences in the part-load characteristics of reciprocating and screw compressors, as well as the sizes of the compressors in use. For example, reciprocating compressors unload linearly; therefore, in systems with two reciprocating compressors, the load should be split evenly between the two. Below 50% load, however, the part-load performance of screw compressors decreases significantly. For that reason, screw compressors should be equally loaded at higher part loads, but as the decreasing part load on each compressor approaches 50% or lower, one compressor should be fully loaded and the other compressor used to meet the remaining load. In addition, if compressors of unequal size are used, proper staging and sequencing will determine the appropriate compressors for various part-load conditions.

These control technologies should be factored into the design of new refrigeration systems. They are also an excellent retrofit measure for existing systems. When installing VFDs on existing motors, the motors should be checked to see that the motor windings are in good condition.

Condenser Criteria

Condenser type. Condenser design also plays a key role in refrigeration system efficiency. The capacity and performance characteristics of the condenser have a direct effect on compressor efficiency. Selection of the appropriate condenser type depends on the ambient weather conditions, the amount of heat rejection needed, and the available space.

- Air-cooled condensers are usually the least expensive; however, the saturated condensing temperature must be higher than the ambient dry bulb temperature, which can lead to high head pressures and increased demand on the compressors. Condenser capacity is dependent on the differential between the condensing temperature and the cooling medium temperature.

- Evaporative condensers can operate at lower head pressures than air-cooled condensers because ambient wet bulb temperature is utilized for cooling the condensing coils. Compressor operating efficiency is therefore benefitting from a reduction in head pressure. Evaporative condensers are the preferred approach for rejecting heat from industrial and large commercial refrigeration systems.

- Water-cooled condensers operate at lower head pressures than air-cooled condensers but at higher head pressures compared to evaporative condensers. When a cooling tower is used with water-cooled condensers, the cool water supplied to the condenser under design conditions is about 17°F warmer than air wet bulb temperature. However, one advantage of water-cooled condensers is that thermal reservoirs such as rivers, lakes, and ponds can be used where available. Extremely large refrigeration plants (greater than 5,000 tons) with many compressors may also warrant the use of cooling towers with water-cooled condensers in order to reduce the number of individual evaporative condensers needed to reject the total heat.[3]

Condenser size. Three factors are typically considered when sizing a condenser:

- Total heat rejection required, which includes the heat absorbed by the evaporators as well as the work imparted to the refrigerant by the compressors.
- Local climate conditions, including the design wet bulb/dry bulb temperature.
- Design condensing temperature (many standard ammonia systems are designed with a condensing temperature of 95° F).

Proper sizing of evaporative condensers is critical for an efficient refrigeration system. An evaporative condenser needs to have the ability to transfer all required heat rejection from the refrigeration system to the ambient environment under the worst case conditions. Local design wet bulb or dry bulb temperatures and the design system condensing temperature must be evaluated to ensure that the condenser capacity is sufficient to meet the required cooling load.

Condenser motors. Equipment selection should also include the use of premium efficiency motors for the condenser fan motors and pumps. For efficient systems that utilize oversized condensers, the importance of premium efficiency motors is more acute, due to the large fan and pump sizes.

Condenser controls. Multiple control technologies are available for condensers. Control options for the condenser fans include the use of VFDs or half-speed motor controls. The benefit of VFD control is explained by the fan affinity laws, which state that the fan power is the cube of fan speed. With half-speed motor control, the motor can be loaded at either 50% or 100% speed. This option does not achieve the savings of a VFD, but it is an improvement on a single-speed motor and may be a more economical alternative.

Evaporator Criteria

Evaporator size. Evaporator sizing and selection is based on the maximum cooling load for the system as well as the design temperature difference (TD), which is defined as the difference in temperature between the inlet air dry bulb temperature and the saturated refrigerant temperature. Increasing the TD increases the capacity of the evaporator; however, the lower refrigerant temperature will increase the load on the compressor. Therefore the optimal TD minimizes both the evaporator fan and compressor power consumption. The evaporator coils should then be sized accordingly. Periodic evaporator capacity reduction resulting from frost accumulation on the evaporator coils must be accounted for when sizing the evaporator.

Evaporator type. As previously discussed, several evaporator options exist for refrigeration systems. Air coil units are generally preferred to operate with liquid overfeed evaporators because of their high system efficiency. The more evaporators used in a system, the more cost-effective the installation of liquid overfeed becomes. Direct expansion evaporators can be less costly to install, but are normally not good designs for systems with lower suction pressures (below 0°F suction temperature) due to poor refrigerant distribution and control problems.

In low-temperature applications, a small temperature differential between the refrigerant and the medium being cooled is advantageous. Flooded evaporators may be desirable in these cases. In a flooded evaporator, the coil is kept full of liquid refrigerant and pumped back to a surge tank where vapor and liquid refrigerant are separated, similar to the surge tank in a liquid overfeed system.

Evaporator fan motors. As with condenser and compressor motors, when selecting evaporator equipment, premium efficiency motors should be utilized for the evaporator fans. In some systems, the motor size is relatively small, but energy savings can be significant due to the large amount of annual operating hours. As an added benefit, the use of premium efficiency motors also reduces the internal load that the heat from the motors contributes to the refrigerated space.

Evaporator controls. Efficient control options for evaporators include VFDs or two-speed motor controls on the evaporator fans. As with condenser fans, the variation of power consumption with fan speed demonstrates that when the system is operating at less than full capacity, energy savings can be achieved by reducing speed on the evaporator fans.

Optimizing the refrigerant suction temperature set point can make it possible to meet the cooling load while minimizing the total work required of the system components. It is critical to ensure that the compressor and evaporator fan load are properly balanced. A lower refrigerant temperature increases the capacity of the evaporator coils which enables the evaporator to achieve the required cooling with less airflow. As a result, the load on the evaporator fan is reduced, and savings can be realized by reducing the speed, size, or duty cycle of the fan. However, the lower suction temperature increases the pressure differential across the compressor, thereby increasing the compressor load. Therefore, the optimal refrigerant set-point temperature for the system should incorporate both the compressor and evaporator fan energy consumption. This will help minimize the overall system power demand, while meeting the system's cooling requirements.

Periodic defrosting of the evaporator coils is usually a required maintenance operation. However, most standard systems use timer-based controls for defrosting, which can introduce additional, unnecessary loads on the system. In some cases, the defrost cycle occurs several times a day, whether defrosting is needed or not. As described earlier, the defrost cycle typically uses hot water, hot gas, or electric heating elements, which adds load to the refrigeration system. When defrost cycles occur more often than necessary, the excessive load introduced to the refrigeration system is an additional burden that must be overcome through additional refrigeration. Demand-based defrosting of evaporator coils is a much more effective method, ensuring that the heat load applied to the system only occurs when defrosting is needed. Several demand-based defrosting systems are available. These systems determine when defrosting is required, based on criteria that include temperature or pressure drop across the evaporator coils, frost accumulation, and humidity levels.

Purger

The purger contributes to the efficient operation of low-pressure refrigeration systems. Its function is to separate and expel from the system unwanted non-condensable gases, such as air, nitrogen, hydrogen, and hydrocarbons. Air is the most common non-condensable that accumulates in the system over time. Low-temperature refrigeration systems can have a significant portion of their system components operating below atmospheric pressure, resulting in leaks that allow air to infiltrate the system. Air can also enter the system due to inadequate evacuation after system servicing. After opening a portion of the system for maintenance purposes, air will occupy that part of the system immediately after reassembly; unless it is properly evacuated before the system is brought back into service, the air will be ingested into the system. Non-condensables tend to accumulate in the evaporative condenser's heat exchanger where they act as an insulator, which interferes with the condenser's ability to transfer heat. As a result of the condenser's reduced capacity, the temperature (and pressure) of the condensing refrigerant must increase in order to reject the required amount of heat. Therefore the compressor must run at a higher discharge temperature, reducing the efficiency of the system.

Other Factors to Consider

The selection and control of other equipment located in the refrigerated space can have a significant impact on the energy requirements of the refrigeration system. Lighting, motors, forklifts, human traffic, and other internal heat sources all contribute to the cooling load and should be considered when pursuing energy saving strategies. Other sources of heat gain include infiltration and fenestration through the building shell. Door openings, ventilation and insulation materials are some of the factors affecting heat gain through the building shell.

Frequently Practiced Energy Efficiency Measures

The following energy efficiency measures are known as major energy savers for common refrigeration systems and refrigerated spaces.

According to the records of PG&E's energy management programs, each measure individually can reduce energy use by 5% to 10%; combining measures can save 25% to 35% over industry standard baselines.[6]

Optimized Compressor Sequencing

An alternative capacity control strategy involves optimizing the sequencing of compressors when multiple compressors are included in a system. Specifically, computer control systems can be utilized to stage or sequence compressor operations so that they match variable-load requirements. Proper sequencing can save energy for customers due to differences in the part-load characteristics of reciprocating and screw compressors, as well as the sizes of compressors in use. The efficiency profiles and capacities of all the compressors in the system should be considered when determining optimal sequencing and loading strategies for the particular system load. Screw compressors generally have higher efficiency at full-load operation, while reciprocating compressors have a more linear loading profile and higher part-load efficiencies. In most cases, with systems using both screw compressors and reciprocating compressors, the screw compressors should be operated only at full load if possible and allow the reciprocating compressors to modulate at part load according to cooling demand.

In addition, if compressors of unequal size are used, proper staging and sequencing will determine the appropriate compressors for various part-load conditions. These control technologies should be factored into the design of new refrigeration systems. They are also an excellent retrofit measure for existing systems.

Moderately Oversized Condensers

Moderately oversized condensers are typically an effective energy efficiency option. The larger condensers lower the saturated condensing temperature, reducing the work required from the compressors. Oversized condensers will require larger fan motors and pumps, which are slightly more expensive and consume slightly more energy; however, typically the energy savings are much more significant than the increase in cost and condenser energy consumption. When sizing compressors for a refrigeration system, the size of the condenser and required head pressure should be considered. The reduction in compressor demand because of the oversized condenser may allow for the selection of smaller compressors. Potentially, additional savings can be realized as a result of this measure by operating a smaller compressor at near full load as opposed to a larger compressor at part load.

Floating Head Pressure Control

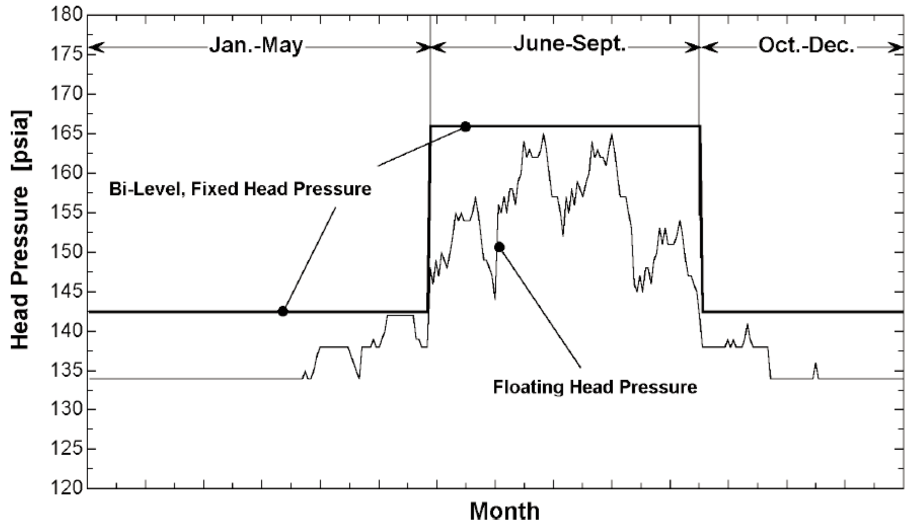
A common and very effective control strategy is condenser floating head pressure control. In many standard systems, head pressure is controlled to be at the fixed design condensing temperature set point--typically high enough for the compressor to be able to meet the maximum system design load at design ambient conditions. In these systems, condenser capacity is controlled through condenser fan cycling or adjustment of the fan speed. With condenser floating head pressure control, the condenser head pressure is allowed to "float" down to lower levels by taking advantage of the increased cooling capacity of the condenser during cooler ambient conditions. For example, during periods of lower wet bulb temperatures, an evaporative condenser's capacity increases; therefore the condensing temperature can be proportionally reduced while achieving the same amount of cooling. The lower limit for the condensing temperature/pressure will be determined by the minimum discharge pressure level required by the compressor and other system components.

Lowering the head pressure reduces the required pressure lift by the compressors, improving their operating efficiency. This control strategy is particularly effective with moderately oversized condensers.

Figure 10 presents an example of reduced head pressure for an industrial refrigeration system. It also includes the use of bi-level, fixed head pressure, which results in reduced head pressure for certain seasons. However, this control method is not as effective as floating head pressure control.

Additional energy savings can be achieved through the use of floating head pressure control in conjunction with VFDs on the condenser fan motors. The optimal head pressure is directly related to ambient temperature. The use of VFDs on the condenser fans allows the fans to operate at part-load. To achieve maximum savings, computer controls can be installed to optimize head pressure and condenser fan speed for the required load and ambient conditions.

Figure 10: Floating Head Pressure Control



Source: Manske, 1999 [3]

Raising Suction Pressure

When conditions allow, raising the suction pressure of a refrigeration system can result in overall energy savings. By increasing suction capacity, the pressure ratio across the compressor is reduced. Pressure ratio reduction results in higher capacity and higher operating efficiency for the compressor. As a rule-of-thumb, compressor capacity increases approximately 2.5% per degree Fahrenheit increase in saturated suction temperature. However, there are limits and penalties to raising suction pressure. Increasing saturated suction temperature reduces the temperature differential (TD) of the evaporator. This decreases the evaporator cooling capacity. Therefore, in order to meet the required cooling load and maintain the cooling set point temperature, airflow and/or evaporator surface area must be increased. This is accomplished by increasing the evaporator fan speed or duty cycle, or increasing the number of evaporators.

Although additional energy is consumed by the evaporators, the increase can be offset by the efficiency gains of the compressors. The system should be optimized to minimize the combined power requirements of the compressors and condensers. It is also important to consider the effect that raising suction pressure has on the system's ability to satisfy transient cooling loads. For instance, when loading large amounts of warm product into the refrigerated space, the refrigeration system is operating at higher capacity until the product is finally cooled to set-point temperature. At higher saturated suction temperatures, the evaporators will require more time to meet the product pull-down loads.

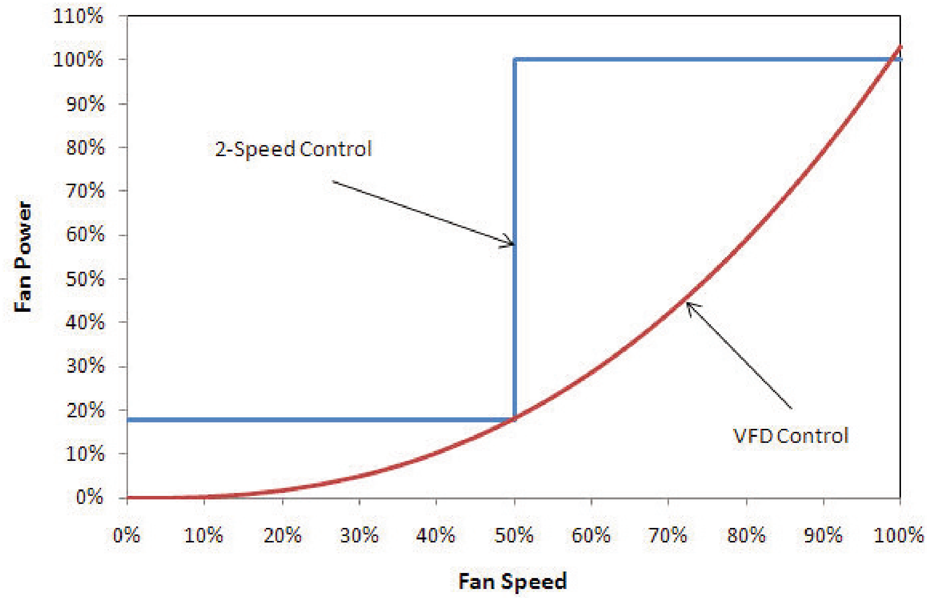
Variable Frequency Drives

There are several opportunities for using variable frequency drives (VFDs) in refrigeration systems to achieve significant energy savings. VFDs or two-speed motor controls can be used effectively on condensers and evaporator fans. The fan affinity laws demonstrate that when the system is operating at less than full capacity during times of reduced cooling load, energy savings can be achieved through reducing the speed on the condenser and evaporator fans. Two-speed fan control can be an improvement over single speed, but VFD control is more effective, as shown by Figure 11. When installed on a condenser fan, VFDs allow for the implementation of floating head pressure controls in addition to realizing energy savings from fan load reduction. Although there is an efficiency penalty with VFD controls—approximately 3% efficiency loss—in most cases the energy saved offsets this loss.

VFDs are also a very efficient control technology for compressor motors, as they control the motor speed based on required load by maintaining the suction pressure set point of a system. VFDs enable more efficient compressor part-load operation over fixed-speed drive alternatives for many screw compressors and other positive displacement machines. However, while VFDs may benefit a reciprocating compressor system for control purposes, it is usually not a good option for energy savings. Because reciprocating compressors have a linear performance loading profile, there is little efficiency benefit for speed control on these systems.

Running a VFD-controlled trim compressor will maximize the efficiency of a variable load refrigeration system when utilizing multiple compressors. The VFD compressor can provide capacity control for the system, while the remaining compressors operate at full load to meet the base refrigeration requirement of the plant. Care must be taken when considering VFD retrofits on compressors, as not all compressor systems are capable of using VFD drives. For example, the lubrication system (bearing lubrication

Figure 11: Fan Speed vs. Power for VFD and Two-Speed Controls



and oil injection) in some screw compressors may not have adequate performance under reduced speed operation. The compressor manufacturer should be consulted for clarification.

Premium Efficiency Motors

Equipment selection should include premium efficiency motors for the compressor motor, condenser fans, evaporator fans, and pumps. The importance of premium efficiency motors is more acute for efficient systems that utilize oversized condensers, due to the large fan and pump sizes.

Typically, premium efficiency motors are available for compressors at a small incremental cost over standard efficiency motors. However, the energy and cost savings potential from utilizing premium efficiency motors is significant given the high number of operating hours in which industrial refrigeration systems are in service. As an added benefit, premium efficiency motors require less power and therefore give off less heat than equivalent standard motors, thereby reducing the internal cooling load that the motors contribute to the refrigerated space.

Table 1 shows the estimated annual operating costs, and energy cost savings across three categories of motors:

Table 1: Estimated Annual Energy Cost Savings with NEMA Premium® Motors1

Annual Operating Hours: 8,000 hours per year				Cost of Electricity: 10C per kWh		
Motor Size2 (hp)	Estimated Annual Operating Costs			Estimated Annual Energy Cost Savings		
	Pre-EPAct Motors	EPAct Motors	NEMA Prem Motors	Pre-EPAct EPAct	EPAct NEMA Prem	Pre-EPAct NEMA Prem
1	$778	$723	$698	**$55**	**$25**	**$80**
1.5	$1,132	$1,066	$1,035	**$66**	**$31**	**$97**
2	$1,477	$1,421	$1,380	**$56**	**$41**	**$97**
3	$2,200	$2,046	$2,000	**$153**	**$46**	**$199**
5	$3,582	$3,410	$3,334	**$172**	**$76**	**$248**
7.5	$5,235	$5,001	$4,881	**$234**	**$120**	**$354**
10	$6,964	$6,668	$6,508	**$296**	**$160**	**$456**
15	$10,337	$9,837	$9,688	**$500**	**$149**	**$649**
20	$13,487	$13,116	$12,834	**$371**	**$282**	**$653**
25	$16,708	$16,147	$15,940	**$561**	**$207**	**$768**
30	$19,982	$19,377	$19,128	**$606**	**$248**	**$854**
40	$26,466	$25,669	$25,369	**$797**	**$300**	**$1,097**
50	$32,683	$32,086	$31,577	**$597**	**$509**	**$1,107**
60	$39,007	$38,256	$37,693	**$750**	**$564**	**$1,314**
75	$48,811	$47,566	$46,918	**$1,245**	**$648**	**$1,893**
100	$64,659	$63,153	$62,558	**$1,505**	**$596**	**$2,101**
125	$80,911	$78,942	$78,197	**$1,969**	**$745**	**$2,714**
150	$96,258	$94,232	$93,445	**$2,026**	**$787**	**$2,813**
200	$127,658	$125,642	$124,075	**$2,016**	**$1,567**	**$3,583**
Size2 (hp)	Pre-EPAct Motors	NEMA Energy Efficient Motors	NEMA Prem Motors	Energy Efficient EPAct	Energy Efficient NEMA Prem	Energy Efficient NEMA Prem
250	$158,386	$157,053	$155,094	**$1,334**	**$1,959**	**$3,293**
300	$189,661	$187,673	$186,112	**$1,988**	**$1,561**	**$3,549**
350	$220,803	$218,952	$217,131	**$1,852**	**$1,821**	**$3,672**
400	$251,814	$250,231	$248,150	**$1,584**	**$2,081**	**$3,665**
450	$282,993	$281,509	$279,168	**$1,483**	**$2,341**	**$3,824**
500	$314,436	$311,482	$310,187	**$2,954**	**$1,295**	**$4,249**

1. This chart provides an estimated comparison of annual energy costs for Pre-EPAct, EPAct and NEMA Prem motors. Actual costs and savings may differ from the values shown.
2. The break in Motor Size between 200 and 250 hp occurs because EPAct applies to motors up to 200 hp. Above that value, NEMA's Energy Efficient Motor specification has been used as the reference.
3. The nominal efficiency values used in these calculations are defined as follows: Pre-EPAct Motors: DOE's MotorMaster+ software version 4.00.01 (9/26/2003) "Average Standard Efficiency" motor defaults ; EPAct Motors: Energy Policy Act of 1992 ; Energy Efficient Motors: NEMA MG 1-2003 Table 12-11 ; NEMA Premium Motors: NEMA MG 1-2003 Table 12-12.

Source: http://motorsmatter.org/tools/savings_chart.xls

- Pre-Energy Policy Act (EPAct) motors, which are typical for standard efficiency motors in refrigeration systems built primarily before EPAct motor standards went into effect in 1997.
- EPAct motors, which are typical for standard efficiency motors in newer refrigeration systems (post-1997). These motors meet the current federal minimum efficiency standards based on the type and size of motor.
- National Electrical Manufacturers Association (NEMA) premium motors, which have been certified as exceeding EPAct efficiency standards.

The annual operating costs for each motor type listed are based on the estimated motor efficiency and an estimated 8,000 annual hours of operation.

Liquid Overfeed Evaporators

Liquid overfeed evaporators are popular in many industrial refrigeration applications and are typically more efficient than direct expansion (DX) evaporators. Air coil units in particular can benefit from liquid overfeed design when suction temperatures are below 0°F. Direct expansion coils are at a disadvantage when operating at low suction temperatures due to the low ammonia mass flow rate. Low mass flow of liquid ammonia is difficult to feed uniformly to the coil, and therefore uneven, incomplete cooling of the coil surface results. Instead, liquid overfeed units can use the evaporator surface efficiently due to good refrigerant distribution and completely wetted internal tube surfaces. In overfeed evaporator systems, excess liquid is forced through organized-flow evaporators, separated from the vapor in a low-pressure receiver, and returned to the evaporators. Another benefit of overfeed systems is that the compressors are protected from liquid slugs that might result from fluctuating loads and control malfunction because liquid is separated from the suction gas in the low-pressure receiver.

Air coil units with DX evaporators may be preferred in some cases due to higher costs for overfeed systems. The installed cost for overfeed systems can be relatively higher for small systems or those having fewer than three evaporators, because overfeed systems generally require larger diameter refrigerant lines and piping insulation. Also, overfeed evaporators can require more maintenance than direct expansion air cooled evaporators.

Demand-based Defrosting

Periodic defrosting of the evaporator coils is usually a required maintenance operation. However, most standard systems use timer-based controls for defrosting, which can introduce additional, unnecessary loads on the system. Demand-based defrosting of evaporator coils is a much more effective method, ensuring that the heat load applied to the system only occurs when defrosting is needed. Several demand-based defrosting systems are available, and these systems determine when defrosting is required, based on such criteria as temperature or pressure drop across the evaporator coils, frost accumulation, and humidity levels.

Purgers

The presence of non-condensable gases in a refrigeration system not only reduces the capacity and efficiency of the system, but leads to unnecessary wear and tear on the compressor. Purgers minimize the negative effects of non-condensables by periodically expelling them at points of accumulation within the system.

Insulation

External loads on refrigeration systems result from heat transmission through the walls, ceiling, and floor. Heat transmission can be reduced through appropriate insulation in the building envelope. Installing tighter insulation beyond industrial standard practices (freezer ceiling: R50; freezer wall: R32; freezer floor: R30; cooler ceiling: R24 to R40; cooler wall: R25) can result in substantially lower cooling energy costs.[7]

Refrigerant suction lines should always be insulated, so that return gas does not gain unwanted heat from the ambient surroundings. High return gas temperatures decrease system efficiencies and unnecessarily increase refrigeration energy usage.

High Efficiency Lighting Fixtures and Controls

High efficiency lighting in the refrigerated space reduces the facility's energy consumption, as well as minimizing heat gains from the lighting, which adds to the internal refrigeration system load. Lighting controls can effectively further reduce energy consumption and internal loads on the system. Available control systems include occupancy sensors, bi-level lighting, and timers that avoid light use when employees are not present.

Rapid-closing Doors

Installing automatic door closers that limit the amount of time the doors are open can minimize energy losses. High-speed cold storage doors allow for rapid entry and exit of the cold storage area while minimizing energy loss due to air exchange between the refrigerated space and the outside. Air curtains and plastic strip curtains can also be useful for reducing external loads on the cooling system.

Example of Energy Efficient Refrigeration System for New Construction

The benefits of energy efficiency measures and design strategies have been proven in many projects. One customer of PG&E that installed multiple measures from among those described above, and achieved significant energy savings, is Dreyer's Grand Ice Cream. In 2005, Dreyer's built three new facilities for its Bakersfield operations to replace and expand its existing facilities and provide more energy-efficient environments for production, distribution, and research and development (R&D).

PG&E's Savings By Design program (also known as Non-Residential New Construction) provided Dreyer's with incentive payments to assist in the design and construction of its new buildings, including refrigeration systems, building envelope, HVAC, and lighting controls. The incentives paid were based on the level of energy efficiency that was above and beyond the current California Title 24 standards and industry standard practice for industrial refrigeration facility construction and system design. The following details are one example of energy and cost savings achievable by incorporating energy efficiency measures in new buildings.

Dreyer's Grand Ice Cream

Bakersfield, CA

Project type: New construction of ice cream production, storage, distribution, and R&D facilities

Facility description: Three buildings totaling 340,000 square feet

Base case: California Title 24 and industry standard practice

Energy efficiency measures installed:

- Evaporative condensers with efficiency of 338 Btu/Watt
- Floating head pressure using variable set-point control strategy
- Premium efficiency compressor motors and air unit fan motors
- Oversize regeneration heat exchanger with 88.3% efficiency
- Increased insulation, using R-50 insulation in freezer walls and roofs
- Lighting controls (occupancy sensors) in freezer
- Reduced lighting power density in offices
- Reduced lighting power density in dry warehouse

Energy savings calculation methodology: DOE2.2R hourly simulation program

Energy savings: 3.26 million kWh per year

Cost savings: approximately $266,000 per year (based on electric rates posted in 2004)

Simple payback (including PG&E incentives): 1.3 years

Additional Information Resources

Additional information on best practices in industrial refrigeration systems can be found at the following sites:

PG&E Fact Sheet on energy efficiency in existing industrial refrigeration systems (http://www.pge.com/includes/docs/pdfs/about/edusafety/ training/pec/inforesource/industrial_refrigeration_systems.pdf)

Industrial Efficiency Alliance Industrial Refrigeration Best Practices Guide (http://www.industrialefficiencyalliance.org/pdfs/irbpg_2005-04-26_cd_excerpt.pdf)

University of Wisconsin-Madison Industrial Refrigeration Consortium (http://www.irc.wisc.edu/)

ASHRAE 2006 Refrigeration Handbook (http://www.ashrae.org/publications/detail/15530)

The Industrial Refrigeration Consortium (http://www.irc.wisc.edu/)

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