Electrical system protection | 32 Integrating lighting, BAS | 44

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Chillers and chilled water systems | page 22

LEDs and energy codes | page 19

Emergency notification systems | page 38

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Winners on page 51

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Selecting chillers, chilled water systems

Selecting the right chiller is generally dictated by capacity, and there are many philosophies on the best way to control, operate, and calculate system operational costs.

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Chilled water systems are cooling systems that circulate chilled water throughout a building for cooling and dehumidifying a building's air. They come in all shapes, sizes, and configurations. Chilled water systems are closed-loop systems, meaning that the system water is continually recirculated and not exposed to atmospheric pressure, similar to domestic water systems. While selecting the type of chiller to use is generally dictated by capacity, there are still many philosophies on the best way to control, operate, and calculate system operational costs.

The first step in chiller selection is understanding the options available. A building's block load will determine the overall capacity, whereas part load will determine the number and quantity of chillers required, with multiple chillers providing the ability to stage chillers in response to load. A block load will take into account building diversity and load

Figure 1: The Northwestern Mutual Van Buren Office Building in Milwaukee was an existing building retrofit that uses two modular chillers to produce chilled water for cooling. In the foreground is a 50-ton heat recovery chiller module that produces chilled water and heating hot water for the building. In the background is a 330-ton water-cooled chiller with five modules producing chilled water for the building. Due to the basement's tight space constraints, the engineers selected modular chillers to fit in the building's elevator. All graphics courtesy: Ring & DuChateau

Figure 2: Two 500-ton water-cooled centrifugal chillers serve an office building with space for future chillers.

changes based on exposure, internal and external loads, and building schedules because all portions of the building will not be peaking simultaneously. The function of a space may also dictate sizing and plant reliability. Essential services, such as data centers or hospitals, require reliability and redundancy with the use of a backup chiller or chillers for N+1 or 2N redundancy based on an owner's requirements. Furthermore, the hourly building profile run time may require equal or unequally sized chillers.

Chiller compressors

The first category of chillers is defined by the method used to compress the refrigerant. Positive displacement compressors operate with two mechanical devices, such as scroll- or screw-shaped rotors. These devices trap refrigerant vapor and compress it by gradually reducing the volume to increase the pressure.

Most small chilled water plants—up to approximately 200 tons in capacity—use scroll compressors for production of chilled water. Scroll chillers start as low as 20 tons and increase in size to approximately 200 tons. As the capacity increases, the chillers increase the quantity of scroll compressors, typically of equal sizes to provide the total chiller capacity required. The disadvantage is that chiller capacity control is provided as stepped control instead of modulating control. Although the multiple compressors may be a disadvantage for capacity control, generally they are piped with multiple refrigerant circuits which provide some system redundancy. For example, an 80-ton chiller may have four 20-ton compressors, with two compressors on each refrigerant circuit. Failure of one compressor will cause a loss of capacity but will still allow the chiller to remain in service and provide partial cooling output.

Once the capacity exceeds the size of multiple scroll compressors, typically four to six 30-ton scroll compressors, chillers use screw compressors. Screw compressors are available in sizes up to about 500 tons. Screw compressors have the ability to vary the cooling output capacity from 100% to 20% via the use of a slide vane to limit refrigerant delivery to the compressor and provide a smooth, modulating transition between capacities. It is important to note that screw chillers have only one compressor, so a loss in the compressor would cause a complete loss in chiller capacity. Screw chillers typically have very good full-load and part-load kW/ton efficiencies. Screw compressors also are generally louder than scroll compressors, with higher noise levels in the lower frequencies octave bands.

The third and final type of compressor, a centrifugal compressor, operates on a different compressor philosophy that relies on dynamic compression to compress and raise the refrigerant pressure. A rotating impeller is used to accelerate the refrigerant and allow the conversion of velocity energy into pressure energy. Centrifugal chillers start at approximately 200 tons and go up to thousands of tons depending on the number of compressors. Centrifugal compressors are typically used for compressing large volumes of refrigerant to relatively low pressures and can be configured specifically to the application by changing the number of stages, compressor speed and size, impeller diameter, refrigerant type, and condenser and evaporator shell sizes. Capacity control of centrifugal chillers is accomplished through inlet vanes at the inlet of the compressor that varies the refrigerant flow in stages in response to the building load. A variable frequency drive (VFD) also could be used for capacity control to vary the speed of the impeller rotation in conjunction with inlet vanes. Inlet vanes and VFDs accomplish different objectives: inlet vanes are used for buildings that may have a large load variation, while VFDs should be used for buildings that have large variations in lift, which equates to changes in condenser relief. VFDs are not always an appropriate option for chillers and their use greatly depends their ability to vary temperatures. Regardless, close

Learning objectives

- Understand the variety of chiller options based on load requirements.
- Learn to calculate a simplified cost/ton estimate for estimating chiller initial investment costs.
- Know the appropriate calculations for determining chiller plant operational costs.

attention should be paid to low load conditions near 20% capacity, in which the efficiency degrades rapidly and causes the chiller to operate in a condition known as surging.

Centrifugal chillers also operate at high speeds, which can result in more vibrations and noise transmission into the building structure, but are extremely reliable and robust devices. Centrifugal compressors have great efficiencies throughout their operating range and are relatively compact for the amount of tonnage that can be provided per sq ft of mechanical room space. A centrifugal chiller can vary capacity continuously in lieu of stepped control, which can provide capacity output based on the building load profile. This enables accurate temperature control while using only the energy required. Figure 2 shows two centrifugal chillers serving an office building.

Heat exchangers

The next category of chillers is defined based on the type of heat exchanger used in the chiller. Heat exchanger selection can be either air- or water-cooled and will have a large impact on the efficiency and cost of the chiller. Air-cooled chillers are limited in size to 500 tons of capacity, whereas water-cooled chillers range to almost 9,000 tons.

Air-cooled chillers operate on the concept of using air to reject the building's heat, which approaches the outside ambient dry bulb temperature. Consequently, air-cooled chillers must raise the refrigerant temperature and pressure to a higher condition and will require more energy to do the same amount of cooling compared to a water-cooled chiller. Despite this, air-cooled chillers offer the advantage of a packaged system with a single source of responsibility. Design and installation time are also reduced due to less equipment being involved: there is no requirement for cooling towers and associated freezing issues, consumption of makeup water and chemical treatment, or condenser water pumps. Air-cooled chillers use scroll compressors up to 200 tons and use screw compressors above 200 tons of capacity.

Figure 3: An end view shows five modular chillers and a heat exchanger on the bottom of the units with two compressors on the top. For this project, a modular chiller was the only option for the basement of an existing building due to space limitations.

The alternative is water-cooled chillers. They operate by using water to reject the building's heat, which approaches the outside ambient wet bulb temperature—which is typically lower than the dry bulb temperature. Therefore, water-cooled chillers are more energy efficient as the condensing temperature is lower and they require less work by the compressor to raise the refrigerant temperature and pressure. Although the chiller energy may be less than that of a comparable air-cooled chiller, one must still evaluate all the costs of the chiller system, including the cooling tower and condenser water pumps. The smallest water-cooled chillers (up to 200 tons) begin with multiple scroll compressors, those from 200 to 500 tons use screw compressors, and those above 500 tons mainly use centrifugal compressors. Water-cooled chillers typically last much longer than air-cooled chillers due to the location of the chiller inside of the building and lower operating pressures using water as a condensing fluid.

Another item to be aware of is the method of cooling the compressor and motor, which can be an open drive or hermetically sealed design. With an open drive chiller, the heat is rejected directly to the mechanical room and must be cooled or ventilated by ambient air, possibly requiring high volumes of air to cool the space. Also, contaminants can potentially get to the motor and refrigerant seals might leak if the seals are not properly maintained. Hermetic or semi-hermetic chillers are refrigerant cooled, and the heat is rejected to the refrigerant, reducing the heat rejection load in the mechanical room. These machines require no seals as the motor is completely contained within an enclosure, so there is no potential for refrigerant to leak out of the system.

Modular chillers

Modular chillers are the newest option in the chiller market and have been increasing in popularity. They are similar to building blocks in that you can add modules of varying capacities to reach the overall desired capacity. Typical modules are available in sizes of 30, 50, 70, and 85 tons consisting of scroll or screw compressors. The chillers are specifically designed to fit through doorways in new or retrofit applications and are extremely compact. Chiller modules up to 85 tons require only 10 to 12 sq ft of building footprint without the large clearance spaces required for evaporator or condenser tube pull. These modules can then be combined to approximately 1,000 tons of overall chiller capacity. When building loads increase or additions are built, an additional module of the necessary capacity can be installed, provided the distribution systems are set up for the additional load. Similarly, instead of purchasing a completely redundant chiller for N+1 capacity, an additional module can be added, providing redundancy for one module at fraction of the cost of purchasing an entire redundant packaged chiller.

Despite the advantages of modular chillers, one major disadvantage is the significant initial cost. Most modular chillers are about 150% to 200% the cost of a similar tonnage water-cooled chiller. Second, modular chiller efficiencies are typically not as attractive as standard water-cooled chiller efficiencies due to the compressors used in the chillers. Third, water treatment is extremely important as modular chillers use a plate and frame heat exchanger instead of a shell and tube heat exchanger, which must be cleaned to prevent fouling and plugging the heat exchangers. Duplex, external strainers should always be used to provide service of one strainer while maintaining operation through the other strainer. Similarly, the heat exchangers shall be fully serviceable with individual isolation valves to isolate the heat exchanger without shutting down the chiller. Figure 3 provides an example of a modular chiller with the heat exchanger in a fully serviceable position.

Chiller categories tend to have a lot of overlap and options within each capacity range and category described above. Figures 5 and 6 provide a simplified method to observe the ranges and compressor types for air-cooled and water-cooled chillers from the major chiller manufacturers.

Figure 4: This shows two 400-ton air-cooled screw chillers in parallel for an industrial building.

Initial investment

Upfront costs are always a critical discussion in any project. In some projects, initial costs can outweigh lifecycle and operating costs. Since chiller costs vary so much, it is difficult to provide an overall initial cost for a chiller based on its size as multiple factors are associated with each chiller size based on manufacturer.

In general, scroll chillers are the most expensive of the three types of chillers discussed. Centrifugal chillers are the most cost-effective option but are not available in all tonnages. When screw and centrifugal compressors are both available options based on the capacity, screw compressors are typically 10% to 15% more expensive. Similarly, air-cooled chillers are typically a more expensive initial investment than a similarly sized water-cooled chiller when comparing strictly the initial cost of an air-cooled chiller versus that of a water-cooled chiller.

However, when evaluating the total installed cost of an air-cooled versus a water-cooled system, including all the necessary components for the system to be fully operational, the investment for the required components in a water-cooled system are always more expensive. The reason: An air-cooled system only requires chillers and chilled water pumps, whereas a water-cooled system requires the chillers, chilled water pumps, condenser water pumps, and cooling towers for fully functional system and to reap the energy efficiency benefits.

Chiller operating costs

Once a chiller is procured, the cost of ownership continues with operation and maintenance costs for the remainder of the chiller's life. The typical life span of an air-cooled chiller is generally 15 to 20 years based on the chiller's location in varying exterior conditions. A water-cooled chiller has a life expectancy of around 20 to 30 years, with some lasting much longer with proper maintenance.

Many items affect the operating cost of a chiller, including building loads, chiller run time, control system integration, compressor unloading, evaporator pressure drop, and condenser pressure drop. Similarly, many programs and methods exist for determining annual operating costs. One commonly used method in chiller plant analysis is to use the integrated part-load value (IPLV) rating from AHRI 550/590 – Performance Rating of Water Chilling Packages Using the Vapor Compression Cycle to calculate costs quickly from a single value. IPLV is a blended kW/ton based on a predefined percentage of operating hours at respective percentages based on pre-defined operating conditions, such as 44 F chilled water supply at 2.4 gpm/ton and entering condenser water at predefined temperatures at 3 gpm/ton. A variation of IPLV is NPLV, which uses nonstandard temperatures based on actual operating conditions instead of the AHRI defined temperatures in the standard. In either case, the kW/ton value is calculated based on the following equation:

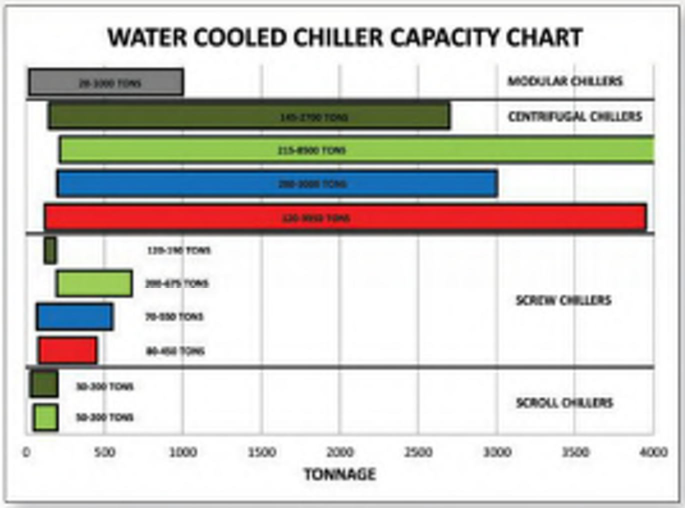
$$\text{IPLV or NPLV} = \frac{1}{\frac{0.01}{A} + \frac{0.42}{B} + \frac{0.45}{C} + \frac{0.12}{D}}$$

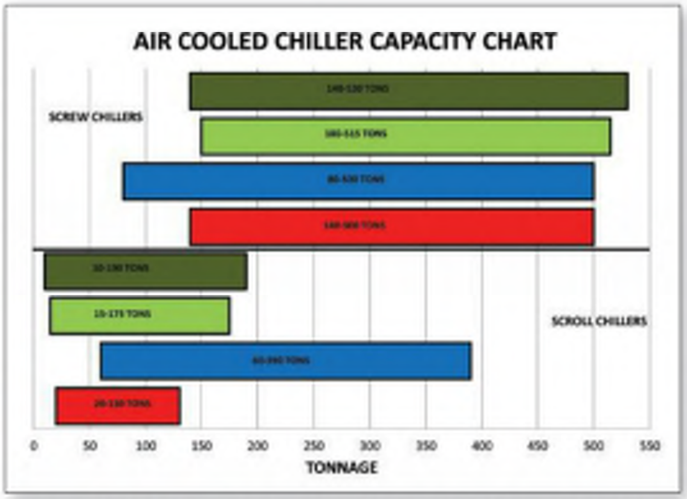
Chillers and chilled water systems

Where:

A = kW/ton at 100%
B = kW/ton at 75%
C = kW/ton at 50%
D = kW/ton at 25%

It is important to note that AHRI 550/590 was created to compare the unloading characteristics of similar chillers and not to be used as a basis to determine operational costs for chillers. Also, most chiller systems are operated in multiple chiller plant systems, not individual operation per the rating method. The whole system must be analyzed as an entire package including pumps, chillers, towers, weather, and building loads to determine the most cost-effective solution and optimize the entire plant in lieu of individual components. A single number IPLV provides a predetermined unloading of your chiller, which may or may not be accurate for your building and assumes that the chiller receives condenser relief, and therefore a reduction in power because lowering the condenser water temperature greatly affects chiller power consumption.





Figures 5 and 6: Water-cooled and air-cooled chiller options based on capacity are shown for the major manufacturers based on unit tonnage.

In lieu of using a single kW/ton value to determine plant operating costs, a more detailed review of the system must be made because kW/ton is highly dependent on the actual operating conditions and the chiller type selected. The weather is continuously changing in all locations, and outside ambient dry bulb and wet bulb have a significant impact on condenser operating conditions (air- and water-cooled). Similarly, a building and chiller load profile also shall be used in conjunction with weather data to determine chiller operating costs. A load profile will be different for every building depending on building type, building schedule, and other outside factors. With this information, one can analyze if the chiller selected can turn down to part-load capacities and what the efficiencies are expected to be at these part-load conditions, as most chillers will operate the majority of their hours at part load.

Finally, energy costs should be calculated using a load program. Some programs do not require entering the entire project to do simple chiller plant analysis. Also, load programs can quickly and easily apply actual building rate structures to an analysis, including any ratchet charges, consumptions charges, and demand charges. To properly analyze each option, chiller selections should be provided with an unloading curve in at least 10% load increments. This is sufficient for an analysis and will yield relatively accurate results without much effort.

Chilled water pumping arrangements

A chiller plant is not complete without the pumping arrangement to distribute chilled water throughout the building or campus to the chilled water coils. There are multiple arrangements for distributing chilled water. This article will describe the two most commonly used methods of chilled water pumping, variable primary flow (VPF) and primary-secondary, and how they relate to initial investment costs and operating costs for the chiller plant.

In both pumping schemes, the flow to chilled water coils in the system is variable flow as the cooling coils are equipped with two-way temperature control valves. The difference exists in the way the pumping is handled through the chillers. In a VPF system, the flow varies in the entire system, including through the chillers, which is a shift from the previous mind-set that chillers always require a constant flow through the evaporator. However, recent advances in control technology have allowed the ability to vary the flow through the evaporators within the manufacturer's recommended ranges and can provide substantial energy savings.

Because of the ability to vary flow, these systems eliminate the need for secondary distribution pumps and use multiple pumps in parallel to serve the entire chilled water system, including the chillers and any coils in the system. These pumps handle the entire system head at the required system flow rate. VPF requires a minimum flow bypass pipe, which includes a

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Wire & Cable Management • Cable Protection Systems • Power Connection & Control • Safety Technology control valve to protect the chiller from falling below the minimum flow rate and temperature control isolation valves at each chiller to isolate flow through the chillers when they are not in operation. Some designers prefer three-way valves at a select number of coils to provide minimum system flow, but this will increase the pumping energy required in the system by increasing flow in all conditions except when the system is at minimum flow. The system minimum flow is maintained by using a flow meter or measuring the pressure drop across the chillers to determine system flow to control the bypass valve.

In a primary-secondary system, two sets of pumps are used, each with a dedicated function to the chilled water system. The primary pumps serve as production pumps and serve only the chillers in the system. These pumps are typically high-flow, low-head constant-flow pumps staged on with a chiller to provide available chilled water to the secondary pumps. The secondary pumps serve only the chilled water coils in the system, which are equipped with two-way control valves as explained above and are high-flow, high-head variable speed pumps that vary the system flow in response to the load. The primary and secondary loops are connected via a common pipe or decoupler that is a shared portion of the piping circuit in each loop that hydraulically separates the two loops so flow in one loop does not affect the flow in the other. This will allow the water to flow through the common pipe in either direc-

Calculating chiller selection

To display the variations in operating costs for chillers, an analysis was completed for a 300,000-sq-ft office building using an energy simulation calculation program with weather data from Milwaukee for a 1,000-ton water-cooled chilled water plant to determine the chiller with the lowest operational costs.

Multiple chiller selections were made varying compressor types, chilled and condenser water temperature ranges, air-cooled versus water-cooled heat exchangers, and variable frequency drives to determine the best combination of variables. Chiller selections were made with two or four chillers in parallel, each sized at equal capacity in a variable primary flow configuration, which is common for a new building with multiple cooling coils and chillers.

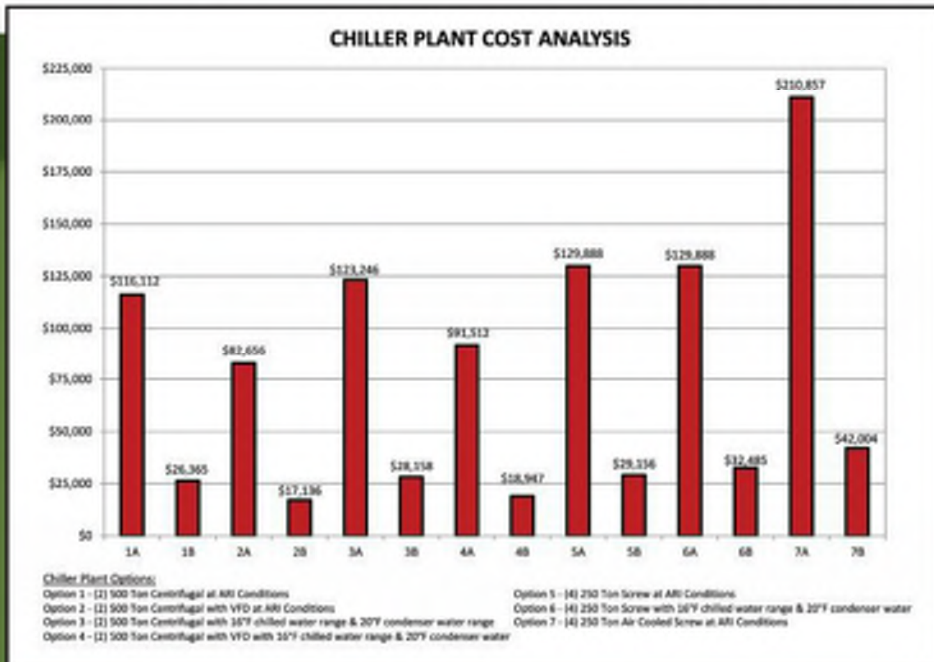

Figure 7: This comparison of chiller operating costs uses a load calculation program and NPLV for a 1,000-ton water-cooled centrifugal chiller plant for an office building.

To focus on the variation in operating costs, each chiller was calculated with an unloading curve in 10% increments and used in the energy simulation program to determine the annualized operating costs. An analysis was also completed using a simplified approach to see if a quick analysis could be completed with a relatively small degree of error without using an energy simulation program. For the simplified method, IPLV was used for determining chiller operating costs by multiplying the IPLV kW/ton value, the chiller plant tonnage, the chiller plant operating hours provided by the load calculation program, and the electrical consumption rate.

For all calculations a typical office building schedule was used with operation from 8 a.m. to 5 p.m., Monday through Friday. An electrical rate of $0.12/kWh was used for on-peak electrical consumption and $0.10/kWh for off-peak electrical consumption with an on-peak period from 9 a.m. to 9 p.m.

The results of the analysis, as well as the chiller selection options, are shown in Figure 7. There is a dramatic difference in chiller operating costs for a building based on chiller selection. Furthermore, the figure shows the resulting error in the simplified method using IPLV for chiller energy consumption as a viable option to calculate operating costs, which ranges from 3 to 5 times the calculated operating cost based on an energy simulation program. The operating cost for each option is provided, with subtitle A for the simplified method and subtitle B for the energy simulation method. In all cases, the IPLV method is dramatically more expensive in determining chiller plant energy consumption. This error can be directly attributed to calculating operating costs from using actual weather data and a true building load profile in lieu of predetermined AHRI operating points.

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tion to hydraulically balance the system. These systems are typically older systems that require a constant flow through the chiller, but can still be used as a fail-safe solution due to their simplicity.

The advantages of VPF systems are directly related to the pumping concepts described above. VPF systems will always have fewer pumps compared to a primary-secondary system, which will save initial costs from less piping and valves, fewer electrical connections, less controls work, and no vibration isolation at the additional pumps. Similarly, one set of pumps will save on mechanical room space requirements, which can lead to substantial initial cost savings in building footprint or increasing useable building square footage. The one thing that must be addressed is the more complex staging controls and ensuring minimum flow in the system at all times, but this will still maintain an overall net savings in initial cost.

The **VPF pumps** allow the designer to select larger, more efficient horsepower pumps.

For operating costs, VPF systems will always have lower operating costs as there is less pressure drop in the system due to fewer pumps and accessories at the pumps, but also because the pumps will be more efficient. The VPF pumps allow the designer to select larger, more efficient horsepower pumps instead of smaller, constant volume, low efficiency circulator pumps typically found on the primary side of the primary-secondary system. Also, the use of variable speed in the entire system will allow the entire system flow rate to vary, which will provide operating cost savings as energy will vary approximately with the cubed power of the flow rate. This is in contrast to constant volume pumping and energy consumption at the primary pumps and variable flow at the secondary pumps in a typical primary-secondary system. |cse|

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More information online at www.csemag.com/archives including:

- References
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