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Overview of Chiller Compressors

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OVERVIEW OF CHILLER COMPRESSORS

Overview

In HVAC industry, the refrigeration machine that produces chilled water is referred to as a “**Chiller**”. A chiller package operates either on the principles of vapor compression or vapor absorption. The vapor compression system uses mechanical energy in the form of electric motor to drive the cooling cycle whereas absorption chillers use heat to drive the process. The vapor compression chiller system, which is far more prominent in commercial buildings, consists of four major components: the compressor, evaporator, condenser and expansion device all packaged as a single unit. The classification of vapor compression chiller packages is generally by the type of compressor: centrifugal, reciprocating, and screw being the major ones.

Chillers are the largest consumer of energy in a commercial building and it is therefore important to understand the relative benefits and limitations of various types in order to make the right economic decisions in chiller installation and operation. This course will talk about the type of compressor used in the water cooled chiller.

The course is divided into 3 parts:

- Part - I: Types of Chiller Compressors
- Part – II: Comparison of Chiller Compressors
- Part –III: Economic Evaluation of Chiller Systems

PART I - TYPES OF CHILLER COMPRESSORS

Most cooling systems, from residential air conditioners to large commercial and industrial chillers, employ the refrigeration process known as the vapor compression cycle. At the heart of the vapor compression cycle is the mechanical compressor. Its function is: 1) to pump refrigerant through the cooling system and 2) to compress gaseous refrigerant in the system so that it can be condensed to liquid and absorb heat from the air or water that is being cooled or chilled.

Not all air-conditioning applications have the same capacity requirements, and for this reason the chillers are grouped by the type of compressor – 1) Positive-displacement and 2) Dynamic.

- **Positive-displacement** compressors physically compress the vaporized refrigerant into a smaller volume and higher pressure, and include reciprocating, rotary, and scroll types. These deliver a constant volume of gas under a constant speed
- **Dynamic** compressors increase vaporized refrigerant pressure by the kinetic energy imparted on refrigerant by a rotating impeller. A centrifugal compressor is a dynamic compressor and is not a constant displacement type.

Each type utilizes a specific and sometimes downright ingenious method to pressurize refrigerant vapor. This course will focus on the various types of chiller compressors, their advantages, disadvantages, limitations and applications. In the text, the words, “chiller/s” and “compressor/s” have been used interchangeably and have the same meaning.

Reciprocating Chillers:

Reciprocating compressors are positive displacement machines that use the reciprocating action of a piston inside a cylinder to compress refrigerant. As the piston moves downward, a vacuum is created inside the cylinder. Because the pressure above the intake valve is greater than the pressure below it, the intake valve is forced open and refrigerant is sucked into the cylinder. After the piston reaches its bottom position it begins to move upward. The intake valve closes, trapping the refrigerant inside the cylinder. As the piston continues to move upward it compresses the refrigerant, increasing its pressure. At a certain point the pressure

exerted by the refrigerant forces the exhaust valve to open and the compressed refrigerant flows out of the cylinder. Once the piston reaches its top-most position, it starts moving downward again and the cycle is repeated.

These compressors are available in 3 configurations namely 1) Hermetic; 2) Semi-hermetic and 3) Direct driven versions.

- In a hermetic unit, the motor and compressor are enclosed in a common housing, which is sealed. Because the components are not accessible for repair, the entire compressor unit must be replaced if it fails. The hermetic sealed units are most common in small capacities.
- In the semi-hermetic unit the motor is also part of the unit, however it is not sealed. Semi-Hermetic compressors have the advantage over hermetic compressors in that they can be re-built a number of times if necessary giving a much longer service life.
- In a direct drive unit the motor and compressor are separated by a flexible coupling. These types of units utilize older technology and are not commonly used today.

The main factors favoring reciprocating compressor is low cost and efficiency when applied in low capacities. Multiple reciprocating machines can be installed for higher building loads. Further advantages include simple controls and the ability to control the speed through the use of belt drives. Available in both air-cooled and water cooled heat rejection configurations, these chillers are available from 0.5 to 150 tons of refrigeration (TR^{*}).



Reciprocating Compressor

A major drawback of reciprocating chillers is their high level of maintenance requirements in comparison with other chiller types. Reciprocating chillers have more

moving parts than centrifugal or rotary chillers, resulting in an increased need for wear-related maintenance activities.

Reciprocating chillers also generate high levels of noise and vibration. Special precautions must be taken to isolate the chillers from the facility to prevent transmission of machine-generated vibrations and noise.

Finally, reciprocating chillers are not well suited for applications with cooling loads in excess of 200 tons. As the units grow in capacity, their space requirements and first costs exceed those of other chiller types. In addition, the energy requirements for larger units exceed that of other chillers types.

Screw Chillers:

Screw compressors are positive displacement machines that use helical rotors to compress the refrigerant gas. As the rotors rotate they intermesh, alternately exposing and closing off interlobe spaces at the ends of the rotors. When an interlobe space at the intake end opens up, refrigerant is sucked into it. As the rotors continue to rotate the refrigerant becomes trapped inside the interlobe space and is forced along the length of the rotors. The volume of the interlobe space decreases and the refrigerant is compressed. The compressed refrigerant exists when the interlobe space reaches the other end. There are two types: 1) Single and 2) Twin screw configuration.

- A **single-screw** compressor uses a single main screw rotor meshing with two gate rotors with matching teeth. The main screw is driven by the prime mover, typically an electric motor.
- A **twin-screw** compressor consists of accurately matched rotors (one male and one female) that mesh closely when rotating within a close tolerance common housing. One rotor is driven while the other turns in a counter-rotating motion. The twin-screw compressor allows better control and variations in suction pressure without much affecting the operation efficiency.

Available in air-cooled and water cooled configurations, screw chiller is available up to 750 tons of refrigeration.



Screw Compressor

With a relatively high compression ratio and few moving parts, screw chillers are compact, smaller and lighter than reciprocating and centrifugal chillers of the same cooling capacity. These also offer quieter, vibration-free operation and are well known for their robustness, simplicity, and reliability. They are designed for long periods of continuous operation, needing very little maintenance. Screw compressors can overcome high lift when speed is reduced, allowing energy savings without the possibility of surge as the compressor unloads.

The major drawback of screw chillers is their high first cost. For small cooling loads, reciprocating chillers are less expensive to purchase and install; for large loads, centrifugal chillers cost less.

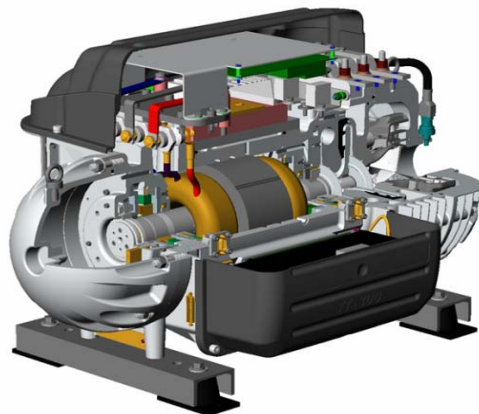
Centrifugal Chillers:

Centrifugal compressor is a **dynamic** machine that uses the rotating action of an impeller wheel to exert centrifugal force on refrigerant inside a round chamber (volute). Refrigerant is sucked into the impeller wheel through a large circular intake and flows between the impellers. The impellers force the refrigerant outward, exerting centrifugal force on the refrigerant. The refrigerant is pressurized as it is forced against the sides of the volute. Centrifugal compressors are well suited to compressing large volumes of refrigerant to relatively low pressures. The compressive force generated by an impeller wheel is small, so chillers that use centrifugal compressors usually employ more than one impeller wheel, arranged in series. Centrifugal compressors are desirable for their simple design and few moving parts.

Centrifugal chillers are categorized either as **positive** pressure or **negative** pressure machines depending on the evaporator pressure condition and the type of refrigerant used. A chiller using refrigerant R-22 and R-134A is a positive-pressure machine,

while the one using R-123 is a negative-pressure machine. Key facts are noted below:

- Mass flow rates for both refrigerants are essentially the same at approximately 3 lb/min ton. However, due to the significantly higher density of R-134A, its volumetric flow rate (cfm/ton) is over five times smaller than R-123 volumetric flow rate. Compressors using R-123 typically use large diameter impellers (approximately 40 inches diameter).
- Compressors using R-134A typically use much smaller impellers (about 5 inch diameter). The large wheel diameters required by R-123 puts a design constraint on the compressor and, to reduce the diameter, they typically utilize two or three impellers in series or stages to produce an equivalent pressure increase.
- Compressors using R-123 use direct-coupled motors that on 60 Hz electric supply turn at 3600 rpm. Compressors using R-134A typically use motor coupled through a gearbox or speed increaser and can operate at speeds approaching 30,000 rpm.
- Since the compressor using R-123, operate in vacuum, it leads to possible contamination from atmosphere, water vapor, air-oxygen. This induces high chances of corrosion and wasteful energy consumption (kW per ton penalty) due to compression of non condensable gases. Continuous purge is required and it takes longer shutdowns for maintenance.



Centrifugal Compressor

Like reciprocating chillers, centrifugal units are available in both hermetically sealed and open construction. Despite its lower operating efficiency, the hermetically sealed unit is more widely used.

Favorable Factors

The main factor favoring centrifugal machine is their high operational efficiency at full load. Unlike reciprocating and rotary screw, centrifugal compressor is not a constant displacement machine, thus it offers a wide range of capacities continuously modulated over a limited range of pressure ratios. They are well suited to compressing large volumes of refrigerant to relatively low pressures. By altering built-in design items as number of stages, compressor speed, impeller diameter, and choice of refrigerant, it can be used in chillers having a wide range of design chilled liquid temperatures and design cooling fluid temperatures.

Due to their very high vapor-flow capacity characteristics, centrifugal compressors dominate the 200 ton and larger chiller market, where they are the least costly and most efficient cooling compressor design. Centrifugals are most commonly driven by electric motors, but can also be driven by steam turbines and gas engines.

Drawbacks

A serious drawback to centrifugal chillers has been their part load performance. When the building load decreases, the chiller responds by partially closing its inlet vanes to restrict refrigerant flow. While this control method is effective down to about 20 percent of the chiller's rated output, it results in decreased operating efficiency. For example, a chiller rated at 0.60 kW per ton at full load might require as much as 0.90 kW per ton when lightly loaded. Since chillers typically operate at or near full load less than 10 percent of the time, part load operating characteristics significantly impact annual energy requirements.

Centrifugal chillers also can be difficult to operate at low cooling loads. When the cooling load falls below 25 percent of the chiller's rated output, the chiller is prone to a condition known as surging. Unrestricted, surging can lead to serious chiller damage. To reduce the chances of damage from surging, manufacturers add special controls, but most of these controls further reduce the part load efficiency of the units.

Scroll Chillers:

The scroll compressor is a positive displacement machine where refrigerant is compressed by two offset spiral disks that are nested together. The upper disk is stationary while the lower disk moves in orbital fashion. The orbiting action of the

lower disk inside the stationary disk creates sealed spaces of varying volume. Refrigerant is sucked in through inlet ports at the perimeter of the scroll. A quantity of refrigerant becomes trapped in one of the sealed spaces. As the disk orbits the enclosed space containing the refrigerant is transferred toward the centre of the disk and its volume decreases. As the volume decreases, the refrigerant is compressed. The compressed refrigerant is discharged through a port at the centre of the upper disk.

Scroll compressors are a relatively recent development that is rapidly overtaking the niche of reciprocating chillers in comfort cooling. They provide small size, low noise and vibration and good efficiency. Available in air-cooled and water cooled configurations, scroll chiller capacity can reach approximately 30 tons or less, which makes them good candidates for spot cooling or make-up cooling applications.



Scroll Compressors

The biggest drawback is that these cannot be repaired and there have been issues of scroll compressors losing oil at low temperatures. On relatively small sizes, these do not affect the life cycle economics drastically and therefore not discussed further in this course.

Compressor Capacities:

The size of refrigeration compressors is given in either motor input horse power (HP), motor input kilowatts (kW input), refrigeration cooling capacity (kW cooling), British Thermal Units per hour (Btu/h) or tons of refrigeration (TR). A refrigeration **ton** is equal to heat extraction rate of 12,000 BTU's/hr; therefore a 3 TR chiller can remove 36,000 BTU's/hr.

The volume and pressure that the refrigerant can be pumped at determines the cooling capacity, specific performance and application areas where the compressor can be used for. Note the key facts:

- ⇒ Capacity (Btu/h) increases as mass flow rate (lb/min) increases. Resulting from a decrease in specific volume (cubic ft/lb);

- ⇒ Capacity (Btu/h) increase as specific volume (cubic ft/lb) decreases resulting from an increase in suction pressure (psig);
- ⇒ Capacity (Btu/h) increases as volumetric flow rate (cubic ft/min) increase. Resulting from an increase in compressor displacement; [note that the compressors type and design determines the volumetric flow rate];
- ⇒ Capacity (Btu/h) increases as compression ratio's decreases. Resulting from a decrease in specific volume (cubic ft/lb).

Available Capacities

- **Reciprocating** machines are manufactured in capacities from 0.5 to 150 TR. Air-cooled **reciprocating** chillers have an energy usage of 1.0–1.3 kW/ton while water cooled chillers have energy usage between 0.7 and 1 kW/ton.
- Air cooled screw chillers are available with cooling capacities between 70 tons and 500 tons and energy usage between 1.1 and 1.5 kW/ton. Water cooled screw chillers are available with cooling capacities between 70 tons and 750 tons and energy usage between 0.65 and 0.9 kW/ton.
- **Centrifugal chillers** are generally manufactured in capacities from 90 to 1,000 tons, with most units falling in the range of 150 to 300 tons. Centrifugal compressor chillers are the most energy efficient chillers with energy usage between 0.5 and 0.6 kW/ton.

Recommendations:

Chillers use one of four types of compressor: reciprocating, scroll, screw, and centrifugal.

- The choice leans towards **reciprocating** compressors for peak loads up to 80 to 100 tons. Between 100 and 200 tons peak cooling load, two or more reciprocating compressor chillers can be used.
- Above 200 tons, **screw** compressor systems begin to become cost effective. The screw chillers are well suited for applications demanding up to 750 TR. Above these capacities, centrifugal chillers are generally more cost effective where water is available for heat rejection.
- **Centrifugal** compressors traditionally provide larger capacities typically above 750 tons. The centrifugal machines offer highest peak load efficiency and operate

reliably for applications demanding a steady state operation. The machines are only recommended with water-cooled condenser option.

We will evaluate chiller compressors further on various other factors in Section II and Section III of this course.

PART II – COMPARISON OF VARIOUS COMPRESSORS

Installed costs and capital offsets are the vital economic parameters for selection; but a more meaningful economic comparison is based on a wider technical framework. This section provides relative comparison of the three most common chiller compressors – Reciprocating, Screw and Centrifugal.

Capital Costs:

The capital cost expressed in dollars per ton is generally lowest for **reciprocating** and highest for **screw** compressors.

- **Reciprocating chillers** are more common and in general are cheaper than other compressor types, particularly for the smaller sized units.
- **Screw** chillers are the most expensive in first cost.
- **Centrifugal** chillers cost lower than **screw** chillers by 10 to 15% in most sizes at the same operating conditions. First cost of **centrifugal** chiller is higher than **reciprocating** under 200 tons but becomes competitive in the larger sizes.

If a choice leans towards centrifugal chiller, a distinction is made between negative pressure and positive pressure chillers:

- Negative-pressure chillers using refrigerant R-123 generally have a higher first cost than positive pressure machines using R-134A. Negative -pressure chillers tend to be larger and heavier, which will also result in larger chiller rooms and heavier structures.
- Negative-pressure chillers however are somewhat more efficient than positive-pressure chillers. A peak load rating of 0.5 kW/ton or less is available for negative-pressure chillers, while positive-pressure chiller ratings below 0.55 kW/ton are difficult to obtain.

When purchasing a chiller, owners must decide if the improved efficiencies of negative pressure chillers are worth the additional first cost, the environmental impact of releasing refrigerants, the higher toxicity of R-123, and the impact of the phase-out of HCFC refrigerants.

Efficiency Ratings:

Chiller efficiency is typically defined in terms of kW/ton and/or its coefficient of performance (COP). The COP is the ratio of output BTU's divided by the input BTU's. If the nominal rating of the chiller is 1 ton of refrigeration capacity, equivalent to 12,000 Btu/hr output, and the input energy is equivalent to 1 kW, or 3,413 Btu/hr, the resulting COP is 12,000/3,413 or 3.52.

- Air-cooled **reciprocating** chillers have a peak load power requirement of 1.0–1.3kW/ton, depending on capacity and ambient air temperature. Thus, the peak load COP for these units will range from 3.52 to 2.70.
- Typical **screw** chillers with water-cooled condensing have a peak load power requirement of 0.5–0.7kW/ton, resulting in a COP of 7.0–5.0. The efficiency of the screw compressor and reciprocating compressor, when operating at the similar compression ratio is similar. The screw compressors have an ability to operate at 30 compression ratios that allows much efficient operation than the reciprocating compressor.
- **Centrifugal** chillers are most efficient at peak load and they consume the least power (kW per ton) at full load operation. At ARI standard rating conditions centrifugal chiller's performance at full design capacity ranges from 0.53 kW per ton for capacities exceeding 300 tons and between 0.6 to 0.7 kW per ton for capacities up to 300 tons. Efficiencies have been improving even further over the years as a result of improved impeller designs, better unit configurations, enhanced heat transfer surfaces, and the increased utility emphasis on reducing energy requirements.

ASHRAE (the American Society of Heating, Refrigerating, and Air-Conditioning Engineers) provide efficiency specifications in its 90.1 standard, as stated below:

Table 9.1: ASHRAE 90.1-2001 and 2004 minimum required efficiencies for water-cooled chillers

Chiller type	Capacity Range								
	< 150 tons			150 to 300 tons			>300 tons		
	Peak load COP	Full load	IPLV (kW/ton)*	Peak load COP	Full load	IPLV (kW/ton)*	Peak load COP	Full load	IPLV (kW/ton)*
Centrifugal	5.0	0.703	0.670	5.55	0.634	0.596	6.10	0.576	0.549

Chiller type	Capacity Range								
	< 150 tons			150 to 300 tons			>300 tons		
	Peak load COP	Full load	IPLV (kW/ton)*	Peak load COP	Full load	IPLV (kW/ton)*	Peak load COP	Full load	IPLV (kW/ton)*
Screw and scroll	4.45	0.790	0.676	4.90	0.718	0.628	5.50	0.639	0.572
Reciprocating	4.2	0.837	0.696	-	-	-	-	-	-

IPLV* - Integrated Part-Load Value (IPLV) rating of a liquid chiller represents a single numeric representation of part load efficiency at different load points. (Refer below for detailed discussion).

Part Load Efficiency:

In air conditioning systems, the peak load occurs only for a very limited number of hours during the year. On an annual basis, the imposed load will vary based on the time of day due to occupancy patterns, solar heat gains, and diurnal temperature swings, etc. and the time of year due to solar and temperature seasonal variations. With all of these variables, every chilled water system operates at “**off-design**” conditions most of the time. Various studies indicate that a chiller is at 100% capacity about 1% of the time, 75% capacity about 42% of the time, 50% capacity about 45% of the time, and 25% capacity about 12% of the time.

System part load performance is thus a crucial factor in chiller selection. Simply put, the system part load, when multiplied by total annual ton-hours of cooling, provides an estimate of the total annual kilowatt- hour consumption or the chiller with the lowest system part load performance will provide the greatest energy savings across its entire operational range. Part load efficiency of various options is stated below:

Recommendations

- **Screw** chiller offer infinite reduction from 100% to 0% and affords good part load efficiency.
- **Centrifugal** chiller accomplishes the capacity reduction in stages. When building load decreases, the chiller responds by partially closing its inlet

vanes to restrict refrigerant flow. While this control method is effective down to about 20% of chiller's rated output, it results in decreased operating efficiency. For example a chiller rated at 0.6 kW per ton at full load might require as much as 0.9 kW per ton when lightly loaded.

- **Reciprocating** compressors stepped capacity control is most efficient at minimum load than the twin-screw compressor. It is easy to closely match the capacity of the chiller to the building load by installing multiple machines which allow the facility manager to stage operation for part-load conditions, increasing operating efficiency.
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Factors that Affect Efficiency

Four factors affecting efficiency are:

1. Suction and discharge pressures
2. Capacity control method
3. Speed
4. Type of refrigerant used

Suction and Discharge Pressures:

While designing a refrigeration system, a specific suction pressure is usually specified, and often time's designers forget that this may change dramatically. Lower suction pressure signify lower evaporator temperature, which is the refrigerant temperature required to absorb heat from the medium being cooled. The capacity (Btu/h) of chiller system increase as specific volume (cubic ft/lb) decreases resulting from an increase in suction pressure (psig).

- **Screw** compressor (twin type) allows large variations in suction pressures with small changes in operation efficiency.
- **Reciprocating** compressor can also accommodate large variations.
- **Centrifugal** compressor DO not allow variations and even a small variation can cause considerable problems.

In simple words the screw and reciprocating machines permit meeting additional cooling capacity requirements to some extent due to any expansion or modification just by control settings.

Discharge Pressure:

Higher discharge pressure signifies higher condensing temperature, which is the refrigerant temperature required to reject heat to the condensing medium. Increasing the condensing temperature 15 deg from a base of 40°F and 105°F reduces the capacity about 13% and increases the compressor HP per ton about 27%. Discharge pressure is of considerable importance in refrigeration systems, particularly in the water-cooled condenser. The lower the temperature of discharge gas; the lesser the fouling within the condenser.

- **Screw** compressor - the discharge pressure/temperature of refrigerant gas is held to a minimum due to the oil lubricant cooling system.
- **Reciprocating** compressor - the highest discharge pressure/temperature occurs in reciprocating compressor.
- **Centrifugal** compressor - System pressure/temperature is kept low due to inter-stage cooling.

Max Compression Ratio's:

The higher the ratio the harder it is on the compressor. Capacity (Btu/h) of chiller system increases as compression ratio's decreases - resulting from a decrease in specific volume (cubic ft/lb).

- **Reciprocating** compressors operate at compression ratios up to 10 to 1.
- **Screw** compressor operates at compression ratio of 20 to 1. These can operate at any discharge pressure as long as it is within the operating design pressure of the compressor casing.
- **Centrifugal** compressor operates at compression ratios of 3 to 1. These are designed for specific pressure differential and if the suction or the discharge pressures vary, it usually is a hunting or surging condition

Capacity Control:

For the vast majority of water chillers, capacity control means controlling the refrigerant flow rate through the evaporator. Depending on the type of compressor used, several methods are applied:

- **Reciprocating** chillers achieve capacity regulation with simple on-off cycling control in small capacities and loading-unloading in bigger sizes. The most common method of reducing refrigerant flow rate and capacity in reciprocating compressor is by opening suction valves, bypassing refrigerant gas within the compressor, or bypassing refrigerant gas flow externally to the compressor. Unloading occurs in distinct steps based on the number of cylinders in each compressor and number of compressors in each chiller. Unloading is operated by pressure or electrically controlled by suction pressure. For a four-cylinder compressor, there are four stages (or steps) of capacity control, 25–50–75–100%. A reciprocating chiller is distinguished from centrifugal and screw compressor-operated chillers by its use of increments of capacity reduction rather than continuous modulation.
- **Screw** compressors achieve capacity control by opening and closing a slide valve on the compressor suction to throttle the flow rate of refrigerant gas into the compressor. This valve, in addition to controlling capacity, also adjusts the location of the compressor discharge port as the load changes. This “axial discharge port” then provides good part load performance without reducing full-load efficiency. Speed control can also be used to control capacity.
- **Centrifugal** compressors achieve capacity control through the use of inlet vanes on the impellers that regulate the refrigerant gas flow rate to the compressor in response to the cooling load imposed on the chiller. Normally, the output of the chiller is fully variable within the range 15–100% of full-load capacity.

Operating Speeds:

Reciprocating Compressors

- Hermetic compressors 3600 rpm
- Semi-hermetic comp. 1800 rpm
- Open Drives 500 rpm to 150 rpm.

Screw Compressors

- Typical operating speed = 3600 rpm

Centrifugal Compressors

- Positive pressure machines using R-134A typically use motor coupled through a gearbox or speed increaser and can operate at speeds approaching 30,000 rpm.
- Negative pressure machines using R-123 use direct-coupled motors turn at 3600 rpm. Not very common due to corrosion problems associated with negative pressure machines.

Speed Control

Speed control option for capacity control is recommended for large screw or centrifugal chillers.

The most common form of capacity control for constant speed centrifugal chillers is to modulate guide vanes at the impeller inlet (also called pre-rotation vanes). As load is decreased, the mass flow of refrigerant moving through the compressor is reduced. On constant speed machines, the guide vanes are closed to match compressor capacity to the load. When centrifugal machines are equipped with variable frequency drive (VFDs) for speed control, the impeller speed can be reduced to match the compressor capacity to the load.

$$\text{Lift}_2 = \text{Lift}_1 * [\text{RPM}_2 / \text{RPM}_1]^2$$

Caution - The lift produced by a centrifugal compressor is also reduced when speed is reduced, we can determine that speed adjustment alone cannot always be used to regulate the variable speed centrifugal chiller. Under certain lift conditions, the speed is reduced as much as lift requirements will allow and then guide vanes are used to complete the load reduction. Mechanical unloaders of any kind introduce inefficiency. So while speed reduction is almost always obtained with any reduction of lift or load requirements, the question become one of magnitude. The amount of capacity reduction performed by speed reduction, relative to the amount of capacity reduction performed by guide vanes is an indication of the centrifugal chillers ability to capture

all theoretical savings at a given operating point. Conversely, the more the guide vanes are closed, the higher the amount of inefficiency introduced into the system.

Given the cubic relationship of speed and power even a small amount of speed reduction yields a significant reduction in energy. However, the more speed reduction possible, the greater the energy savings.

For **positive displacement** compressors, speed is independent of lift, or in other words; the compressor can develop the same amount of lift at any speed. Therefore, mechanical loaders can be replaced entirely by speed control. As discussed earlier, centrifugal compressors may require speed control coupled with some closure of the inlet guide vanes. The variable speed screw compressor never has to temper speed control with a guide vane or slide valve, and therefore captures the maximum energy reduction available at a given operating condition. Even small changes in speed create significant changes in energy consumption.

Applications where high lift requirements remain even as cooling loads decrease may favor variable speed screw chillers more significantly. An example of this application is a building located in a hot and humid climate where cooling loads can vary while outdoor-air temperatures (dry bulb/wet bulb) remain high. A variable speed screw compressor chiller is approximately 10 to 20% more efficient than all variable speed centrifugal compressors with constant 85 F entering condenser water.

Types of Refrigerants:

The refrigerant technology is changing because of concerns of Ozone depletion. The production of several commonly used refrigerants will soon end, including R-22 in 2010 and R-123 in 2020 in accordance to the requirements of the Montreal Protocol. Suppliers currently offer a range of refrigerants based on chiller type, capacity and regulatory requirements. Current refrigerants available for use include:

- **Reciprocating (Open drive)** – R22, R134a, R401A, R409A, R410A, R413A
- **Semi-hermetic (includes reciprocating & scroll)** – R22, R123, R134a, R401B, R404A, R407C, R409B, R410A, R507
- **Screw** – R22, R134a, R401A, R409A, R410A, R413A
- **Centrifugal** – R134a, R123

R-22, R-407C, and R-410A are high pressure refrigerants, R-134A is medium pressure and R-123 is low pressure refrigerant. R123 is classified in B1 category and has very low AEL and TLV limits. Due to its toxicity, rusting, corrosion, and many other negative factors, R123 is not considered as a good option. R123 was born as a temporary substitute to R11, since no other permanent refrigerant without chlorine has still been found with similar temperature-pressure characteristics.

Every effort should be made to specify equipment which does not require any CFC refrigerants, including R-11, R-12, R113, or R114, or R-500. HCFC refrigerants such as R-22 and R123 are discouraged. By considering the phase-out of CFC refrigerants and fast approaching deadlines for HCFC refrigerants, the recommended refrigerants should be **HFC** such as R134a or azetropes R407c or R404a where possible.

Hunting or Surging:

- **Reciprocating** compressors will not hunt or surge.
- **Screw** compressors will not hunt or surge.
- **Centrifugal** compressors are prone to surging at low and high pressures.

A minimum volumetric rate flow through a centrifugal compressor is required for stable operation. If the volumetric flow rates fall below this minimum (at low load conditions), the centrifugal machines will become susceptible to surge condition and will cause considerable vibration and eventual damage to the compressor. The other reason for surge is the high discharge pressure, which is a fault condition. Because of nature of compression process, the flow through the compressor can become unstable if the compressor is required to produce a pressure rise in excess of its design limit. Typically the faults are:

- Excessive fouling of the condenser,
- A partial failure of the condenser coolant flow,
- Or accumulation of a non-condensable gas in the condenser

To prevent surge from occurring, internal hot gas bypass may be used to allow capacity to be reduced while maintaining sufficient gas flow through the compressor. Alternatively, a variable frequency drive option could be considered to vary compressor speed in relation to control capacity. Generally, speed control improves

efficiency over inlet vane control down to about 55% of rated capacity; while inlet vane control is more efficient below 55% of rated capacity.

Heat Rejection Options:

The heat collected by the water chiller, along with the excess compressor heat, must be rejected to a heat sink. The heat rejection could be by means of air cooled or water cooled condenser. Directly or indirectly, ambient atmospheric air is typically used as this heat sink.

- The **air cooled condenser** is where the refrigerant rejects heat (energy) directly to the outside air. Air cooled condensers can be an integral chiller component or be a remote condenser with refrigerant piping connecting it to the chiller. The performance of the air cooled condenser is dependent on the airflow rate and the air's dry bulb temperature. Typically, the air flow rates range from 600 to 1200 cfm/ton with a 10–30°F approach between the ambient dry bulb temperature and the refrigerant condensing temperature. Note at high ambient temperatures, the condensing temperature will increase and the chiller capacity gets reduced by about 2% for each 5°F increase in condensing temperature.
- **Water cooled condensers** typically involve a shell-and-tube heat exchanger with condenser water running through the tubes and the refrigerant in the shell space. The condenser water flow must have the same flow velocity range as the evaporator, 3 feet per second (fps) to 12 fps. Condenser water is typically supplied at 70–85°F and the flow rate is selected for a 10–15°F range. A cooling tower is typically utilized to provide condenser water cooling, but other cool water sources such as wells, ponds etc. can be used. At the chiller, with 85°F condenser water supplied from the cooling tower, condensing temperatures are reduced to 94–98°F, reducing the lift required of the compressor and significantly improving the chiller COP compared to air-cooled machines.

Recommended Criteria

- For cooling loads below 100–125 tons, the chiller(s) shall be **air-cooled**. The capital cost and increased maintenance requirements for a water-cooled system are rarely justified on the cooling loads below 125 tons.

- Above 200 tons peak cooling load, the **water-cooled systems** become justifiable.
- Between 100 and 200 tons cooling load, it becomes a matter of the owner's ability to deal with the maintenance requirements of a cooling tower system, and the capital funds available.

Reciprocating chillers have a higher condensing temperature than other chillers, making them more suited for applications where air-cooled condensers must be used. Note that the air-cooled condenser is NOT an option for the **centrifugal** machines, which generally utilize low/medium pressure refrigerants. While some smaller air-cooled centrifugal models are manufactured, they are largely exported to the Middle East and other arid areas where water is simply not available for HVAC condensing use. The centrifugal compressors mentioned here will be using HCFC-123, HCFC-22 and HFC-134a. This usually calls for semi-hermetic designs, with single or multi-stage impellers. Two manufacturers (Carrier and McQuay) offer semi-hermetic gear driven models. Trane offers multi-stage direct drive semi-hermetic units. York offers an integrated open-drive geared design.

The **screw** and **reciprocating** machines are available in both air-cooled and water-cooled condenser options.

Reliability and Maintenance:

- **Reciprocating** compressors are prone to frequent wear and tear because of highest number of moving parts. The continuous wear and tear causes leakage past piston resulting in lower capacity resulting in reduced performance and lower COP as the machine gets older. These compressors require heavy foundations due to unbalanced forces and moments on the base.
- **Screw** compressors will usually require less maintenance than centrifugal compressors and it is very common for screw compressors to operate unattended in on continuous basis for over 50,000 hours. These compressors are not subject to unbalance problems with rotors operating at half below the first critical speed. These need only load bearing level ground to position them.
- **Centrifugal** compressors have the least number of moving parts. But since the centrifugal machines operate at high speed these are susceptible to

unbalance & vibrations. The centrifugal machines require more items to be checked regularly.

Other factors that affect maintenance costs include:

- Gear-drive machines require higher maintenance than direct-drive machines.
- Open-drive machines have slightly higher maintenance costs than hermetic machines, although they are less costly to repair should there be a motor burnout.
- Whether the system is air- or water-cooled has by far the most significant impact on maintenance costs. Water-cooled systems will always cost more to maintain due to the constant water treatment requirements and the need for regular tube cleaning. Water-cooled chillers will generally last longer in coastal areas, where salt in the air can significantly shorten the life of air-cooled condensers.

Field Serviceability:

- Most **reciprocating** chillers are field serviceable but it is tedious due to large number of parts.
- Field serviceability of **screw** chillers is relatively simple and is serviceable in the field as all parts are removable and replaceable.
- The above is true for **centrifugal** chillers but may pose significant problems if impeller is failed. Centrifugal impellers are one of a kind and are not standard equipment or a stock item that will fit in a similar unit in the field.

Stock Availability of Spares:

- **Reciprocating** compressors spares are normally available from local stocks.
- Most **screw** compressors manufacturers have a number of machines in stock, as well as the rotors, bearings seals etc.
- **Centrifugal** compressors do not stock impellers and require 10 to 12 week delays to fabricate the same.

Oil Lubrication:

- In **screw** compressor, oil is injected into the rotor chamber for sealing and lubrication purposes and is removed in an oil separator. The screw compressor has a considerable amount of oil pumped through it at all times and therefore it can absorb liquid slugs in large quantities.
 - In **reciprocating** compressors lubricating oil is allowed to circulate with the refrigerant, this avoids the necessity for fitting an oil separator. Large quantities of liquids during upset conditions can destroy reciprocating compressors but the centrifugal compressors are most susceptible to water.
 - **Centrifugal** machines are oil free dry units. Even small quantities of liquids shall have detrimental effect on centrifugal compressor rotors.
-

Chiller Performance Standards:

The two dominant organizations promoting certification programs are:

1. ARI (Air-Conditioning & Refrigeration Institute) is a trade institute that represents the manufacturers more than 90% of North America's HVACR companies.
2. Eurovent – used as a common voluntary certification program in Europe, but open to all manufacturers,

ARI Standard 550/590 is the primary performance standard for screw and centrifugal chillers up to 2,000 tons chillers. This standard provides a testing protocol for determining the chiller capacity (tons), energy usage (kW/ton), fluid pressure drop (ft of water), and IPLV/NPLV.

1. IPLV stands for Integrated Part Load Value that predicts chiller efficiency at the ARI Standard Rating Point and
2. NPLV is for Non standard Part Load Value that predicts chiller efficiency at rating conditions other than the ARI Standard Rating Point but within prescribed limits.

The IPLV number is calculated as a weighted average of four load points. The weighting is based on a “blend” of operating-hour scenarios from many different building types and 29 geographic locations.

IPLV Rating Conditions (ARI Standard 550/590-98) – Note¹

	Load%	Weightage (%)	Entering Cooling Water Temperature - ECWT (°F) (For water cooled condensers)	Entering Dry Bulb Temperature - EDB (°F) (For air cooled condensers)
A	100%	1%	85	95
B	75%	42%	75	80
C	50%	45%	65	65
D	25%	12%	65	55

Note¹ - The Air Conditioning and Refrigeration Institute (ARI) Standard 550/590-98 established the Integrated Part Load Value (IPLV) to “provide a single number part load performance number for water chilling products. Apart from the temperature mentioned above in the table for IPLV rating, ARI requires flow in condenser and evaporator would be 3 gpm/ton and 2.4gpm/ton respectively and fouling factor for condenser and evaporator would be 0.00025 h-ft²-F/Btu and 0.0001 h-ft²-F/Btu respectively.

The formula for calculating IPLV is:

$$IPLV = 1 / ((0.01/A) + (0.42/B) + (.45/C) + (0.12/D))$$

The result of the equation is a chiller efficiency number expressed in kW/ton.

Where

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

The equation was derived to provide a representation of the average part load efficiency for a single chiller only where the condenser water supply temperature is allowed to fall as the outdoor wet bulb temperature falls. Anytime multiple chillers are used, the IPLV has little validity. Likewise, if control of the condenser water temperature control method does not allow the supply temperature to go as low as 65°F, then the IPLV is not valid. ARI recommends another efficiency term, Non-standard Part Load Value (NPLV), if chiller design conditions are anything other than the standard ARI Standard 550/590-98. *The NPLV uses the same equation weighting*

as *IPLV* and it emphasizes part load, (not full load efficiency) over a wide range of conditions and is normally used in specifications. The *NPLV* rating however includes both off-design efficiency and design efficiency. Note that two chillers can have the same design efficiency, and yet can have *NPLV* ratings that vary widely, depending on capital cost. For example, a chiller with a design efficiency of 0.58 kW/TR can have an *NPLV* rating anywhere from 0.55 to 0.35 kW/TR. That's because chillers can have different off-design efficiencies. If you stress on meeting both the design efficiency and the *NPLV*, it is possible by adding more heat-exchanger surface but in meeting the design-efficiency specification, the chiller will be more expensive.

Chiller Instrument Controls:

The modern chiller control systems are almost exclusively microprocessor based electronic controls that allow precision, programming, flexibility to regulate, reliability and information feedback. All the three chiller options are available with factory installed controllers that allow remote monitoring and sequencing (RMS) features and can be interfaced with building management systems (BMS) or industrial plant distributed control systems (DCS)

- The controllers offer the programmable set points, lead/lag scheduling, optimal start control, compressor soft loading, demand limit control etc as standard features.
 - Phase failure/reversal protection, high return water unloading, acoustical enclosures around the compressor are factory installed optional features that are available at extra cost.
-

The Economic Life:

The economic life of a machine is the time frame within which it provides a positive benefit to the owner. Thus, when it costs more to operate and maintain a piece of equipment than it would to replace it, the economic life has ended. Typically, the economic life (sometimes called “service life”) is the period over which the equipment is expected to last physically.

The economic life for **reciprocating** compressor chillers is normally selected as 15 years, while **rotary** and **centrifugal** chillers have an expected economic life of 25 years.

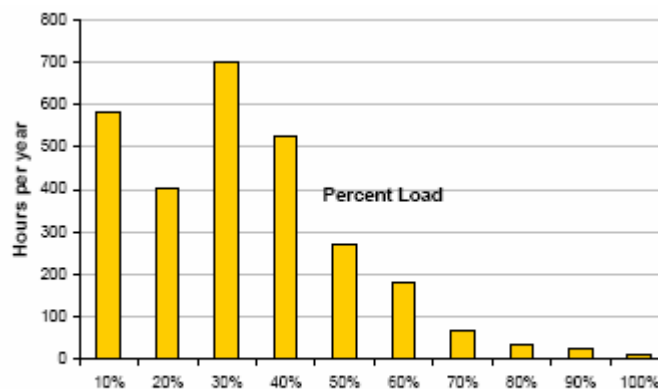
PART III - ECONOMIC EVALUATION OF CHILLER SYSTEMS

When selecting a chiller for a new or retrofit application, the following assessment tasks should be carried out to enable an appropriate conclusion to be reached.

- Determine the functional and operational requirements by assessing the cooling load and load profiles including location, hours of operations, number/type of occupants equipment being used etc.
- Determine the required system configuration in terms of number and plant capacity by taking into account the total capacity and operational requirement, reliability and maintenance considerations
- Identify planning and environmental issues, in particular those that would prohibit the use of certain type of equipment or costly treatment or measures required to render the proposed equipment fit for use.

Cooling Load Profile:

In order to select the right configuration of chillers the cooling load profile is very important. Cooling load profile will help to determine the type of chiller to use and if single or multiple chillers should be installed. For instance, if there are many hours at low load, it is advantageous to install a small “pony” chiller or a variable-speed drive. Figure below shows a typical load profile for an office building.



Typical Load Profile of an Office Building

- **Peak load** determines the overall capacity of the system. The total chiller capacity in tons of refrigeration should match the peak building load.
- **Part load** requirements determine the number and size of chillers required.

Multiple chiller configurations is a common method of meeting peak load in large installations. It allows facilities professionals to stage their operation to match building loads while keeping the chillers operating at energy efficient loading. It also provides redundancy for routine maintenance and equipment failure. For many typical facilities, sizing one chiller at one-third and another chiller at two-thirds of the peak load enables the system to meet most cooling conditions at relatively high chiller part-load efficiencies.

Minimum Number of Chillers:

There are some applications where failure of refrigeration equipment could result in serious financial loss beyond the equipment repair expense. In such cases, it is advisable to consider a multiple compressor chiller system. Multiple chillers offer operational flexibility, standby capacity, and less disruptive maintenance. The chillers can be sized to handle a base load and increments of a variable load to allow each chiller to operate at its most efficient point. Multiple chiller systems offer some standby capacity if repair work must be done on one chiller. Starting in-rush current is reduced, as well as power costs at partial load conditions. Maintenance can be scheduled for one chilling machine during part load times, and sufficient cooling can still be provided by the remaining unit(s). However, these advantages require an increase in costs and space.

Multiple chiller installations may be **symmetrical** (where all chillers are sized for equal capacity) or **asymmetrical** (where one or more chillers may be of different sizes). The key to deciding the symmetrical or unsymmetrical arrangement is dependent on the minimum anticipated load. Once the plant load is reduced to below the capacity of a single chiller, we want that chiller to operate in an efficient region (i.e., above 30% capacity) as long as possible.

Let's see this with an example.

A building with a peak cooling load of 750 tons and a minimum cooling load of 100 tons could be served by three chillers, each rated at 250 tons. At 100 tons, a single chiller would operate at 40% capacity, which is still within the efficient region. Had two 375 ton chillers been selected, the last chiller on line would operate at 27% of its capacity to meet the minimum cooling load requirement.

The 750 peak load could have been met with a 600- and a 150-ton chiller. Both chillers would operate to produce 750 tons at peak load conditions, but the smaller

chiller would meet the minimum load operating at 50% of its peak capacity, which would normally be a very efficient operating point that would result in lower operating costs. However this arrangement has a disadvantage that in an event if the 600 ton chiller fails, only 20% of the plant capacity is available. If a single chiller fails with the symmetrical design, two-thirds of the peak capacity is still available. Also there may be some maintenance advantages (common parts, etc.); different sized chillers can be operated together.

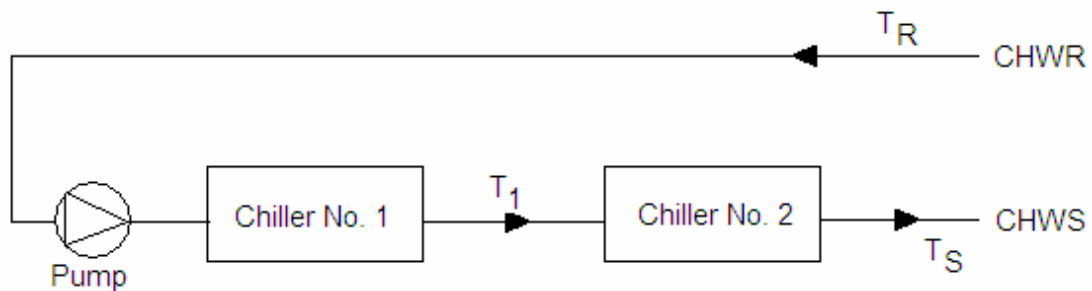
Generally, 60/40 asymmetrical split allows better capacity-to-load matching and improved performance.

Multiple Chiller Configurations:

A multiple chiller system has two or more chillers connected by parallel or series piping to a common distribution system.

Series Arrangement:

In the series configuration with two chillers, as shown in Figure below, each chiller is selected to produce half of the required cooling at the full system flow rate. Thus, half of the total design range is produced by each chiller.



Series Chiller Configuration

Load ratios other than 50/50 are possible, but this is by far the most common condition because of control problems with chillers at very small temperature differences.

Table below summarizes the temperatures at various load conditions for the series chiller configuration shown above.

Series Configuration Temperatures

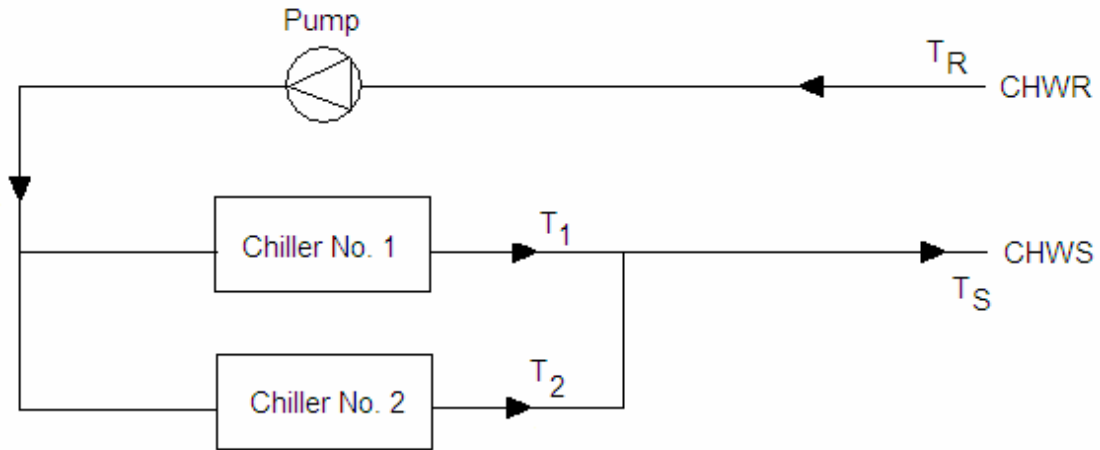
Temperature	100% Load	75% Load	50% Load	25% Load
TS	44	44	44	44
TR	56	53	50	47
T1	50	50	50	47

Series chiller systems are rarely done any longer because this configuration requires a constant chilled water flow rate at all times, resulting in high pumping costs. But, if a relatively large temperature difference is required or if there is a very steady base cooling load, the series configuration may offer some advantages. Unlike parallel arrangement, no over-chilling by either unit is required, and compressor power consumption is lower than it is for the parallel arrangement at partial loads.

Parallel Arrangement:

In the parallel arrangement, liquid to be chilled is divided among the liquid chillers; the multiple chilled streams are combined again in a common line after chilling. As the cooling load decreases, one unit may be shut down. Unless water flow is stopped through the inoperative chiller, the remaining unit(s) provide colder than design chilled liquid. The combined streams (included one from the idle chiller) then supply the chilled water at the design temperature in the common line. All units should be controlled by the combined leaving water temperature or by return water temperature. Chilled water temperature can be used to cycle one unit off when it drops below a capacity that can be matched by the remaining units.

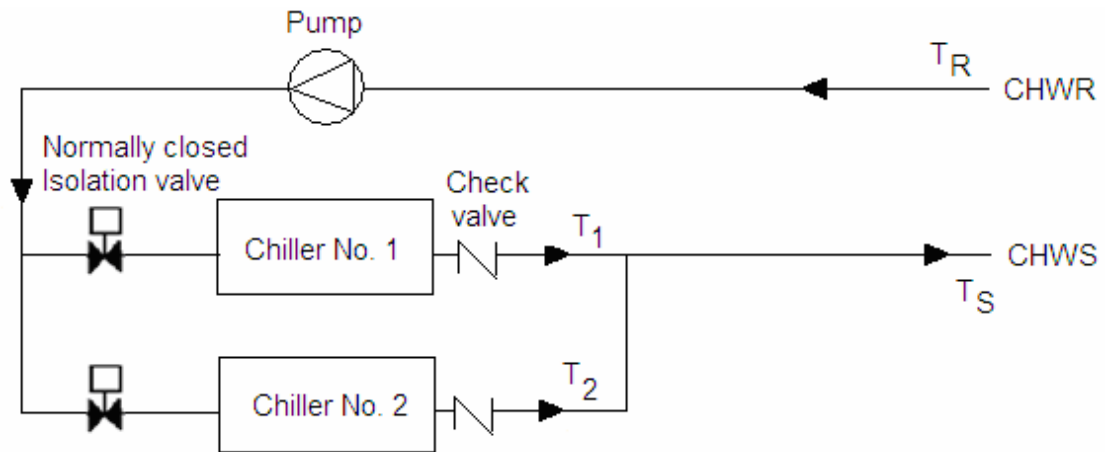
The parallel chiller configuration with one pump arrangement along with the overall system performance and temperature conditions is illustrated below:



Parallel Chiller Configuration (One Pump)

With this configuration, when the system load drops to less than 50%, one chiller is shut off. However this arrangement has an inherent problem. When one chiller is not in operation, chilled water from the operating chiller will mix (blend) with the return water passing through the non-operating chiller, effectively raising the chilled water supply temperature to the system. An elevated chilled water supply temperature may not satisfy the interior load conditions.

The refinement of this arrangement is to provide isolation valves at the inlet of the each chiller and check valve at the outlet. This will allow the flow through the non-operating chiller to be shut, when not in operation.

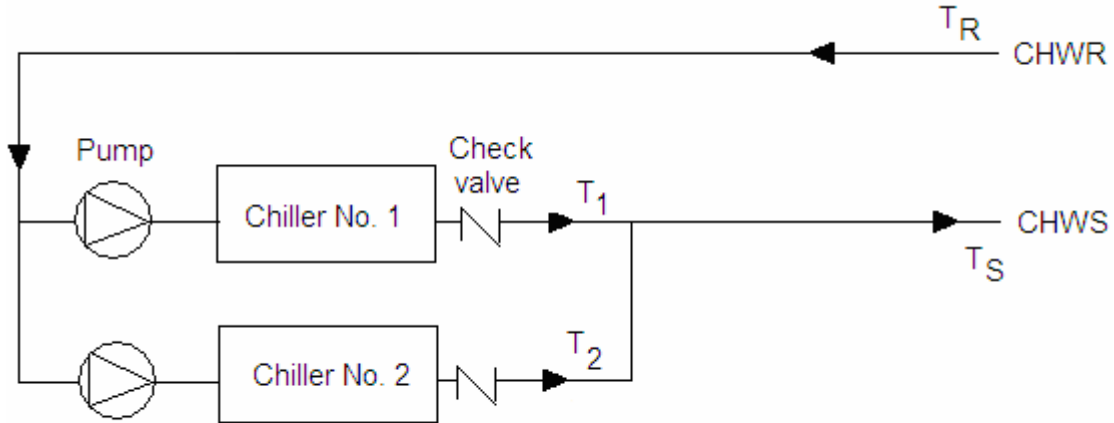


Parallel Chiller Configuration with Isolation Valves

The above scheme will reduce the blending problem but has another point to consider. With constant flow pumping, this will result in increased flow through the operating chiller. Two options are possible:

Option #1: Use variable speed drive for pump. This will reduce the flow rate to 50%, when one chiller is off.

Option #2: Use multiple pump parallel configurations as shown below:



Parallel Chiller Configuration with dedicated Pumps

With this configuration, each chiller has its dedicated pump and the check valve at discharge from chiller. Check valve is used to prevent backflow when chiller and its pump is off. Thus, when one chiller is not operating—one pump is off, flow through the non-operating chiller is zero, and no blending results. Table below summarizes the performance and temperature conditions for this configuration at various load conditions.

Load	Chilled water return temp (T_R)	Chiller No. 1		Chiller No. 2		Chilled water supply temp (T_S)
		Flow (%)	T_1	Flow (%)	T_2	
100	56	50	44	50	44	44
75	53	50	44	50	44	44
50	50	50	44	0 (off)	NA	44
25	47	50	44	0 (off)	NA	44

The energy efficient alternatives available today use primary-secondary chilled water arrangement with variable speed pumping. For more detailed information on the subject refer to a separate course “Chilled Water Piping Schemes” available on this site.

Note that in both, series or parallel arrangement, one unit should be shut down as soon as possible with the remaining unit(s) carrying the full load. This not only reduces the number of operating hours on a unit, but also reduces total power consumption because the COP tends to decrease below the full load value when unit load drops much below 50 %.

Operational Regimes:

It is imperative to determine which portion of the total load required 24 hours operations. Say in a office building operating for 10 hours a day and the data center room requiring 24 hrs operation, it shall be prudent to use multiple chillers with capacity matching nearly the critical essential load for overall economics.

It would be more cost efficient to operate a smaller capacity chiller at full load than a bigger capacity at part load.

Infrastructure Availability:

- The places where the price differential between the electricity and natural gas is high, gas driven centrifugal chillers or absorption chillers could be considered. In some development sites, it may involve huge cost to set up an infrastructure of say 6.6 or 11kV for large chiller capacities or to bring energy to the remote site.
 - The places where water is scarce, the chiller machines should be selected for air-cooled condensers. Centrifugal chiller is NOT a right choice for air-cooled configurations.
-

Microclimate conditions:

High humidity, tropic climatic conditions would favor the selection of air –cooled chillers. Centrifugal chillers require cooling tower and make up water. These may not be a good choice in the humid and tropic regions.

System maintenance and serviceability considerations:

The facilities professionals must take into consideration the maintenance requirements of different types of chillers. The following must be noted:

- Use technologies that are reliable, can stand long hours of continuous operation, minimum downtime and requires minimal maintenance
- Must consider the level of service and support that can be provided by the manufacturer in that location.

Reciprocating chiller requires more routine maintenance and the **centrifugal** chiller require more tedious service than the **rotary** chillers.

Required Level of Redundancy:

Typically, an analysis of chiller options assumes that the chiller plant operates normally. But what happens if a chiller fails?

The applications where cooling is required for critical services such as the hospital, industrial process or data centre; continuity of service is essential and the provision of cooling cannot be relied on a single chiller. For redundancy and reliability at least two chillers or dual compressor options may be specified. One back up unit would be required. The provision of 1 additional back up unit is known as “N+1” strategy. This strategy involves the provision of one more unit than the quantity required so that even if one unit fails, 100% of the design cooling load can still be met. For example if the total capacity requirement is 1500 TR, 2 units each of 750 TR should be considered. A life cycle cost economics of using 3 X 50% option could also be investigated.

Physical Attributes:

Environmental planning constraints on the proposed plant location need to be considered. To a great extent space availability will dictate the type of chiller to be installed.

- **Siting** - The area and space requirements for chiller package must be examined. The **screw** chillers might be the best solution where mechanical room space is restricted. For a complete package, decision for air-cooled v/s water-cooled chiller package should be evaluated. In addition to availability of quality water concerns, it should be noted that space requirement for the cooling tower is roughly 25% the area needed by the air-cooled system on large installation. Both screw and reciprocating chillers are suitable for air cooled configurations. Centrifugal machines are typically water cooled.

- **Noise** - Reciprocating chillers are noisy because of the reciprocating movements of the pistons. Even the high-pitched whine of **centrifugal** compressor can be a serious problem. **Screw** chiller is the quietest and is a best choice in noise sensitive areas.
-

Health, Safety and Jurisdictions:

All the HVAC design & selection must adhere to the statutory codes and regulations. The federal or state local code jurisdictions may not permit the use of some materials. For instance use of hazardous material such as ammonia in buildings is prohibited outright. In some places due to noise concerns air-cooled machines are prohibited. In others for minimizing risk of Legionella bacteria the use of cooling tower is prohibited, therefore **centrifugal** machines may not be a choice for such places. The safety and building code guidelines must be evaluated thoroughly at a nascent stage itself.

Procurement Strategies:

1. Calculate or estimate the required plant total tonnage;
 2. Pick a short list of chiller vendors based on past experience, local representation, etc;
 3. Request chiller bids based on a performance specification;
 4. Adjust bids for other first-cost impacts;
 5. Estimate energy usage of options with a detailed computer model of the building/plant;
 6. Estimate maintenance cost differences between options;
 7. Calculate life-cycle costs;
 8. Select the chiller option with the lowest lifecycle cost.
-

Performance Specifications:

To define capacity and performance requirements for any chiller; the following parameters must be specified:

- a. Maximum cooling capacity (tons)
-

- b. Chilled water supply temperature (°F)
- c. Chilled water return temperature (°F)
- d. Chilled water flow rate (gpm)
- e. Maximum evaporator pressure drop (ft wg)
- f. Evaporator fouling factor (usually 0.0001)
- g. Condenser water return temperature (°F)
- h. Condenser water supply temperature (°F)
- i. Condenser water flow rate (°F)
- j. Maximum condenser pressure drop (ft wg)
- k. Condenser fouling factor (usually 0.00025)
- l. Electrical service: V/ph/Hz
- m. Maximum sound power level (dBA)
- n. Allowable motor type (hermetic and/or open)
- o. Motor FLA
- p. Maximum kW/ton at full load
- q. Maximum IPLV (kW/ton)

Life cycle costing considerations:

The computations required to determine life cycle cost utilizing the total owning and operating cost methodology are simple. However, the methodology's accuracy depends wholly on the accuracy of the data utilized. Two different individuals, faced with the same evaluation may compute wildly different life cycle costs because they use significantly different data and/or assumptions in their computations.

There are three elements to life cycle-costing.

1. Initial cost
2. Total operating cost
3. Total maintenance cost

The following subsections define the basic elements that make up the life cycle cost.

Capital costs:

Initial cost includes all the necessary equipment costs plus the cost to install the components and make the system operational. This would include the equipment itself, installation, piping, wiring, controls etc. Equipment costs can be obtained directly from the prospective equipment vendors. Installation cost estimates can be obtained from local contractors or, lacking that, from cost data published by R. S. Means Co., Inc. (Construction Plaza, 63 Smiths Lane, Kingston, MA 02364-0800, 781/585-7880 or 800/334-3509). The construction cost estimate must include the following, in addition to the cost of the chiller itself:

- Refrigeration room safety requirements (ASHRAE Std. 15);
 - Additional ventilation required for open motor;
 - Noise and vibration control;
-

Recurring Costs:

Recurring or operating costs result from the actual operation of the system and include energy and water usage and water-treatment chemicals. The energy cost requires that two quantities be known: (1) the amount of electrical energy consumed by the chiller and (2) the unit cost or rate schedule for that energy. The second quantity is relatively easy to determine by contacting the utilities serving the site or, for some campus facilities, obtaining the cost for steam or power. That may be furnished from a central source. The energy cost, then, is computed by multiplying the electrical energy consumption by the unit cost for electricity. **Note** that virtually all utilities charge both for energy consumption as well as for demand. Since chillers are one of the largest energy users in typical buildings, it is essential that demand charges be properly taken into account. This is particularly true when demand charges are ratcheted, meaning the owner pays some percentage of the maximum peak demand over the year, regardless of actual monthly demand.

Maintenance Costs:

Maintenance costs are those required to keep the system operational, including routine servicing, replacement parts, repairs, cleaning and disinfection and so on. Maintenance costs are more difficult to estimate accurately than energy costs. There are little data available indicating the relative maintenance costs of various chiller

types and among the various manufacturers of each chiller type. Manufacturers make claims about their products' advantages, but they seldom have hard, independently collected data to support those claims. To further complicate the issue, annual maintenance costs are not constant. The costs are low for the first few years, jump during years when a complete overhaul is required, and increase gradually as equipment wears. The length of time that different pieces of equipment last before they must be replaced also varies, although usually this is not an issue in chiller selection unless very long life cycles are analyzed.

Because maintenance costs are difficult to estimate, they are often ignored in the chiller selection life-cycle costing and considered only as a "soft issue" used when making the final chiller selection. This is probably a reasonable approach when the number and types of chillers are the same. However, when the number of chillers in each option varies, both air- and water-cooled options are being considered, or chillers of different types (e.g., electric and gas-engine driven) are being considered, maintenance costs need to be included explicitly in the life-cycle cost calculation for best results. Lacking other information, the annual routine maintenance cost associated with chillers can be estimated as 1–3% of the initial equipment cost.

Course Summary and Technology Trends

The refrigeration equipment used for air-conditioning is almost invariably supplied in the form of a packaged unit. The classification of the chiller packages is by the type of compressor. The most common commercial available chilled packages can be one of the following:

- Reciprocating
- Centrifugal
- Screw
- Scroll

The primary application of **reciprocating** chillers is for small systems that require cooling loads less than 150 TR. Above 150 TR either the multiple reciprocating or the screw and centrifugal compressors may be evaluated subject to the wider framework of life cycle analysis, energy performance, health and safety.

Centrifugal chillers are best suited for the larger installations typically above 750 TR. The centrifugal machines offer high peak load efficiency and operate reliably for applications demanding a steady state operation. On acute load variations, the centrifugal machines are susceptible to surge conditions. The machines are only recommended with water-cooled condenser option.

The **screw** chillers are well suited for applications demanding up to 750 TR. Above these capacities, centrifugal chillers may be more cost effective.

More than the initial capital costs, the cost of operation must be evaluated. The most important thing to remember is that the air-conditioning hardly runs on peak load. Therefore part load efficiency is paramount.

Install sufficient capacity to meet the imposed cooling loads. It is normal for an installation to have several chiller packages, both to provide standby and to enable cooling load to be matched with the minimum consumption of power. It is important for economy of operation, that the optimum equipment selection is achieved.

For applications where chiller must operate at 50% or less of capacity for more than 50% of the time, staged reciprocating units, screw chillers or a centrifugal unit equipped with VFD offer the most energy efficient solution. If the chiller is to operate at higher loads for longer periods of time, centrifugal or rotary units may be the best.

New Technology Alternatives and Trends

- 1) Air-conditioning systems consume high energy. The part load efficiency is very critical to minimize the overall energy costs. The problems with centrifugal machine having low part load efficiency and inability to operate during low load to a great extent have been eliminated through the provision of variable frequency drive (VFD). VFD technology enables centrifugal machines to operate at off design conditions at 0.50, 0.40 and even at 0.30 kW/ton. As the cooling load decreases, the VFD decreases its output voltage/ frequency, slowing chiller. The result the chiller operates at near full load efficiency for almost the entire operating range and allows the chiller to operate as low as 10% of rated output without experiencing surging.

One VFD system drawback: It increases the chiller's full-load current draw by 5 percent to 10 percent due to internal losses and conversion inefficiencies. While this penalty is more than offset by savings produced under part-load conditions, it can be significant, particularly in facilities with high electrical demand charges.

- 2) If the cooling load profile indicates that there will be significant chiller usage at or below 30% of peak load, it may be advantageous to use a dual compressor chiller or multiple single compressor chillers. The dual compressor chiller typically uses two compressors, each sized for 50% of the peak load. At 50–100% of design load, both compressors operate. However, if the imposed load drops below 50% of the design value, one compressor is stopped and the remaining compressor is used to satisfy the imposed load. This configuration has the advantage of reducing the inefficient operating point to 15% of full load (50% of 30%), reducing significantly the operating energy penalties that would result from a single compressor operation.
- 3) Gas driven centrifugal machines are an alternative to electric driven chillers in areas where demand charges are high and natural gas rates are low. The gas/turbine driven machines tend to be more than twice as expensive as the electrical driven machines of equivalent capacity. The use of gas/turbine driven machines is recommended for remote locations where either the electric power is not available or where the high capacity chiller machines typically above 750 HP demand expensive electrical distribution network, switchgear and transformers.
- 4) In large centrifugal machines, the expansion valve is replaced with 2-phase turbine. With expansion valves, the energy potential available across the expansion valve due to the high-pressure differential is lost. By replacing the

valve with a turbine, some of the energy can be recovered and used to help drive the chiller compressor, reducing energy the motor must supply.

- 5) New chiller designs include features to significantly reduce refrigerant losses. Before CFC were an issue, a loss rate of 15% per year was considered acceptable. But now the CFC and HCFC refrigerants are both an environmental and an economic concern. The new developments minimize shaft seals; install isolation valves around filter assemblies and use brazed instead of flared fittings. In addition high efficiency purge units can limit the refrigerant losses to less than 0.5% per year, including the losses that occur during system maintenance.
- 6) The new technology chillers available today offer as high as 15 to 20 EER. The current minimum air conditioning energy efficiency standard recommended by ARI is 10 EER and is proposed for revision to 13 EER.

Acronyms:

- EER stands for energy efficiency ratio. This represents cooling capacity in Btu/hr divided by power input in watts at a standard conditions specified by American Refrigeration Institute, ARI. EER for refrigeration machine is always above 1.
- CFC stands for chloro fluoro carbon compounds. HCFC stands for hydro chloro fluoro carbon compounds. These are the category of refrigerant compounds that are considered major source of ozone layer depletion. CFC has been phased out completely and HCFCs are permitted to use on running machines until year 2020. HCFCs are responsible for ozone layer depletion to certain extent.