

CHILLER BASICS



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Indian Society of Heating, Refrigerating and Air-Conditioning Engineers

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1. Basic refrigeration cycle and basics of chillers

In Air conditioning systems, chilled water is typically distributed to heat exchangers, or coils, in Air handling units or other type of terminal devices which cool the air in its respective space(s), and then the chilled water is re-circulated back to the chiller to be cooled again. These cooling coils transfer sensible heat and latent heat from the air to the chilled water, thus cooling and usually dehumidifying the air stream.

Basic Refrigeration Cycle for Chillers :

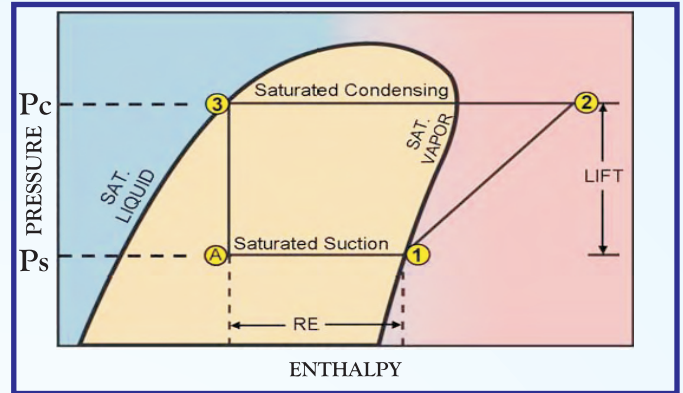
The refrigeration cycle the components of a chiller are Compressor, Condenser, Expansion Device and Evaporator.

In the evaporator of a water-cooled chiller, liquid refrigerant at approximately at lower temperature takes on heat from building return water flowing through the evaporator with this heat the liquid refrigerant changes to a vapor. The refrigerant vapor is drawn into the compressor and its temperature and pressure are elevated by the compression effect.

The compressor provides the work necessary to compress the gas to a temperature and pressure required by the condenser. The gas is then discharged into the condenser where it condenses on tubes through which water flows. This is the entering condenser water from the cooling tower.

The condensed liquid refrigerant then fall to the bottom of the condenser, flow through a pressure reducing device such as a float valve or an orifice or an expansion device to reduce its pressure & temperature. This low pressure & low temperature refrigerant flows into the evaporator and where the process repeats itself.

The cycle can be shown on a pressure-enthalpy (p-h) diagram. Pressure is the force exerted per unit area, while enthalpy is the total heat content expressed in Btu per pound (K-cal/Kg) of the substance. When the compressor is close-coupled to the evaporator, there is negligible pressure loss in the suction line, and gas enters the compressor at approximately the saturated conditions that exist in the evaporator, Point 1.



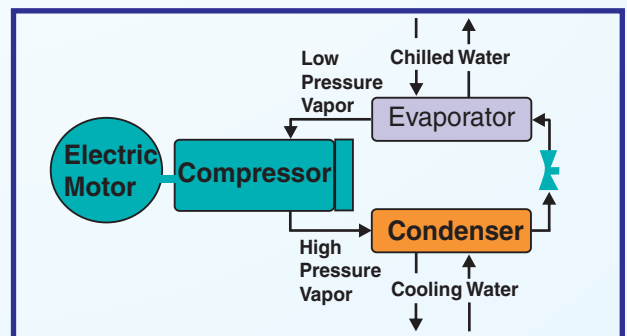
If we follow the steps shown, we can see that from A to 1 is the refrigeration effect. In this step, building heat from the chilled water is absorbed by the refrigerant, and the refrigerant transitions from a liquid to a saturated vapor, at Step 1. From Step 1 to 2 is the compression stage. This stage raises the temperature and pressure of the saturated refrigerant vapor to the saturated condensing temperature, so that heat can be rejected to the condensing fluid. This compression is also called the “lift” of the compressor or worked done by the compressor.

A chiller is a machine that removes heat from a liquid via :

Vapor-Compression Refrigeration Cycle or Absorption Refrigeration cycle.

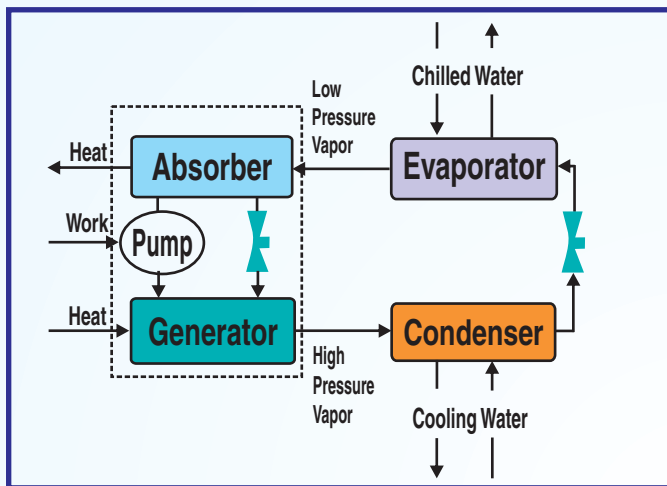
Vapor-Compression Water Chiller comprise of the 4 major components compressor, evaporator, condenser and a expansion device. These machines use a variety of refrigerants.

VAPOR COMPRESSION CYCLE



Absorption Chillers utilize water as the refrigerant and rely on the strong affinity between the water and a lithium bromide solution to achieve a refrigeration effect. Most often, pure water is chilled, but this water may also contain a percentage of glycol and/or corrosion inhibitors; other fluids such as thin oils can be chilled as well.

ABSORPTION CYCLE



A chiller for air conditioning applications is rated generally between 2 TR to 6000 TR (7kW to 21,101kW) in cooling capacity. Chilled water temperatures can range from 36°F to 68°F (2.2°C to 20°C), depending upon application requirements. A temperature lower than 36°F can also be achieved however instead of chilled water, brine solution is used for application requiring lower temperatures. The chillers can be used in stand alone application or in parallel for larger capacity requirements.

Sometimes chillers are used in series /counter or series parallel configurations to achieve higher capacities

2. Types of Chillers

Based on the 3 major components of the chiller, the chillers types are defined :

Based on Compressor Used :

- Scroll Compressor (up to 150TR / 527.5 kW)
- Screw Compressor (up to 500TR / 1758 kW)
- Reciprocating Compressor (Up to 400TR / 1407 kW)
- Centrifugal Compressor (up to 6000TR / 21,101 kW)

These compressor can further be typed based on the driver used and the construction of Compressor and Drive. Which are Hermetic (sealed compressor and motor in one casing), Semi Hermetic Compressor and motor in one casing with bolted construction, Open Type Compressor and motor in separate casings. Each of these types has its own advantage based on the application.

Based on Second Major Component i.e Condenser chillers are classified in

- (I) Air - cooled chillers (or evaporative cooled)
- (ii) Water cooled chillers .

AIR - COOLED CHILLER



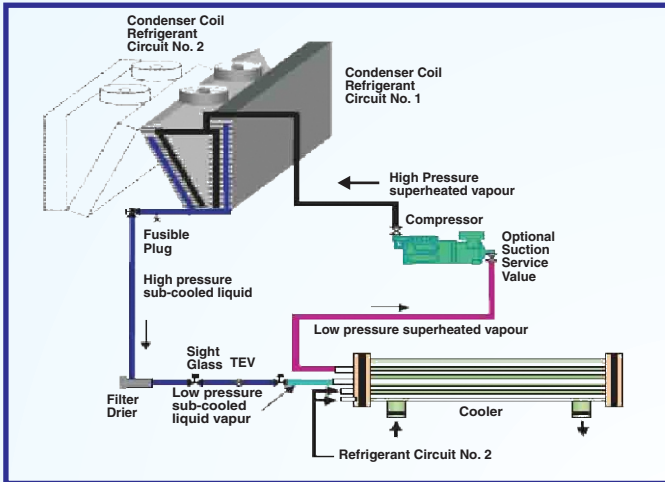
WATER - COOLED CHILLER



Water chillers can be either water cooled or air - cooled. Water - cooled chillers incorporate the use of cooling towers which improve the chillers' thermodynamic effectiveness as compared to air-cooled chillers. This is due to heat rejection at or near the air's wet-bulb temperature rather than the higher, sometimes much higher, dry - bulb temperature.

Evaporative cooled chillers offer efficiencies better than air cooled, but not lower than water cooled ones.

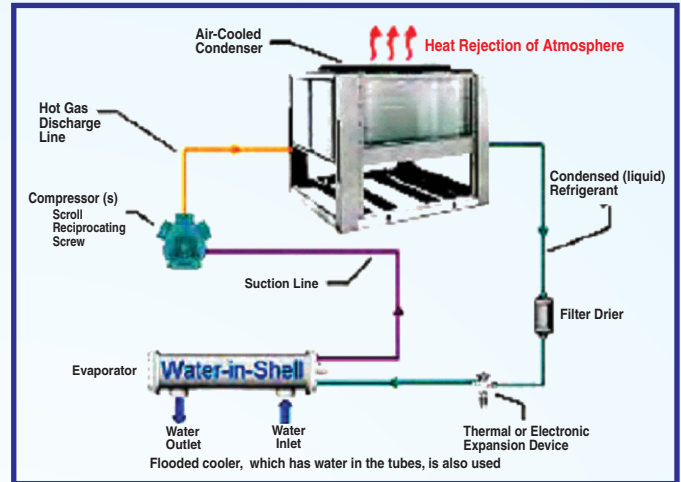
Water cooled chillers are typically intended for indoor installation and operation, and are cooled by a separate condenser water loop and connected to outdoor cooling towers to expel heat to the atmosphere



Refrigeration Cycle for Air - Cooled Chiller

In the air-cooled chiller refrigeration cycle, water enters the evaporator (also known as the cooler) and is cooled by the colder refrigerant flowing through the other circuit inside the evaporator. The chilled water is pumped from the chiller to the building coils to provide cooling. In the evaporator, the chilled water cools the building or process load and the cycle is completed when warmer water flows back to the evaporator. A mixture of cold liquid refrigerant and flash gas passes through the evaporator circuit opposite the water to be chilled.

The refrigerant in the evaporator absorbs heat from the warmer return water, evaporates to a vapor, and finally exits the evaporator as a superheated vapor. The superheated refrigerant vapor then enters the suction inlet of the compressor. In the compressor, the refrigerant is compressed, raising its pressure and temperature. High pressure and temperature refrigerant gas exits the compressor, passes through the discharge line and enters the condenser. While in the air-cooled condenser coil, the hot gas condenses to liquid inside the tubes as it gives up heat to the cooler outside air being drawn across the condenser coil by the condenser fans.



The condensed liquid refrigerant then leaves the condenser and enters the expansion device. As the refrigerant passes through the expansion device, its pressure and temperature is decreased to the point that some of the liquid flashes to vapor. The expansion device controls the amount of flashing in order to maintain a certain superheat to ensure no liquid droplets enter into the compressor suction. After leaving the expansion device, the refrigerant enters the evaporator and the cycle is repeated. Air cooled chillers are available in packaged sizes ranging up to approximately 500 TR/ 1758 kW

Water Cooled Chillers

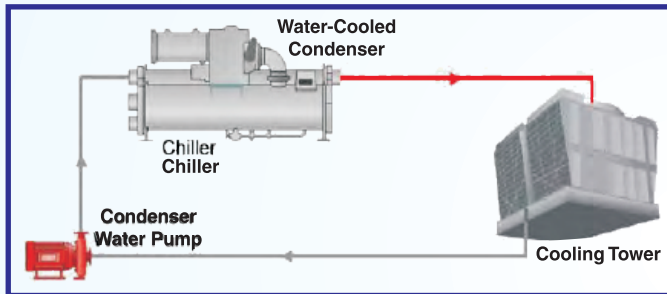
A typical water-cooled chiller uses recirculating condenser water from a cooling tower to condense the refrigerant. Cost and efficiency are the important factors when considering air or water-cooled chillers.

Chilled-water systems with air-cooled chillers typically have lower installed and maintenance costs than water-cooled because a condenser water system using a cooling tower is not required. A condenser water pump and chemical treatment for the condenser water loop adds to the maintenance required with a water-cooled system.

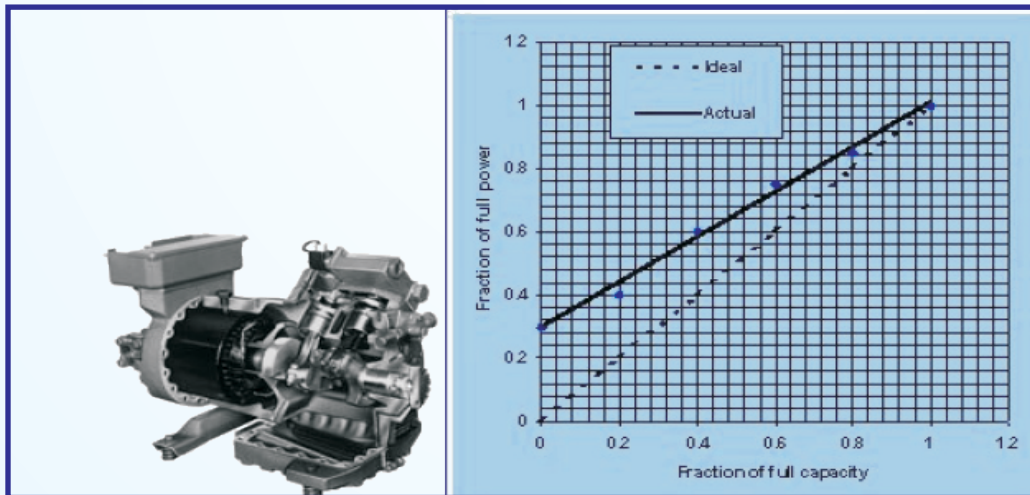
However, water-cooled chillers have higher efficiency and therefore lower operational costs. Air-cooled chillers are chosen when it is impractical to use a cooling tower, such as when little water is available or water is highly corrosive.

The refrigerant condensing temperature in an air-cooled chiller is dependent on the ambient dry-bulb temperature. In a water-cooled chiller, refrigerant condensing temperature is dependent upon the entering condenser water temperature (and flow rate), which is a function of the ambient wet-bulb temperature.

Since the wet-bulb temperature is always lower than the dry-bulb temperature, the refrigerant condensing temperature (and pressure) in a water-cooled chiller is often significantly lower than in an air-cooled chiller. This is why water-cooled chillers are more efficient. Water cooled chillers are typically available up to 3000 TR / 10,550 kW with limited custom designs available up to 10,000 TR / 35,168 kW



RECIPROCATING COMPRESSOR



In a reciprocating compressor, the refrigerant vapor is compressed by movement of the piston in a cylinder. Reciprocating compressors are commonly used up to single machine capacities of 250 TR / 879 kW. In the case of small machines, the arrangement may be cyclic on/off control based on temperature sensing.

However, in larger machines, as frequent starts and stops of motors are not permitted, other methods of capacity control are adopted. In reciprocating compressors with multiple cylinders, cylinders are selectively loaded or unloaded, based on set pressures (reflecting the temperatures); the variation in power with cylinder unloading.

Unloading implies that the suction valve is kept open so that the vapor, taken in during the suction stroke, returns back through the suction valves itself during the discharge stroke. Reciprocating compressors cannot tolerate liquid slugging, which can happen when the evaporator load is less and the superheat controlled expansion valve is unable to regulate the flow of refrigerant correctly, resulting in excess liquid refrigerant entering the evaporator and getting sucked into the compressor. Liquid slugging can cause serious damage to the compressor.

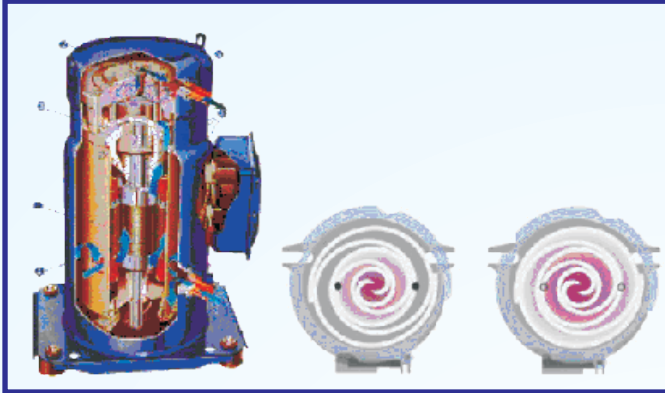
Reciprocating chillers offer several advantages. Compared with other types of chillers, their initial cost is low for units of 100 TR / 352 kW or less. Reciprocating chillers have a higher condensing temperature than other chillers, making them more suited for applications where air-cooled condensers must be used. It is easy to closely match the capacity of the chiller to the building load by installing multiple machines.

Multiple machines also allow the facility manager to stage operation for part-load conditions, increasing operating efficiency.

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.

SCROLL



In the Scroll compressor, the main components are two involute scrolls that intermesh. The top scroll, which contains the gas discharge port, is fixed and the bottom scroll orbits.

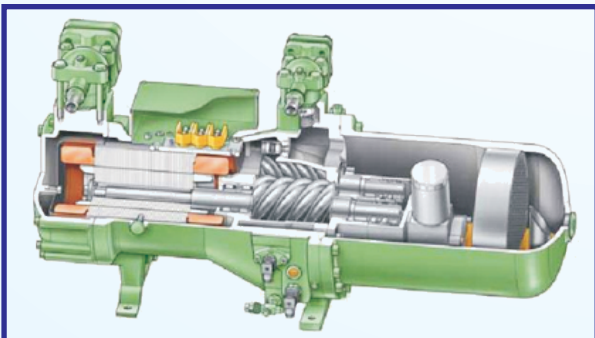
The two scrolls are maintained with a fixed annular phase relation (180°) by an anti-rotation device.

As the bottom scroll orbits within the other, crescent shape gas pockets are formed, their volumes are reduced until they vanish at the center of the scroll. Suction, compression and discharge are simultaneously performed in a continuous sequence by the orbiting motion of the scroll.

Scroll compressors are available for capacities up to 30 TR / 105 kW; multiple compressors are used to build larger packages. The capacity control of Scroll compressors is by cyclic on/ off control. Some new Scroll designs have the facility to operate at 100% and 67%. Scroll compressors can tolerate some liquid slugging and particulate contamination. Scrolls can tolerate high discharge temperatures and pressures.

Screw

In a screw compressor, there is male rotor with lobes and female rotor with gullies.



Compact semi hermetic twin screw compressors: The main screw (male, with five lobes) is driven directly by the electric motor, while the secondary screw (female with six vanes) is driven by the primary one.

The intrinsic volumetric ratio is precisely planed to be applied in the field of air-conditioning with ecological refrigerant R-134a. The screws are made from steel alloy and the axial bearings are in tandem configuration for greater sturdiness.

The seal is guaranteed by extremely accurate tolerances in the machining of all moving parts and by the specific circulation of oil between the screws.

Continuous modulation of cooling capacity (Stepless) with oil control dynamic. The free flow lubrication system resulting from pressure differences, is equipped with a highly efficient separator, level indicator and oil filter (replaceable). An oil heater prevents excessive dilution of the oil by the refrigerant, and is automatically activated at all stages where the compressor is switched off.

The asynchronous three-phase two pole motor is suction gas cooled, reduced load start of the star delta type or Part Winding (according the compressor's size)

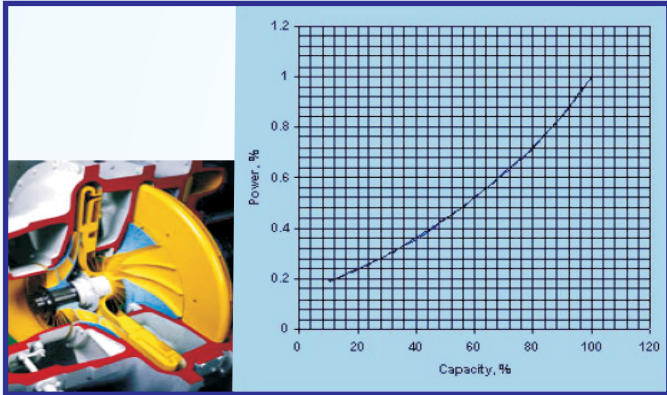
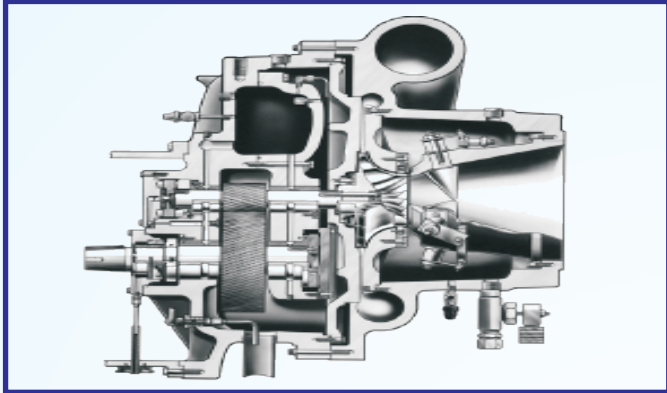
Fully protected electronic module, with safety sensor for monitoring discharge temperature, sensors for monitoring maximum temperature of the windings, device to monitor the motor rotation direction and device to monitor absence of phase.

Incorporated silencer non return valve and shut-off valve on the compressor discharge.

Filter on the suction line, at the inlet to the compressor.

Centrifugal :

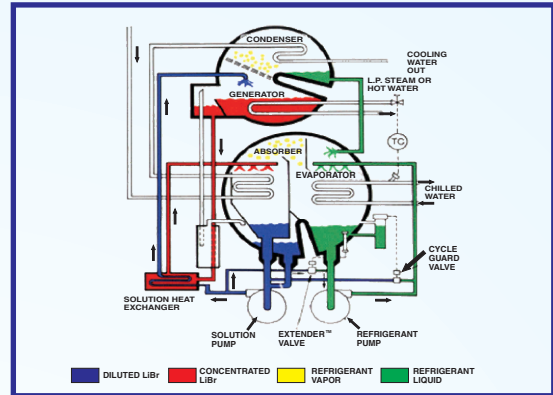
In the Centrifugal compressor , large volumes of vapor are centrifugally accelerated to high velocity and this velocity energy is converted to pressure.



The speed of the centrifugal compressor goes very high at around **20,000 rpm**. These machines are manufactured in the range of **35 TR/ 123 kW** to **10,000 TR / 35168 kW** capacity. Centrifugals are generally used beyond **150 TR / 527 kW** single machine capacity. In centrifugal compressors, capacity control is usually by inlet guide vanes at the suction. Capacity control in the range of **10% to 100%** is possible. The partial load operation of all compressors is inefficient compared to full load operation as the power does not drop in proportion to the drop in capacity.

Capacity control for all types of compressors can be done very efficiently by varying the speed of the compressor. The permitted range of speed variation will vary depending on the compressor type and the lubrication arrangement. Centrifugal chillers typically use Variable Speed drives to have very high efficiency at part load condition and in off design lift conditions.

ABSORPTION CHILLERS



The energy source for Absorption Chillers is heat provided by steam, hot water or fuel burner. In absorption chillers the compressor and motor of the Vapor- Compression Cycle are replaced by two heat exchanger (Generator and absorber) and a solution pump.

The refrigerant in these systems commonly is water and the absorbent usually is Lithium Bromide. Though Chloride also was common in the past and still used infrequently.

Small Absorption Chillers may use an alternative fluid pair, such as ammonia as refrigerant and water as the absorbent.

The Principle of Absorption cooling

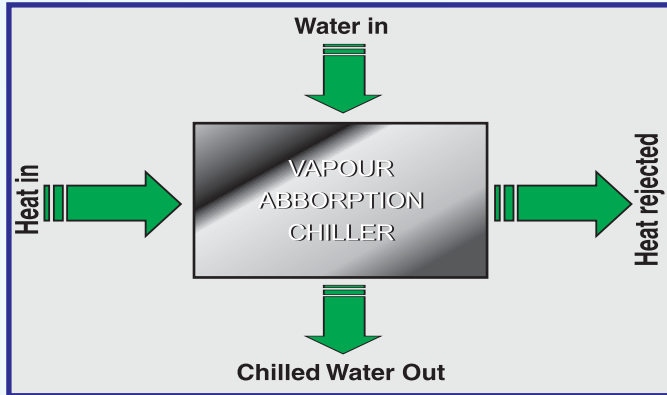
The two basic principles on which all Air conditioning and Refrigeration plants operate are:

1. When a liquid evaporates, it absorbs heat and when it condenses it gives up that heat. This heat is called Latent Heat of evaporation and Latent Heat of condensation.
2. Boiling point of liquid increases as pressure increases, decreases if pressure decreases.

Example : At Atmospheric Pressure (**760 mm of Hg.**) Water boils at **100°C/ 212 °F** and at **6 mm of Hg.** It boils at **3.7°C/ 38.66 °F**

The absorption cycle is a process by which refrigeration effect is produced through the use of two fluids and some quantity of heat inputs, rather than electrical input as in the more familiar vapor compression cycle.

Absorption chillers work in primarily the same manner as conventional compressor based systems with the exception that the compressor is replaced by an absorber, a solution pump and a generator.



The absorption cooling works on the affinity of some pairs of chemical to dissolve in one another. For example Lithium Bromide solution has affinity towards water. Water has affinity towards Ammonia. This affinity depends on two factors - temperature and concentration of the solution.

Affinity $\propto$ Concentration and Affinity $\propto 1/\text{Temperature}$.

How an absorption machine works

In the Vapor Absorption chillers, a low pressure (vacuum) is maintained in the evaporator. At this pressure the refrigerant boils at very low temperature

This boiling causes the refrigerant to absorb heat from the medium being cooled, thus lowering the temperature.

On absorbing the heat the refrigerant gets vaporized. The refrigerant vapor thus formed tend to increase the pressure in the vessel. This in turn increase the boiling temperature and the desired cooling effect will not be obtained. So it is necessary to remove the refrigerant vapors from the vessel.

A liquid having affinity towards the refrigerant vapor is sprayed in the absorber which absorbs the vapor and maintains the low pressure in the shell. As the absorbent absorbs the refrigerant vapor, it becomes dilute and losses its capacity to further absorb refrigerant vapors.

To maintain continuous cycle it is essential that the absorbent is enriched to its original level of concentration and the refrigerant vapors are condensed back to the liquid. This is achieved by pumping the dilute solution continuously from absorber to the generator. In the generator the addition of heat boils off the refrigerant from the absorbent and the absorbent regains its original level of concentration. The re-concentrated absorbent returns to the absorber to resume the absorption process.

The refrigerant vapor released in the generator flows to the condenser. In the condenser cooling water is circulated through the coils, which picks up the heat carried by the refrigerant vapor and vapor condenses back to the liquid phase. The condensed liquid is returned back to the evaporator. Thus completing the Absorption Cycle.

Absorption chillers are identified by the number of heat input levels they employ (i.e., single-, double-, or triple effect), and whether they are direct-fired with a burning fuel or use steam or hot water as the heat energy source.

Single-effect absorption applications are limited typically to sites that can utilize waste heat in the form of hot water or steam as the energy source or where boilers must be run year-round such as in hospitals.

Other sites include co-generation systems where waste engine heat or steam is available. Double-effect machines can be driven by hot water or steam or can be direct-fired.

Double-effect absorption chillers can have primary-energy-based efficiencies that approach 60 to 65% of those of vapor-compression systems.

For example, double-effect absorption chillers can have a cooling coefficient of performance up to 1.5 based on source energy input. Electrical vapor-compression systems have a COP as high as 7.8, which must, in the case of thermal power plants, be multiplied by the heat-source to-electricity delivery efficiency of the power plant and distribution system - around 35% for heat-driven generators which are predominant.

3. Range of Chiller Capacities available.

Chiller Type	Capacity Range TR (kW)
Reciprocating Chillers	15 - 400 (52.75 - 1407)
Scroll Chillers	5 - 150 (17.6 - 527.5)
Screw Chillers	60 - 500 (211 - 1758)
Centrifugal Chillers	200 - 6000 (703 - 21,101)
Absorption	200 - 6000 (703 - 21,101)

4. Refrigerant used in various Chillers & phase out schedule.

Reciprocating chillers are produced in both water-cooled and air-cooled versions using DX evaporators. Air-cooled versions have increased market share in recent years. Most of the volume increase is moving to scroll and screw compressors. Reciprocating chiller markets are decreasing.

Prior to the advent of the Montreal Protocol, Reciprocating chillers were offered with **CFC-12** as the refrigerant.

Now most chillers employed **HCFC-22** as the refrigerant & **HFC-134a**. Some water cooled reciprocating chillers were manufactured with ammonia as the refrigerant, but the number of these units is very small compared to the number of chillers employing fluorocarbon refrigerants.

Scroll chillers are produced in both water-cooled and air-cooled versions using DX evaporators. Refrigerants offered include **HCFC-22**, **R-410A**, an **R-407C**. **R-407C** has been used as a transition refrigerant, especially in countries where HCFC-22 has been phased out by regulations in advance of the Montreal Protocol deadlines. R-407C continues to be offered in chillers from a number of manufacturers. New scroll chiller products are using R-410A.

Screw chillers using a higher pressure refrigerant, R-410A, also have been introduced recently, largely in Europe.

Screw chillers using ammonia as the refrigerant are available from some manufacturers. They are found primarily in northern European countries. The numbers produced are small compared to chillers employing **HCFC-22** or **HFC R134a**.

Centrifugal chillers are manufactured in the United States, Asia, and Europe. Prior to 1993, these chillers were offered with **CFC-11**, **CFC-113**, **CFC-12**, **CFC-114**, **R-500**, and **HCFC-22** refrigerants. Of these, **CFC-11** was by far the most common because it was the most efficient refrigerant for centrifugal chillers. With the implementation of the Montreal Protocol, production of chillers using CFCs or refrigerants containing CFCs (such as R-500) essentially ended in 1993 in developed countries. Centrifugal chillers using HCFC-22 rarely were produced after the late 1990s. The primary refrigerant alternative for CFC-11 is HCFC-123, and for CFC-12 and R-500 is HFC-134a. These refrigerants began to be used in centrifugal chillers in 1993 and continue to be used in new production chillers.

The acceptable refrigerants for new equipment purchase.

- R-123, an HCFC with a scheduled phase out date of 2020 in new equipment. It is only used in centrifugal chillers and only provided by one major manufacturer.
- R-134a, an HFC with no scheduled phase out date. Provided in equipment by all major manufacturers, it is used in centrifugal chillers, water-cooled screw chillers, and air-cooled positive displacement chillers.
- R-410a, an HFC with no scheduled phase out date. Provided in equipment by most major manufacturers, it is used in smaller positive-displacement chillers, packaged rooftop equipment and residential equipment.
- R-407C, an HFC with no schedule phase out date, provided in equipment by some major manufacturers, it is used in smaller air-cooled positive displacement chillers and packaged rooftop equipment.

- Ammonia and Propane refrigerants which are gaining acceptance in Europe is not being discussed here as the same is being contemplated that whether it can be put to commercial use at this stage or not due to flammable and toxic properties of Ammonia.

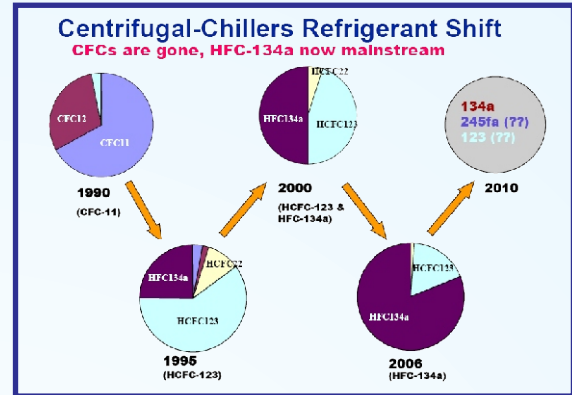
Two Environmental Challenges Today Stratospheric Ozone Depletion

Addressed by the Montreal Protocol, 1987, (191 countries) -Mandatory phase-out of ODS (CFCs & HCFCs for HVAC industry)

Global Climate Change

Addressed by Kyoto Protocol, 1997, (150 countries)

Limit greenhouse gas emission of developed countries (CO₂, CH₄, N₂O, HFC, SF₆, PFC).



5.Variable Speed Drive in Chillers

Variable Speed Drives are generally applied to:

Improve efficiency = lower operating costs

Improve system or process control capability

VSD use is increasing rapidly, due to reduced initial investment for VSD and better operating efficiency performance and improved reliability

The bottom line is better ROI

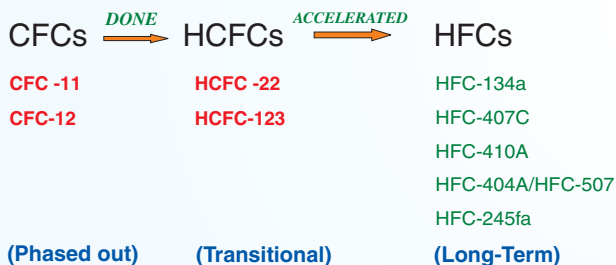
To determine system interactions, the fundamentals of chiller operation must be considered.

Typically, the chiller motors are the largest power consumer in the chiller plant.

$$\text{Compressor HP} = \frac{\text{Mass Flow}}{\text{Compressor/Cycle Efficiency}}$$

Application of VSDs to centrifugal chillers requires a control strategy that understands chiller and drive operations. With advanced microprocessor control technology, the integration of VSDs in the special efficient offerings is but a natural step. Typical ARI conditions are 44/54°F (7/12°C) chilled water and 85/95°F (30/35°C) condenser water temperatures. ARI also specifies Integrated Part Load Values (IPLV) which take into consideration the part load capacity operation of the chillers with varying entering condenser water temperatures. One such standard used for centrifugal chillers is **ARI Standard 550/590-2003**. Although, this standard provides a commonly used formula to calculate the operating costs for the centrifugal chiller during its life span, the operating characteristics may not be realistic for every application.

Shift of Refrigerants in last 15 years



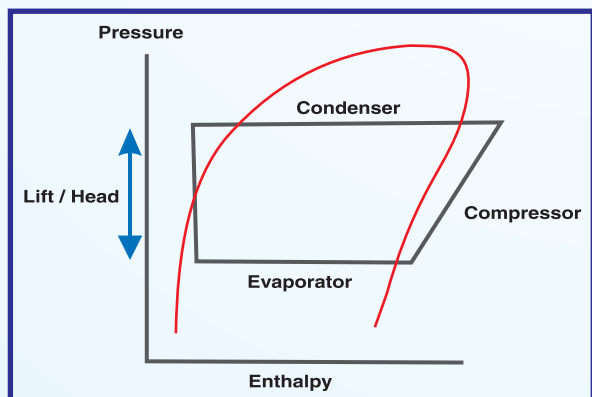
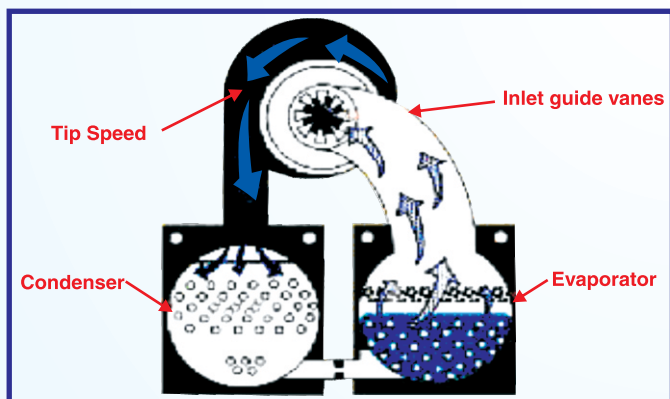
Montreal Protocol Requirements

1996	CFCs	
2020	HCFC-22	in new equipment
	HCFC-123	
2030	HCFC-22	production
	HCFC-123	

A centrifugal compressor performance relies on the impeller design tip speed, which is the tangential velocity of the refrigerant at the edge of the impeller wheel when it leaves the impeller, to increase the refrigerant pressure between evaporator and condenser.

This pressure difference created between the evaporator and condenser is called 'lift' or the 'head' that the compressor must create to move the refrigerant through its cycle.

This pressure difference created between the evaporator and condenser is called 'lift' or the 'head' that the compressor must create to move the refrigerant through its cycle. The head depends on many parameters such as chilled water and condenser water temperatures and also the fouling factors. Impeller speed is directly proportional to the head created. Obviously, greater the head, higher the energy input and hence higher impeller speeds. However, the head conditions may change with a change in load pattern and outside ambient conditions (reduced condenser water temperature). Constant speed drive in this case will over-accelerate the refrigerant as it leaves the impeller, resulting in a waste of input energy. VSDs reduce the compressor speed as the head drops and move the compressor into a higher efficiency region in the compressor map, often allowing the compressor to operate more efficiently than at the full load condition.



Design Advantage

The VSD needs information to work. VSD has to continuously monitor several operating conditions such as chilled water temperature, chilled water set point, refrigerant pressures, prerotation vane position and the actual motor speed. This information is then fed to a microprocessor that determines the most efficient way to operate. It optimizes both motor speed and the pre-rotation vane position and changes the frequency of the power input to the motor, in order to consume the least amount of energy.

Chiller Plant Optimizer

The Chiller Plant Optimizer proven in high tech industrial application is a low cost control method that will pay back..

The patented application technology uses a unique and fool proof method to accurately apply several proven control strategies such as condenser water reset, & cooling tower relief to save energy and operating costs.

Compare this stand alone control technology with the Hartman Loop and others that offer more complicated installations for cost, ease of use and across the board utility.

How It Works

The Chiller Plant Optimizer uses a secure and patented method to control condenser water temperature. Plus additional savings are achieved by limiting cooling tower overloading and better control of condenser water flow and pressure.

There is a simple experiment that we can try that will help to explain the kind of savings we can achieve with the Chiller Plant Optimizer.

On a moderately warm day, lower the condenser water temperature set point. It will take a few minutes for the cooling tower to lower the temperature, during this time take notes and compare the condenser water temperature to the chiller load amps.

If the load amps don't begin to drop off with condenser water temperature then we will have to reset the condenser water temperature back to the original set point and try the experiment again on a cooler day.

If the chiller begins to surge then we must also stop the experiment.

Finally after a short period of time with the lowered set point, return the condenser water set point back to its design operating point.

The Chiller Plant Optimizer maintains a safe condenser water set point that varies with the chiller operation and therefore avoids the potential problems that can occur with a dangerous and low set point.

A Patented Application Method

The Chiller Plant Optimizer uses proven strategies to reduce energy usage, Condenser Water Reset, Cooling Tower Relief, and Variable Flow.

In the past and even today, these strategies are rarely used because; (1) They are difficult to apply using automatic controls, and (2) they can cause problems with capacity, and refrigerant stacking if not safely applied.

Only recently have systems been developed that can safely apply these proven strategies. Each of these different methods is patented.

The Chiller Plant Optimizer is different from the other systems in that it is designed to operate independently as a stand-alone control, or integrated with an automatic control system.

The Chiller Plant Optimizer also uses a unique method to determine the actively controlled condenser water set point. This method is highly accurate and takes into account the chiller's current operating conditions, its operating load, and its efficiency of operation before determining a new set point and controlling to this new set point.

Not only will we save energy and real money that is applied to our bottom line, but the active control improves compressor operation by reducing compressor loading and internal forces by allowing chiller operation with reduce head pressure.

Variable Condenser Water Flow

The chiller flow rate is established by the manufacturer to meet the maximum demand of the chiller and is also based on the projected performance of a cooling tower.

Since the chiller and cooling tower manufacturers are different, the design criteria becomes somewhat arbitrary. A typical rule of thumb for chiller cooling is 3 gpm(11.35 lit/min) / ton rated. This is not a fast rule and sometimes where the cooling tower size is limited the chiller design is re-configured to operate at 2 gpm(7.57 lit/min) / ton.

ASHRAE recommends a minimum condenser water flow velocity of 3.3 ft/sec (1meter/sec) to maintain turbulent velocity and prevent formation of deposits in the condenser. This 3.3 ft/sec (1meter/sec) is well above the low the 6 to 8 ft/sec (1.83 to 2.44 meter/sec) encountered in today's chiller designs.

Heat exchange calculations show us that the main factor in condensing the hot refrigerant gases is a large surface area requirement for the copper tubes found in most condensers. The water velocity at the typical design flow rates is a small and nearly negligible factor in the heat transfer equation. The factor for condensing efficiency in a chiller is the number and size of tubes and not the water flow velocity.

Condenser Water Temperature Reset

If our facility uses water cooled chillers it is unlikely that it is using the optimizing strategy known as Condenser Water Temperature Reset. For those few sites that employ some form of this strategy, the method of application in use limits the useful range of control and does not take advantage of all of the potential savings.

This strategy simply means that the cold water temperature leaving the cooling tower basin is controlled to a set point where the set point is allowed to decrease with the changing requirements of the chiller. It is no secret that refrigeration machines using common centrifugal or reciprocating compressors are more efficient at lower condensing temperatures. The conundrum has always been that lowering the condensing temperature also reduces the chiller's capacity.

The challenge has been to develop a control method that can adequately match the requirements of the chiller without limiting its ability to develop full capacity when ever needed. The use of this technique was relegated to a manual set-back , if used at all until recently. Several patents have been recently granted for methods that can reliably achieve provide Condenser Water Temperature Reset on an ongoing basis.

If we want to whet our appetite on the potential savings just consider this. Some very efficient chillers have a full load rating of **0.6 kW/ton** with entering water temperatures of **85°F(30°C)**. That same chiller can have a part load rating of **0.3 kW/ton** with **65°F(18°C)** entering water temperature.

There is a trade-off. In order to achieve the lower temperatures the cooling tower fan will run longer and harder. Therefore, it is feasible for the cooling tower fan to chew up nearly half of the energy savings realized by the chiller.

There is a cold water temperature set point that will significantly reduce the fan energy load and still obtain significant savings for the entire plant. The three technologies address this control solution in different but still effective ways. They will also apply a strategy known here as Cooling Tower Temperature Relief, to limit the cooling tower fan energy use.

Cooling Tower Temperature Relief

Cooling Tower Temperature Relief is a difficult strategy to explain and prove. But we will use an analogy and does not rely on detail and difficult to follow spread sheets and calculations. Just know that the developer of the Chiller Plant Optimizer has developed a method of calculating these savings which can be laid out in a spreadsheet format.

Consider a single chiller system of a given size operating at part load, say **75%**. Then compare it to a smaller chiller system operating at the same load. Say the first example is a **1200 Ton(4220kW)** chiller (system) operating at **900 Tons(3165kW)** and the second example is a **1000 Ton(3517 kW)** plant operating at **900 Tons(3165kW)**. Both systems are then operating with the same outside conditions.

If the smaller chiller system was designed using the same criteria as the larger system, it will have a smaller cooling tower with a smaller fan motor. The fan energy use by the smaller system will be less than the larger system.

Now, since it is impractical to switch to a smaller cooling tower or smaller fan motor. Cooling Tower Temperature Relief is simply a control method that insures a similar action by limiting the maximum speed of the cooling tower fan motor.

The standard control method for cooling towers uses a temperature sensor for the cold water (basin temperature) and controls the fan to achieve this temperature. A control method that provides for Cooling Tower Temperature Relief requires additional information than cold water temperature. The control may reset the cold water temperature set point, or use some other control strategy, that results in a different and possibly slightly higher cold water temperature than the primary (or full load design) cold water temperature.

As an independent strategy the savings are limited for Cooling Tower Temperature Relief, and must be applied very judiciously. But as a strategy combined with Condenser Water Temperature Reset it is a very effective tool for energy optimization.

Performance Monitoring for Chiller Plants

The HVAC industry has been loath to provide and install meaningful tools to monitor the performance of chiller plants in a meaningful manner. When it does the results are so limited that their usefulness is problematic. We propose a systematic and methodical method that can be used to compare results with other chiller plants providing similar service and even with some not so similar.

Measure the output of the chiller plant, don't make assumptions from chiller data. That means one measures the actual BTU's of cooling that is produced, preferably as near the chillers as possible.

Measure real power consumed, don't use amperage and assume that definitive results can be calculated. Real power means Kw including power factor, not KVA.

Only include the chiller, condenser pumps, and cooling towers. In this manner the long term results will be more meaningful from year to year and sensible comparisons can be made for plant to plant.

Provide an executive report on a periodic basis that is easy to read and can be analyzed by management in 60 seconds or less.

This means recording data on a continuous basis so that true averages for various operating periods, night vs day and weekend vs week day can be reported, if necessary. Produce a single meaningful number, i.e. say it in kW/Ton.

6. Power Consumption in Chillers, IPLV & NPLV

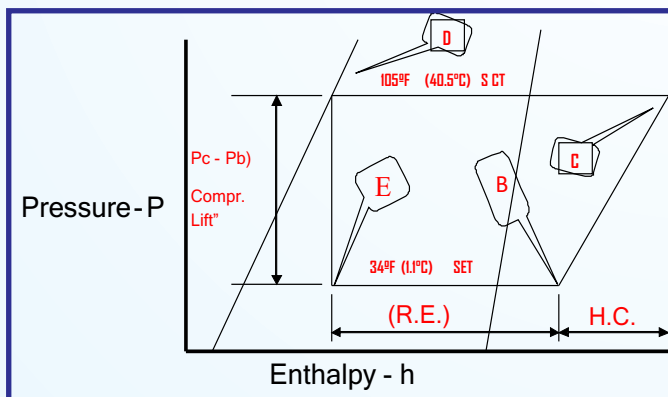
Power Consumption in chillers is defined as IKW/TR i.e Input KW /TR. Input KW is the power consumption at the inlet of Chiller Motor.

The power consumed by the compressor in a Refrigeration Cycle and the ultimate chiller size is a function of three items:

1. The refrigerant mass flow being pumped by the compressor.
2. The pressure rise across which the compressor must operate ($P_c - P_b$). This referred to as the compression ratio or compressor lift.
3. The actual efficiency of the compressor.

In today's market place, the cost and availability of energy have become important considerations in the purchase of a water chiller. The era of cheap energy has passed. Smaller sized equipment is also being demanded to meet the rising costs of building space.

Therefore, any device or means that improves any of the above three items will lower compressor energy and reduce chiller size. Let's take a look at some of the common ways manufacturers have used to make chillers smaller and more efficient. We will start with reducing the pressure rise across the compressor.



Refrigeration Effect (R.E.)

- Heat of Compression (H.C.) (Compressor Efficiency)
- Pressure Rise ($P_c - P_b$)
- The power consumed by the compressor is a function of three items:

Refrigerant mass flow through the compressor in lb/min (R.E.)

- ◆ Pressure rise ("lift") across the compressor ($p_c - p_b$)
- ◆ Compressor efficiency (heat of compression)

- Any device which improves any of the above three items, lowers chiller energy and/or size.

- Let's look at reducing compressor "lift"

Reducing Chiller Lift

Compressor Lift:

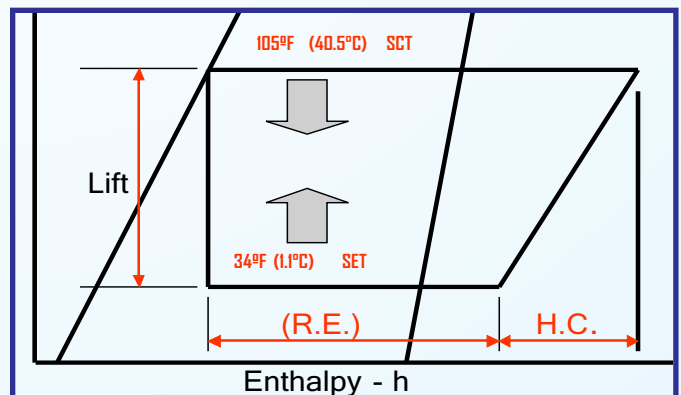
Compressor lift can be defined as the pressure produced at the base of a column of refrigerant that would be equivalent to the pressure rise across the compressor. Lift is very much like the concept of feet of water when expressing water pressure.

Compressor lift can be reduced by altering two of the basic refrigeration cycle variables:

1. Increasing the Saturated Evaporator Temperature (SET) for a given chiller load.
2. Lower in the Saturated Condensing Temperature (SCT) for a given chiller load.

Chiller manufacturers employ mechanical devices and sophisticated control systems to improve the cycle in both of these areas.

Let's begin our look into chiller power improvement by taking a look at devices that increase the SET for a given load on the evaporator.



Ways to reduce compressor lift :

- ❖ Increase the Saturated Evaporator Temperature (SET)
- ❖ Decrease the Saturated Condensing Temperature (SCT)

We will begin by looking at increasing the SET

The ability to increase the Saturated Evaporator Temperature of a chiller is directly related to the available options provided by the manufacture and the application options chosen by the designer.

All methods are related to the underlying heat transfer process taking place. We will take a close look at the basic evaporator heat transfer process and how it is impacted by the variables.

Increasing Set Point

Manufacturer options and application choices.
Increasing the heat transfer coefficient - “U”

- ❖ Reducing water film resistance
- ❖ Reducing water fouling resistance
- ❖ Reducing metal film resistance
- ❖ Reducing refrigerant film resistance

Increasing heat exchanger tube surface area - A

- ❖ Increase tube fins per inch i.e. Heat Transfer Area.
- ❖ Increase number of tubes for a heat exchanger frame size.
- ❖ Increase heat exchanger frame size
- ❖ Increase heat exchanger length

IPLV & NPLV in Chillers

The Air Conditioning and Refrigeration Institute (ARI) Standard 550/590-2003 established the Integrated Part Load Value (IPLV) to “provide a single number part load performance number for water chilling products. The equation was derived to provide a representation of the average part load efficiency for a single chiller only.” (ARI Standard 550/590-2003) ARI also established the Non-Standard Part Load Value (NPLV) for chillers that are optimized at design conditions other than what is described in the standard.

Many people have used the standard's IPLV /NPLV value as an indicator of chiller operational cost. This was not the intent for the IPLV or NPLV value

The IPLV number is calculated as a weighted average of four load points. The weighting is based on a “mix” of operating-hour.

Chiller Load	IPLV/ NPLV* Weighting	Condenser Water Temperature
100 %	0.01	85°F
75%	0.42	75°F
50%	0.45	65°F
25%	0.12	65°F

*NPLV uses the same equation weighting as IPLV, but the chiller is optimized at conditions other than standard design conditions described in ARI Standard 550/590-2003.

The IPLV is then calculated with the following formula:

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

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

ARI

EUROVENT

<u>IPLV/NPLV</u> (INTEGRATED PART LOAD VALUE /NON STANDARD PART LOAD VALUE) Formula for Calculation of IPLV/NPLV	<u>ESEER</u> (EUROPEAN SEASONAL ENERGY EFFICIENCY RATIO) Formula for Calculation of ESEER
$\frac{1}{(0.01/A)+(0.42/B)+(0.45/C)+(0.12/D)}$	$3\% \text{ EER(A)} + 33\% \text{ EER(B)} + 41\% \text{ EER(C)} + 23\% \text{ EER(D)}$
Where, A : IKW/TR at 100% Load (1% of time) B : IKW/TR at 75% Load (42% of time) C : IKW/TR at 50% Load (45% of time) D : IKW/TR at 25% Load (12% of time)	Where, A : EER at 100% Load (3% of time) B : EER at 75% Load (33% of time) C : EER at 50% Load (41% of time) D : EER at 25% Load (23% of time)

In fact, because the IPLV/NPLV weighting minimizes the effects of full load, we are ignoring the effects of full load energy requirements and the cost of operating there.

7. Oil Less Chiller

OIL LESS CENTRIFUGAL CHILLERS REDUCES MAINTENANCE

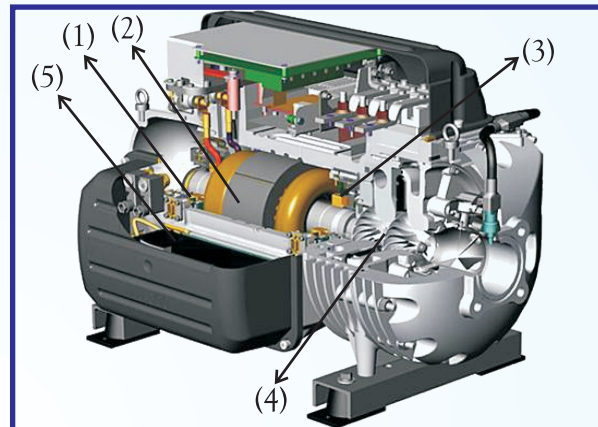
Advanced Compressor Technology having magnetic bearing, permanent magnet synchronous motor technology used in the chillers offers many benefits.

Totally Oil-Free Operation: Friction loss and the oil management and controls associated with conventional oil lubricated bearings are totally eliminated. Magnetic bearing technology enables outstanding energy efficiency and reliable, long life frictionless operation. Compressor's moving part rotor shaft and impellers is levitated during rotation by a digitally controlled magnetic bearing system consisting of two radial and one axial magnetic bearing. Position sensors at each magnetic bearing provide real time feedback to the bearing control system.

Variable Frequency Drives for Ultra-Low IPLV : One of the best energy performance advantages of large central plant type variable speed centrifugal chiller compressors are now in the mainstream, applications through the use of high-speed, centrifugal compression with integral variable-speed drive.

The compressor speed reduces as the condensing temperature and or cooling load reduces, optimizing energy performance through the entire operating range. Movable inlet guide vanes redirect gas flow into the first stage impeller during very low loads, after the compressor has reached minimum speed.

Chillers having digital control electronics to proactively manage unit operation, while providing control of external circulating pumps and the cooling tower.



1. Magnetic Bearings and Bearing Sensors
2. Permanent Magnet Synchronous Motor
3. Touchdown Bearings
4. Shaft and Impellers
5. Compressor Cooling

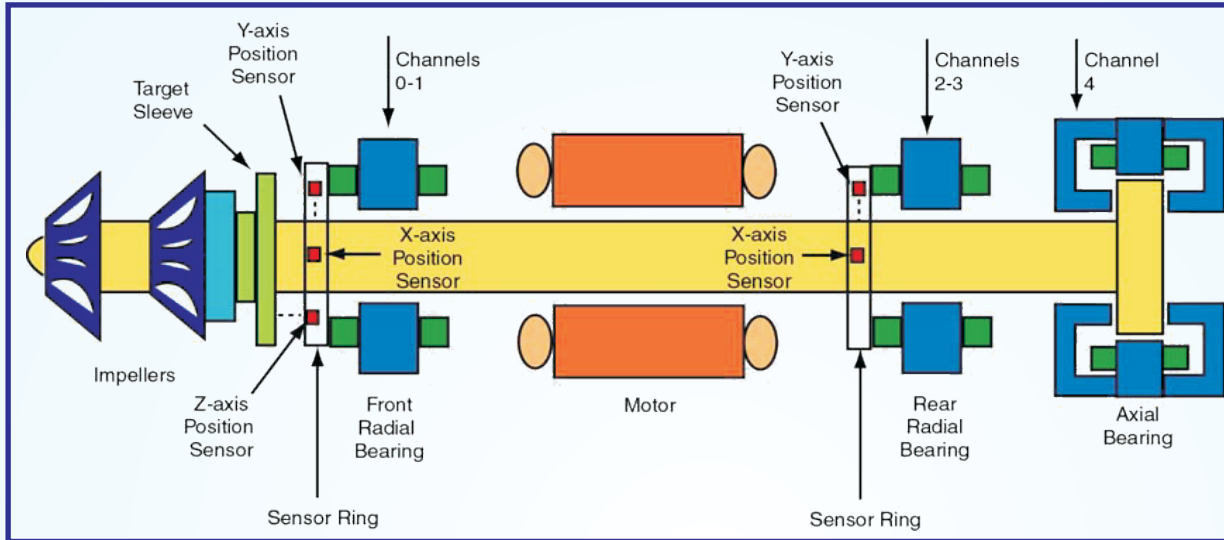
Easy to work with this compressor :-

- ❖ Frictionless magnetic bearing design needs no oil management system. No oil coating on the heat transfer surfaces, a gain in heat exchanger efficiency can be realized.
- ❖ Compressor sound level much less with no structure borne vibration, the need for expensive attenuation accessories not required.
- ❖ Compressor weight is much less than the weight of normal compressors and approximately 50% smaller, so it can mount on lighter and smaller frames.
- ❖ Compressor is optimized for **HFC-134a**, the positive pressure, environmentally and operator safe refrigerant that is the first choice in the industry.

- ❖ In case of a power failure, the compressor motor acts as a generator, providing power for the bearing control system during coast down. It also has a system to gently de-levitate the shaft and very low starting currents.

A multiple chiller installation commonly provides at least a 10 percent increase in efficiency annually. Multiple chillers also provide facilities with backup in the event of a chiller failure.

COMPRESSOR MAJOR RUNNING COMPONENTS



Another change that has improved the operating efficiency of chiller plants is the move from single-chiller installations to the use of multiple chillers. Single-chiller installations typically carry lower first costs and require less space, but two serious drawbacks exist. First, no level of backup exists. A chiller failure can mean a loss of chilled water to the entire facility, often for an extended period of time.

Single-chiller plants also must have the capacity to handle the facility's peak design load. Since this peak load typically occurs for only a few hours each year, the chiller will spend the vast majority of its operating time under part-load conditions.

But chillers are most efficient when operating at or near full load. So as the load decreases in this scenario, so does the operating efficiency of the chiller. On a seasonal basis, the overall efficiency of the chiller plant will be well below the peak efficiency of the chiller.

By contrast, multiple chillers allow managers to pick and choose the chillers to operate, based on the cooling load. As the load changes, operators can bring more chillers online or take them offline as needed to maximize operating efficiency.

8. Multiple Chiller Controls

“Because IPLV represents an average single chiller application it may not be representative of a particular job installation. It is best to use a comprehensive analysis that reflects the actual weather data, building load characteristics, number of chillers, operational hours, economizer capabilities, and energy drawn from auxiliaries such as pumps and cooling towers, when calculating the overall chiller plant efficiency.”

It is estimated that 86% of chillers are installed in some type of multiple chiller application. It is therefore important to understand how typical chiller systems will operate as a whole, particularly since many engineers will only assume the evaluation of a single machine, even though there are multiple machines in the system. Chillers will operate very differently when placed in a system, as opposed to a single chiller application. This will explain how typical multiple chiller systems operate and how they are controlled.

When using multiple chillers to maintain building load conditions, proper controls are critical to meet constantly changing building requirements. The first step is to determine the type of chilled water system needed to meet the building load requirements. A chilled water control system should be provided, to both supervise and optimize the operation of the chilled water plant. All elements of the plant must be considered, e.g., cooling towers, pumps, variable frequency drives (VFDs), heat exchangers and the control valves used on the building's air handlers.

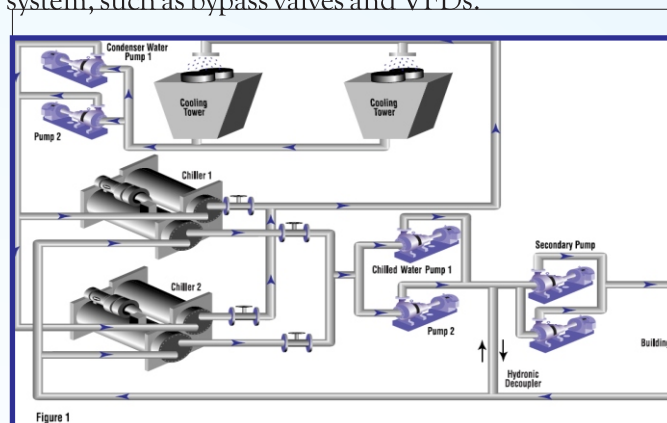
Two Chillers Equal Tonnage

Let's examine an application using two chillers of equal tonnage. In this application, each machine is designed, when it is operating at 100% capacity, to maintain 50% of the total building load. There is a primary and a secondary chilled water loop with a hydronic decoupler. The secondary chilled water pumps are equipped with VFDs, to maintain a differential pressure across the supply and return of the system; and two-way control valves are used on the load side. Figure 1 shows a diagram of this system.

When the building load dictates a need for cooling, the plant control first enables one chiller, referred to as the lead chiller. This chiller has a pull down timer program to allow it to cool the supply water before starting the second or lag machine. The lead chiller continues to ramp up to meet the requirements of the load. As it reaches its full capacity, and building load is approximately 50% (based on system supply water temperature, return water temperature, delta temperature or kW%), the chilled water plant control system ramps the lead chiller down and enables the lag chiller. Ramping down the lead chiller before starting the lag machine helps to avoid demand charges that can occur when operating one chiller at full capacity while enabling another. From this point on, if the building load increases, the two chillers ramp up together as a system, to meet the building demand.

A load prediction calculation is incorporated into the plant control to determine when the lag chiller can be disabled. This control routine calculates a reduced cooling capacity kW set point based on present chiller tonnage, capacity of the lag chiller to be stopped, and adjustable dead band to prevent short cycling.

In addition to the chillers themselves, the chilled water plant control system must also control the chilled water pumps (primary and secondary), condenser water pumps, cooling tower fans, and any other devices in the system, such as bypass valves and VFDs.



Typical control of the primary chilled water pumps (see Figure 1) is as follows: the lead chilled water pump is started when a call for cooling is received. As the building load increases and there is an additional call for cooling, the lag pump is enabled. It is also common practice to have a backup chilled water pump, in case either the lead or the lag pump fails.

Looking at Figure 1, let's assume the building load has two way valves on the cooling coils. In order to maintain an acceptable differential pressure of the secondary water system, there are variable speed drives for each secondary water pump. The speed of the pumps are controlled to maintain a system differential water pressure as sensed by transmitter(s) located at the end of the loop. When the system is in operation the lead pump will be enabled.

This pump will ramp up to its full speed as dictated by the system. When this pump reaches its full output speed, after a time delay, the lag pump will be enabled. The lag pump will ramp up and follow the lead pump to maintain the system differential.

Three Chillers Two Of Equal Tonnage, One Of Less Tonnage

Next, an application using two chillers of equal tonnage and a third chiller of less tonnage. The two larger machines are each sized to handle 40% of the total building load. The third, smaller machine is sized for 20% of the building load, and is used as the lead chiller (see Figure 2).

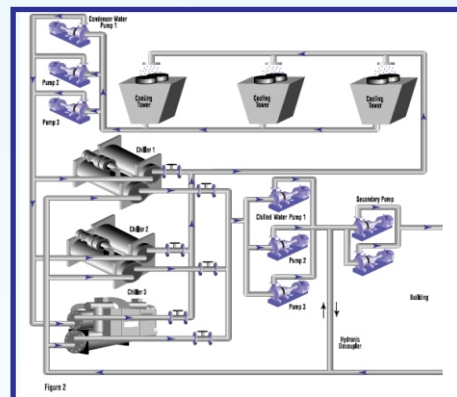
When the building load need for cooling, the smallest tonnage chiller is enabled. As the building load increases above 20% of total building load, the first lag machine is enabled. As this machine ramps up, the lead machine (smallest tonnage) is disabled. If the load increases to greater than 40% of total building load, the other lag machine is then enabled. The lead machine ramps down and ramps back up in conjunction with the lag machine(s). If the building load increases to greater than 80% of total building load, the lead machine is re-enabled to meet the building load requirements.

Condenser Water Systems and Controls

The condenser water system differs from the evaporator (or, cooler) system in a number of ways. The condenser is an open-loop system, while the evaporator is closed-loop. In addition, the condenser system is typically constant flow, while the cooler loop may be variable flow.

Typically, the condenser system functions as follows: the chiller requests that the condenser pump and cooling tower become active. If the chiller is equipped with an isolation valve, the position of the valve (open/closed) needs to be verified before starting the pump.

Once flow has been established, and verified by a differential pressure (or flow) switch, and all other safety conditions are satisfied, the chiller will start. As the chiller loads up, the heat of the refrigeration cycle will be rejected to the cooling tower. As the water continues to increase in temperature, the cooling tower fans are cycled on, to maintain the desired temperature set point.



As the condenser water temperature is reduced, the chiller has less work to perform and therefore, energy usage is reduced, increasing efficiency. A general rule is: for every one degree drop in condenser water temperature, chiller efficiency will increase 2%. When decreasing condenser water temperature, minimum “lift” must be maintained. Lift is the amount of pressure differential required to get the refrigerant to flow from the cooler compressed by the compressor and into the condenser. Insufficient lift results in the refrigerant “stacking up” in the cooler; excessive lift causes the compressor to surge.

The cooling tower is limited in the amount of heat it can reject. This is based on the design of the cooling tower and the outside wet bulb temperature the difference between these two variables is called the cooling tower “approach.” Typically, cooling towers can reduce the water temperature to within seven degrees of the wet bulb.

To optimize the efficiency and reduce the overall energy costs of the condenser system, the following steps should be taken:

- ❖ Determine the lift requirements of the chiller. This will dictate the lowest condenser water temperature at which the chiller can operate.
- ❖ Determine the cooling tower design and approach. For a new installation, consider a larger tower and/or increasing flow, to reduce the approach factor.
- ❖ Install a direct digital control (DDC) system to calculate and control the cooling tower and fans.

Understanding how multiple chillers interact and work together in a chilled water system is critical for anyone involved in designing, specifying or purchasing chiller-based HVAC systems. Knowledge of the appropriate number and tonnage of chillers, as well as how condenser systems and controls work, is a key factor in arriving at the best solution for a given application.

In addition, to thoroughly understand an application, a comprehensive review of the many factors contributing to chiller efficiency should be considered. These include geographic and climate conditions, building load characteristics, anticipated operational hours, economizer capabilities and predicted energy drawn from auxiliaries such as pumps and cooling towers. The Integrated Part Load Value (IPLV) formula, while helpful as a guideline, should not be relied on to accurately represent a particular, multiple-chiller installation.

9. Formulaes & Their Significance

Cooling capacity is defined in

TR of Refrigeration =

$$\frac{GPM(Evaporator) \times (T_{Ew} - T_{LW}) \times Sp. Gr \times Sp. Ht.}{24}$$

For water Sp. Gr and Sp. Ht. = 1.

(Simplified for Water) Tons = GPM X Temp Diff / 24

Example: A chiller reduces the temperature of 6000 GPM of water from 54°F to 44°F. The capacity of the Chiller = $6000 \times (54 - 44) / 24 = 2500$ Tr

Determining water flow rates :

Typical Problem

What is the required chilled water and condenser water flow rates for a 100 ton chiller, with a 10F rise in the evaporator, and a 10F drop in the tower water?

$$\begin{aligned} \text{Cooler GPM} &= (24 \times \text{tons}) / \text{Temp Rise} \\ &= (24 \times 100) / 10 \\ &= 240 \text{ GPM} \end{aligned}$$

$$\begin{aligned} \text{Condenser GPM} &= (28.8 \times \text{tons}) / \text{Temp drop} \\ &= (28.8 \times 100) / 10 \\ &= 288 \text{ GPM} \end{aligned}$$

The Basis of the 24 and 28.8 factors:

The chiller is rated in cooler tons (tons of refrigeration). By definition, a ton is the amount of heat required to make one ton of ice in a 24 hour period.

$$1 \text{ ton} = (2000 \text{ lbs} \times 144 \text{ Btu/lb}) / 24 \text{ hrs}$$

$$1 \text{ ton} = 12,000 \text{ Btuh}$$

The heat transferred to or from the water can be calculated as follows:

$$\text{Heat in Btuh} = 500 \times \text{GPM} \times \text{Temp Rise}$$

$$\text{Since } 1 \text{ ton} = 12,000 \text{ Btuh}$$

$$\begin{aligned} \text{Tons} \times 12,000 \text{ Btuh} &= 500 \times \text{GPM} \times \text{Temp Rise} \\ \text{Tons} (12,000/500) &= \text{GPM} \times \text{Temp Rise} \end{aligned}$$

$$\text{Tons} \times 24 = \text{GPM} \times \text{Temp Rise}$$

$$\text{Tons} = (\text{GPM} \times \text{Temp Rise}) / 24$$

$$\text{GPM} = (24 \times \text{Tons}) / \text{Temp Rise}$$

If the fluid passing through the cooler is a brine, then the equation must be adjusted to reflect the specific heat and specific gravity of the brine:

$$\text{Tons} = (\text{GPM} \times \text{Rise} \times \text{Specific Heat} \times \text{Specific Volume}) / 24$$

In the condenser, the heat of compression must be added to the cooler load in order to calculate condenser GPM. Considering an average water cooled chiller will add about 20% more energy to the cooler load, the heat to be rejected in the condenser becomes $(12,000 \times 1.20) = 14,400$ Btuh

$$\begin{aligned} \text{The equation for the condenser becomes:} \\ \text{Tons} \times 14,400 &= 500 \times \text{GPM} \times \text{Temp Drop} \\ \text{Tons} \times 28.8 &= \text{GPM} \times \text{Drop} \\ \text{Condenser GPM} &= (28.8 \times \text{Tons}) / \text{Temp Drop} \end{aligned}$$

Note: Older chillers are less efficient and it is more common to see about 25% added to the cooler load by the compressor. Under this circumstance the above equation would become:

$$\begin{aligned} \text{Condensed GPM} &= [(24 \times 1.25) \times \text{Tons}] / \text{Temp Drop} \\ \text{Condenser GPM} &= (30 \times \text{Tons}) / \text{Temp Drop} \end{aligned}$$

Thus, the required condenser GPM varies directly with the efficiency of the compressor.

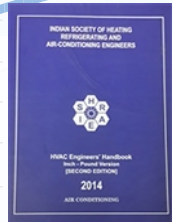
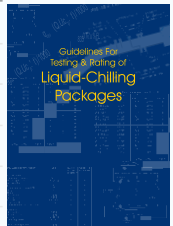
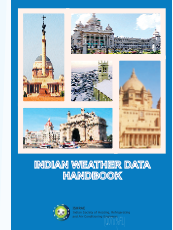


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