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Overview of Vapor Absorption Cooling Systems

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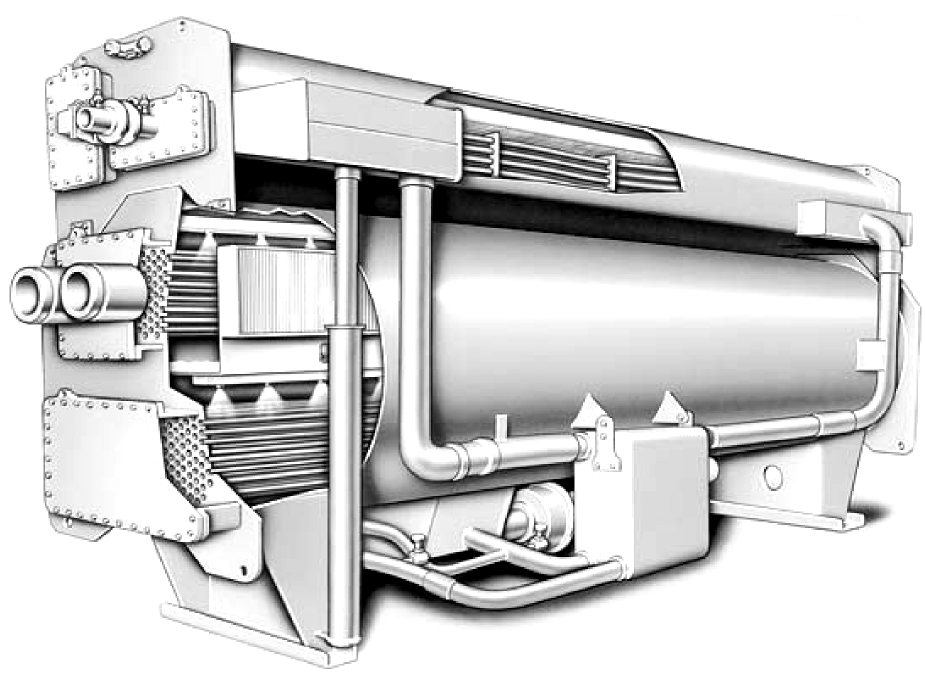
Overview of Vapor Absorption Cooling Systems



Course Content

A vapor absorption chiller machine (VAM) is a machine that produces chilled water using a heat source rather than electrical input as in the more familiar vapor compression cycle. It seems unreasonable that cooling can be achieved with heat, but that is what occurs within an absorption chiller.

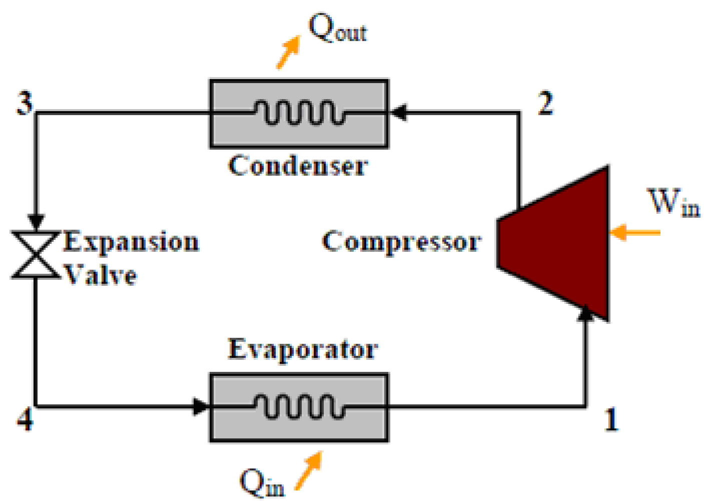
Both vapor compression and absorption refrigeration cycles accomplish the removal of heat through the evaporation of a refrigerant at a low pressure and the rejection of heat through the condensation of the refrigerant at a higher pressure. The basic difference is that an electric chiller employs a mechanical compressor to create the pressure differences necessary to circulate the refrigerant whereas the absorption chillers use heat source and do not use a mechanical compressor. The differences cause an absorption system to use little to no work input, but energy must be supplied in the form of heat. This makes the system very attractive when there is a cheap source of heat, such as solar heat or waste heat from electricity or heat generation.

Absorption chillers have recently gained widespread acceptance due to their capability of not only integrating with cogeneration systems but also because they can operate with industrial waste heat streams.

What is Absorption?

Comparing the absorption refrigeration cycle with the more familiar vapor compression refrigeration cycle is often an easy way to introduce it.

The standard vapor compression refrigeration system is a condenser, evaporator, throttling valve, and a compressor. Figure below is a schematic of the components and flow arrangements for the vapor compression cycle.

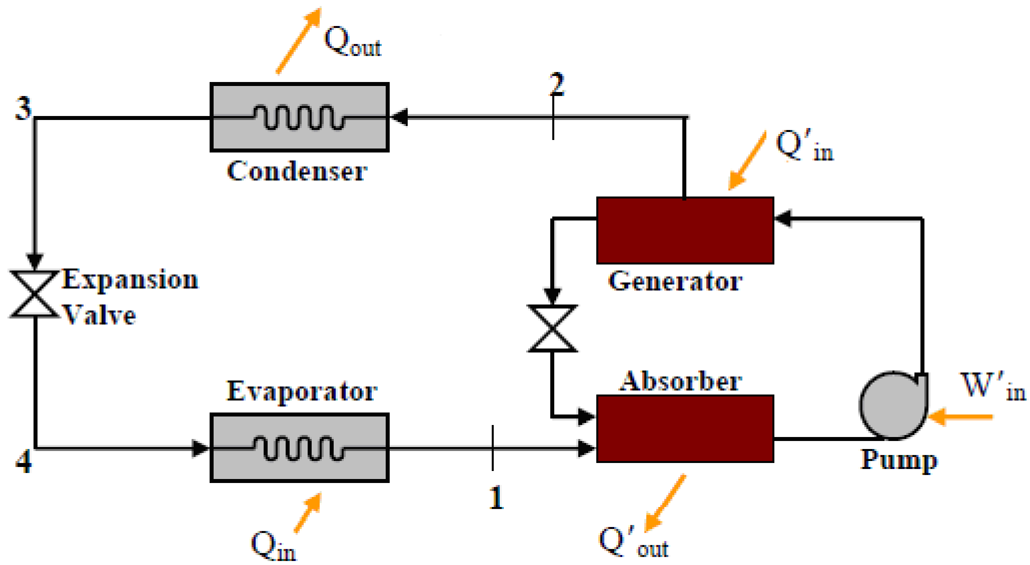


Vapor Compression Cycle

In the vapor-compression refrigeration cycle, refrigerant enters the evaporator in the form of a cool, low-pressure mixture of liquid and vapor (4). Heat is transferred from the relatively warm air or water to the refrigerant, causing the liquid refrigerant to boil. The resulting vapor (1) is then pumped from the evaporator by the compressor, which increases the pressure and temperature of the refrigerant vapor.

The hot, high-pressure refrigerant vapor (2) leaving the compressor enters the condenser where heat is transferred to ambient air or water at a lower temperature. Inside the condenser, the refrigerant vapor condenses into a liquid. This liquid refrigerant (3) then flows to the expansion device, which creates a pressure drop that reduces the pressure of the refrigerant to that of the evaporator. At this low pressure, a small portion of the refrigerant boils (or flashes), cooling the remaining liquid refrigerant to the desired evaporator temperature. The cool mixture of liquid and vapor refrigerant (4) travels to the evaporator to repeat the cycle.

Much like in the vapor compression cycle, refrigerant in the absorption cycle flows through a condenser, expansion valve, and an evaporator. However, the absorption cycle uses different refrigerants and a different method of compression than the vapor compression cycle.



Vapor Absorption Cycle

Absorption refrigeration systems replace the compressor with a generator and an absorber. Refrigerant enters the evaporator in the form of a cool, low-pressure mixture of liquid and vapor (4). Heat is transferred from the relatively warm water to the refrigerant, causing the liquid refrigerant to boil. Using an analogy of the vapor compression cycle, the absorber acts like the suction side of the compressor—it draws in the refrigerant vapor (1) to mix with the absorbent. The pump acts like the compression process itself—it pushes the mixture of refrigerant and absorbent up to the high-pressure side of the system. The generator acts like the discharge of the compressor—it delivers the refrigerant vapor (2) to the rest of the system.

The refrigerant vapor (2) leaving the generator enters the condenser, where heat is transferred to water at a lower temperature, causing the refrigerant vapor to condense into a liquid. This liquid refrigerant (3) then flows to the expansion device, which creates a pressure drop that reduces the pressure of the refrigerant to that of the evaporator. The resulting mixture of liquid and vapor refrigerant (4) travels to the evaporator to repeat the cycle.

<u>Similarities between Vapor compression and Vapor absorption cycles</u>

The basic absorption chiller cycle is similar to the traditional vapor compression chiller cycle in that

1. Both cycles circulate refrigerant inside the chiller to transfer heat from one fluid to the other;
2. Both cycles include a device to increase the pressure of the refrigerant and an expansion device to maintain the internal pressure difference, which is critical to the overall heat transfer process;
3. Refrigerant vapor is condensed at high pressure and temperature, rejecting heat to the surroundings
4. Refrigerant vapor is vaporized at low pressure and temperature, absorbing heat from the chilled water flow

Differences between Vapor compression and Vapor absorption cycles

The basic absorption chiller cycle is different to the vapor compression chiller cycle in that

1. The absorption systems use heat energy in form of steam, direct fuel firing or waste heat to achieve the refrigerant effect;
2. The absorption cycle use a liquid pump, NOT a compressor to create the pressure rise between evaporator and condenser. Pumping a liquid is much easier and cheaper than compressing a gas, so the system takes less work input. However, there is a large heat input in the generator. So, the system basically replaces the work input of a vapor-compression cycle with a heat input;
3. The absorption cycle uses different refrigerants that have no associated environment hazard, ozone depletion or global warming potential (for example lithium bromide absorption system use distilled water as the refrigerant). The vapor compression refrigeration cycle generally uses a halocarbon (such as HCFC-123, HCFC-22, HFC-134a, etc) as the refrigerant;
4. Compared to compression chillers, absorption systems contain very few moving parts, offer less noise and vibration, are compact for large capacities and require little maintenance;

5. Compared to compression chillers, the performance of absorption systems is not sensitive to load variations and does not depend very much on evaporator superheat;

6. Compared with mechanical chillers, absorption systems have a low coefficient of performance (COP = chiller load/heat input). However, absorption chillers can substantially reduce operating costs because they are powered by low-grade waste heat. The COP of absorption chiller is NOT sensitive to load variations and does not reduce significantly at part loads.

From the standpoint of thermodynamics, the vapor compression chiller is a heat pump, using mechanical energy and work, to move heat from a low to a high temperature. An absorption chiller is the equivalent of a heat engine – absorbing heat at a high temperature, rejecting heat at a lower temperature, producing work – driving a heat pump.

Applications of Absorption Systems

The main advantage of absorption chillers is their ability to utilize waste heat streams that would be otherwise discarded. In terms of energy performance, motor-driven vapor compression chillers will beat absorption chillers every time. Still there are specific applications where absorption chillers have a substantial advantage over motor-driven vapor compression chillers. Some of those applications include:

1. For facilities that use lot of thermal energy for their processes, a large chunk of heat is usually discarded to the surrounding as waste. This waste heat can be converted to useful refrigeration by using a VAM.

2. For facilities that have a simultaneous need for heat and power (cogeneration system), absorption chillers can utilize the thermal energy to produce chilled water.

3. For facilities that have high electrical demand charges. Absorption chillers minimize or flatten the sharp spikes in a building's electric load profile can be used as part of a peak shaving strategy.

4. For facilities where the electrical supply is not robust, expensive, unreliable, or unavailable, it is easier to achieve heat input with a flame than with

electricity. Absorption chillers uses very little electricity compared to an electric motor driven compression cycle chiller.

5. For facilities, where the cost of electricity verses fuel oil/gas tips the scale in favor of fuel/gas. Various studies indicate that the absorption chillers provide economic benefit in most geographical areas, due to the differential in the cost between gas and electric energy.
6. For facilities wanting to use a “natural refrigerant and aspiring for LEED certification (Leadership in Energy and Environmental Design) absorption chillers are a good choice. Absorption chillers do not use CFCs or HCFCs - the compounds known for causing Ozone depletion.
7. For facilities implementing clean development mechanism (CDM) and accumulating carbon credits, the absorption use coupled to waste heat recovery and cogeneration system help reduce problems related to greenhouse effect from CO_2 emission.

Vapor absorption system allows use of variable heat sources: directly using a gas burner, recovering waste heat in the form of hot water or low-pressure steam, or boiler-generated hot water or steam.

The Basic Principle of Absorption Cooling

Water boils and evaporates at 212 °F [100 °C] at standard atmospheric pressure (14.7psia [101.3kPa]). When the pressure is reduced, water boils at a lower temperature. The following table gives the total pressure in inches of mercury and the corresponding approximate water boiling temperature at different pressures:

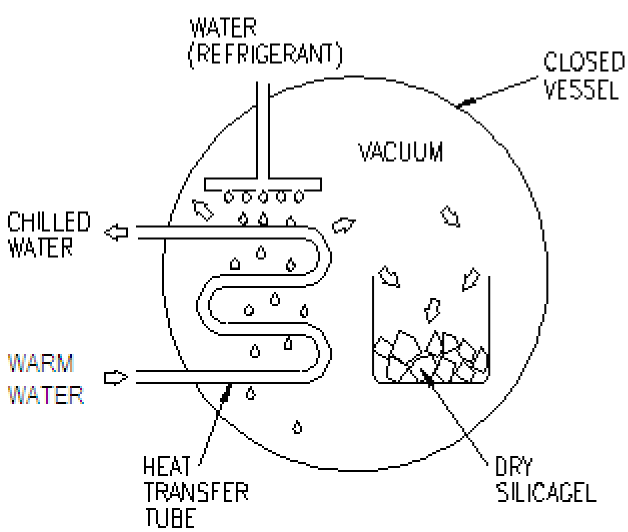
Absolute pressure	**Water boiling point (°F)**
760 mm-Hg (1 atm)	212°
76 mm-Hg (0.1 atm)	115°
25.6 mm-Hg (0.34 atm)	80°

7.6 mm-Hg (0.01 atm)	45°
6.5 mm-Hg	40°

The fundamental principle of VAM is that water boils at about 40°F at the low-pressure vacuum condition of 6.5 mm-Hg. Let's examine this closely.

Consider a closed vessel placed under a vacuum of say, 6.5 mm Hg (refer to the figure below). Assume the closed vessel contains a high quality absorbent material such as dry silica gel, and a heat transfer coiled tube through which warm water is circulated. When water is sprayed on the outer wall of the heat transfer tube:

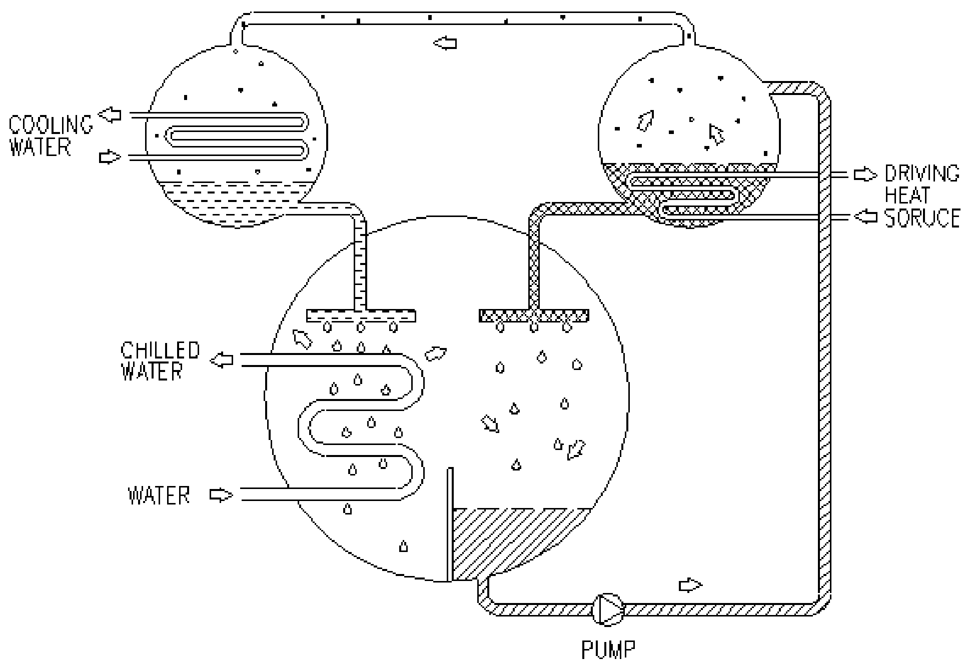
1. It gets boiled at low temperature 40°F (4°C) under vacuum, and in doing so, absorbs heat from the running water in the heat transfer tube. (The sprayed water is also called the refrigerant).
2. The running water in the heat transfer tube is optimally cooled equivalent to the heat of evaporation.



Vapor Absorption System with Silica Gel Absorbent

The vapors produced, as a result of evaporation, will immediately be absorbed by the silica gel. But when the silica gel reaches the limit of its absorbing capacity, the process continuity cannot be maintained. To ensure a continuous process, some means of converting the absorbent to its original concentration is necessary.

In commercial practice, silica gel is replaced with an aqueous absorbent solution. Continuing with the same explanation, as the aqueous absorbent solution absorbs refrigerant vapors; it becomes diluted and has less ability to absorb any further water vapor. To complete the cycle and sustain operation, the dilute solution is pumped to higher pressure where with application of heat, the water vapor is driven off and the re-concentrated absorbent is recycled back to the absorber vessel. The released refrigerant vapor is condensed in a separate vessel and returned for evaporation. The simplified diagram here illustrates the overall flow path.



Vapor Absorption System with Aqueous Absorbent

Most commercial absorption chillers use pure water as refrigerant and lithium bromide (LiBr) as absorbent salt. Another common refrigerant–absorbent pair is ammonia as the refrigerant and water as the absorbent. There are other refrigerant–absorbent combinations; but in this course will focus on lithium bromide VAM.

How Absorption Machine Works

Absorption system employs heat and a concentrated salt solution (lithium bromide) to produce chilled water. In its simplest design the absorption machine consists of 4 basic components:

1. Generator
2. Condenser
3. Evaporator
4. Absorber

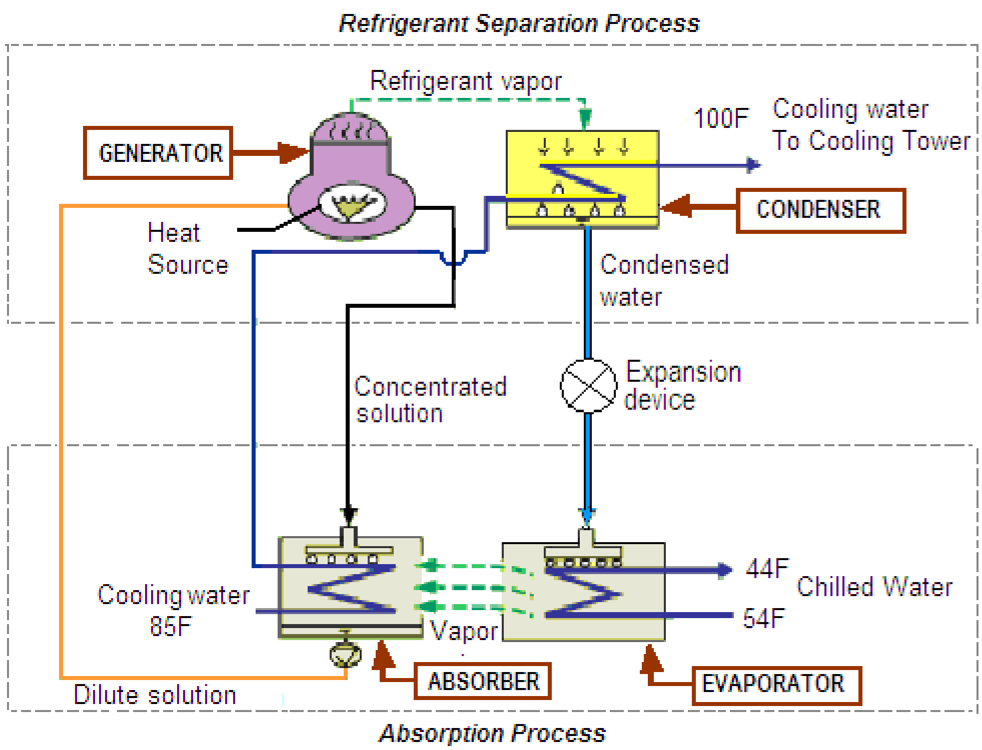


Figure VAPOR ABSORPTION CYCLE

Just like the vapor-compression refrigeration cycle, the absorption machine operates under two pressures – one corresponding to the condenser-generator (high pressure refrigerant separation side) and the other corresponding to evaporator-absorber (low pressure absorption process in vacuum). For air-conditioning applications, the evaporator-absorber is at a pressure of 6.5 mmHg and temperature of about 40ºF. The pressure on the high-pressure side of the system (condenser) is approximately ten times greater than that on the low-pressure side to allow the refrigerant to reject heat to water at normally available temperatures. Typically the condensation of water in the condenser-generator takes place at a pressure of 75 mmHg and temperature of about 113ºF.

Function of Components

Generator:

The purpose of the generator is to deliver the refrigerant vapor to the rest of the system. It accomplishes this by separating the water (refrigerant) from the lithium bromide-and-water solution. In the generator, a high-temperature energy source, typically steam or hot water, flows through tubes that are immersed in a dilute solution of refrigerant and absorbent. The solution absorbs heat from the warmer steam or water, causing the refrigerant to boil (vaporize) and separate from the absorbent solution. As the refrigerant is boiled away, the absorbent solution becomes more concentrated. The concentrated absorbent solution returns to the absorber and the refrigerant vapor migrates to the condenser.

Condenser:

The purpose of condenser is to condense the refrigerant vapors. Inside the condenser, cooling water flows through tubes and the hot refrigerant vapor fills the surrounding space. As heat transfers from the refrigerant vapor to the water, refrigerant condenses on the tube surfaces. The condensed liquid refrigerant collects in the bottom of the condenser before traveling to the expansion device. The cooling water system is typically connected to a cooling tower. Generally, the generator and condenser are contained inside of the same shell.

Expansion Device:

From the condenser, the liquid refrigerant flows through an expansion device into the evaporator. The expansion device is used to maintain the pressure difference between the high-pressure (condenser) and low-pressure (evaporator) sides of the refrigeration system by creating a liquid seal that separates the high-pressure and low pressure sides of the cycle. As the high-pressure liquid refrigerant flows through the expansion device, it causes a pressure drop that reduces the refrigerant pressure to that of the evaporator. This pressure reduction causes a small portion of the liquid refrigerant to boil off, cooling the remaining refrigerant to the desired evaporator temperature. The cooled mixture of liquid and vapor refrigerant then flows into the evaporator.

Evaporator:

The purpose of evaporator is to cool the circulating water. The evaporator contains a bundle of tubes that carry the system water to be cooled/chilled. High pressure liquid condensate (refrigerant) is throttled down to the evaporator pressure (typically around 6.5 mm Hg absolute).

At this low pressure, the refrigerant absorbs heat from the circulating water and evaporates. The refrigerant vapors thus formed tend to increase the pressure in the vessel. This will 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 into the lower pressure absorber. Physically, the evaporator and absorber are contained inside the same shell, allowing refrigerant vapors generated in the evaporator to migrate continuously to the absorber.

Absorber:

Inside the absorber, the refrigerant vapor is absorbed by the lithium bromide solution. As the refrigerant vapor is absorbed, it condenses from a vapor to a liquid, **releasing the heat** it acquired in the evaporator.

The absorption process creates a lower pressure within the absorber. This lower pressure, along with the absorbent’s affinity for water, induces a continuous flow of refrigerant vapor from the evaporator. In addition, the absorption process condenses the refrigerant vapors and releases the heat removed from the evaporator by the refrigerant. The heat released from the condensation of refrigerant vapors and their absorption in the solution is removed to the cooling water that is circulated through the absorber tube bundle.

As the concentrated solution absorbs more and more refrigerant; its absorption ability decreases. The weak absorbent solution is then pumped to the generator where heat is used to drive off the refrigerant. The hot refrigerant vapors created in the generator migrate to the condenser. The cooling tower water circulating through the condenser turns the refrigerant vapors to a liquid state and picks up the heat of condensation, which it rejects to the cooling tower. The liquid refrigerant returns to the evaporator and completes the cycle.

Efficiency of Vapor Absorption Machine (VAM)

Efficiencies of absorption chillers is described in terms of Coefficient of Performance (COP), and is defined as the refrigeration effect, in Btu, divided by the net heat input, in Btu.

$$\text{COP} = \frac{\text{Cooling capacity obtained at evaporator}}{\text{Heat input for the generator}}$$

The COP can be thought of as a sort of index of the efficiency of the machine. The absorption systems with a COP of 1.0 will burn 12,000 BTUs of heat energy for each ton-hour of cooling. For example, a 500-ton absorption chiller operating at a COP of 0.70 would require: (500 x 12,000 Btu/h) divided by 0.70 = 8,571,429 Btu/h heat input.

*Cooling capacity is measured in tons of refrigeration. A ton of refrigeration is defined as the capacity to remove heat at a rate of 12,000 Btu/hr at the evaporator.

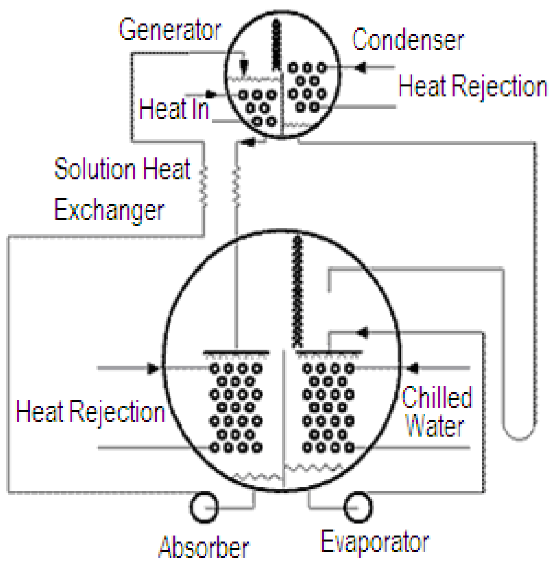
TYPES OF VAM

Absorption chillers are classified as:

1. Single effect absorption chiller
2. Double effect absorption chiller

Single Effect Absorption Chillers

The single-effect absorption chiller includes a single generator, condenser, evaporator, absorber, heat exchanger, and pumps. Fig. below shows a Single Effect Chiller.



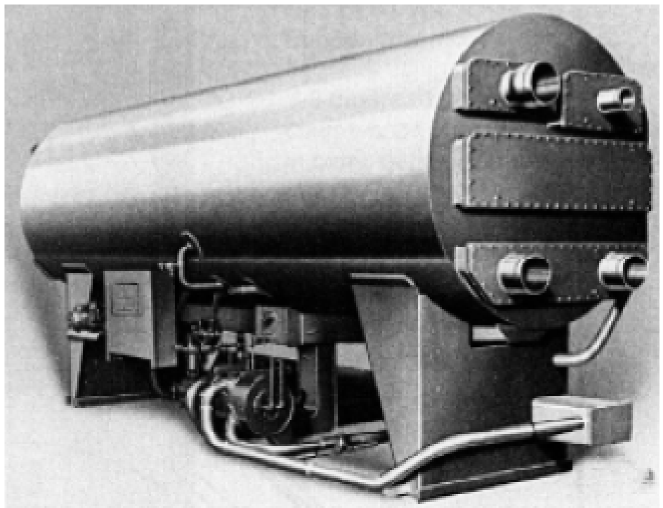
Basic Cycle of Single Effect Chiller

We have already discussed the operational principle of VAM. Physically in a single effect VAM, the evaporator and absorber are contained inside the same shell, allowing refrigerant vapors generated in the evaporator to migrate continuously to the absorber. Also the condenser and generator are in same shell.

The basic absorption cycle as discussed earlier may be modified in several ways to reduce the heat required to operate the chiller and to reduce the extent of heat transfer surface incorporated in the machine. One is to utilize all possible opportunities for heat recovery within the cycle in order to improve the heat economy within the cycle. For example, a heat exchanger is placed to recover some of heat from the concentrated hot lithium bromide solution going from the generator to the absorber to heat the dilute cold lithium bromide solution going from the absorber to the generator. Heat exchangers optimize the energy transfer between the hot, concentrated lithium bromide that is recycling and the cooler, dilute sorbent solution that is yet to be boiled.

Also the modifications are possible in cooling circuit; for example, the cooling water is arranged in series i.e. made to pass through absorber first followed by condenser. Some absorption chiller designs split the cooling water and deliver it directly to both the absorber and the condenser.

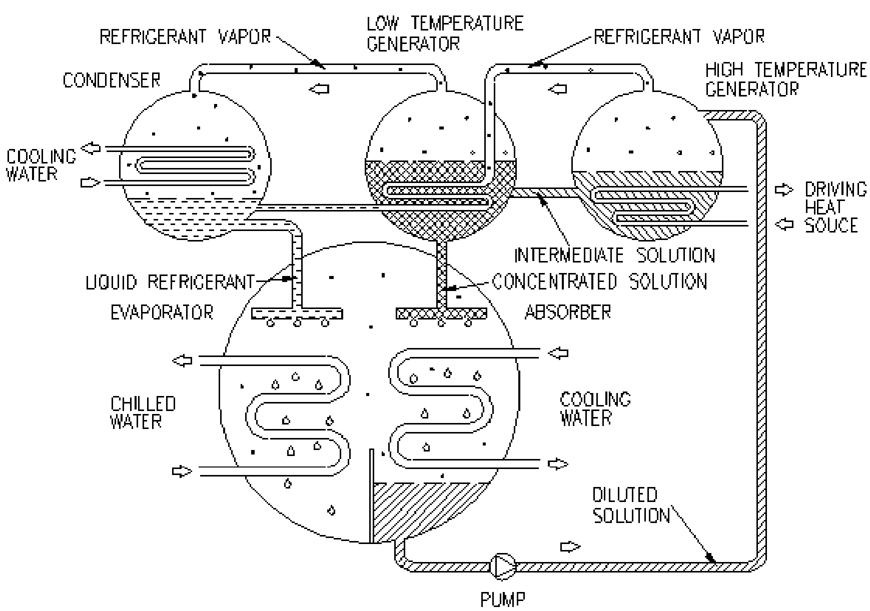
A typical single effect system use low pressure steam (20 psig or less) or hot water at 185°F to 200°F, as the driving force. These units typically require about 18 pounds per hour (pph) of 9 psig steam at the generator flange (after control valve) per ton of refrigeration at ARI standard rating conditions.



Single Effect Steam Fired Vapor Absorption Chiller Machine

Double Effect (2-Stage) Absorption Systems

A double-effect chiller is very similar to the single-effect chiller, except that it contains an additional generator.



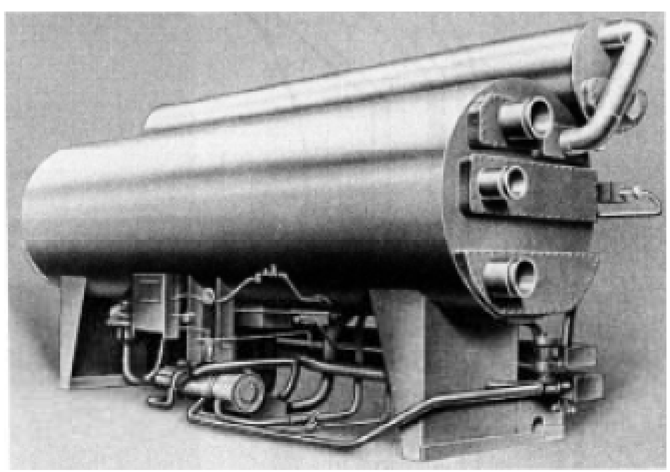
Basic Cycle of Double Effect Type Chillers

In a single-effect absorption chiller, the heat released during the chemical process of absorbing refrigerant vapor into the liquid stream, rich in absorbent, is rejected to the cooling water. In a multiple-effect absorption chiller, some of this energy is used as the driving force to generate more refrigerant vapor. The more vapor generated per unit of heat or fuel input, the greater the cooling capacity and the higher the overall operating efficiency.

Operation of Double Effect VAM

Before we discuss the operation of double effect indirect fired VAM, it is important to understand some terminology that defines the physical and chemical properties of absorbent solution during absorption process.

- **Dilute Solution:** The term dilute solution refers to a mixture that has a relatively high refrigerant content and low absorbent content.
- **Concentrated Solution:** A concentrated solution has a relatively low refrigerant content and high absorbent content.
- **Intermediate Solution:** An intermediate solution is a mixture of dilute and concentrated solutions.



Two Stage Vapor Absorption Chiller Machine

In the high-temperature generator, very high temperature steam or hot water flows through tubes that are immersed in an absorbent solution that is at an intermediate concentration. The solution absorbs heat from the warmer steam or water, causing the refrigerant to boil and separate from the absorbent solution. As the refrigerant boils away, the absorbent solution becomes concentrated and returns to the absorber.

The hot refrigerant vapor produced in the high-temperature generator migrates to the low-temperature generator, where it flows through tubes that are immersed in a dilute solution. The solution absorbs heat from the high temperature refrigerant vapor, causing the refrigerant in the low-temperature generator to boil and separate from the absorbent solution. As that refrigerant boils away, the concentration of the absorbent solution increases and the concentrated solution returns to the absorber.

The low-temperature refrigerant vapor produced in the low-temperature generator migrates to the cooler condenser. Additionally, the liquid refrigerant that condensed inside the tubes of the low-temperature generator also flows into the condenser. Next, the refrigerant travels through the condenser, expansion device, evaporator and absorber in a manner similar to refrigerant travel in the single effect absorption chiller.

Double-effect systems can be configured either in series or parallel flow. The difference between the two systems is the fluid path taken by the solution through the generators.

- **Series flow cycle:** In the series flow cycle, the dilute solution from the absorber is pumped entirely to the high-temperature generator. As the refrigerant boils away and migrates to the low-temperature generator, the absorbent solution becomes concentrated. The resulting intermediate solution then flows to the low temperature generator, where it is further concentrated by the refrigerant vapor that was created in the high-temperature generator. The concentrated solution then flows back to the absorber to repeat the cycle. The series flow cycle has been the mainstay of most double-effect absorption chiller designs for many years. It is simple because it requires only one generator pump and is fairly straightforward to control. The series cycle, however, requires a significantly larger heat exchanger to obtain similar COPs to the other cycles.

- **Parallel flow cycle:** In the parallel flow cycle, the dilute solution from the absorber is split between the low-temperature and high-temperature generators. Both streams of dilute solution are concentrated in the generators and mix together again before returning to the absorber. The parallel flow cycle can be implemented using one generator pump, if a throttling device is used to control the flow of solution to the low-temperature generator. Separate generator pumps should be used for control over the full range of operating conditions.

The performance of a double-effect absorption chiller mainly depends on the choice of operating conditions, the amount of heat transfer surface area, the effectiveness of the purge system, the materials of construction, the design of the controls, and the manufacturing techniques.

COMPARISON OF SINGLE EFFECT vs. DOUBLE EFFECT VAM

Performance Efficiency

- Single effect units typically have a COP of 0.6 to 0.75
- Double effect units typically have a COP of 1.0 to 1.2

Energy Use

- Single effect units typically require about 18 pounds of 15-pound-per-square-inch-gauge (psig) steam per ton-hour of cooling.
- Double-effect machines are about 40% more efficient, but require a higher grade of thermal input, using about 10 pounds of 100- to 150-psig steam per ton-hour.
- Double effect units operating on direct firing have specific fuel consumption of about 0.35 m^3/hr/TR of natural gas or about 0.30 kg/hr/TR of fuel oil. Single effect machines are not available in direct firing mode.

Operating Temperatures

- In a single-effect VAM, the optimum generator temperature is around 200°F. Here the low-pressure steam (15 to 20 psig) is the most common heat source. Hot water (180°F or higher) can also be used.
- In double effect VAM, the temperature required at first generator is around 370°F and therefore when utilizing the process exhaust from a gas turbine or diesel generator, the temperature should be typically over 550°F.

In general, the more stages in the system, the higher the required temperature at the first generator.

Water Use

Since the efficiency of double effect machine is high, the cooling water requirement is low and the cooling tower size is reduced.

Applications

- Generally, the ability to use a low grade heat source makes the single-effect systems attractive when waste heat from processes or low pressure steam is available. Low pressure steam in the 12 to 40 psig range can be used at temperatures as low as 162°F, but capacity and COP drop with decreasing heat source temperature. Units are available in capacities from 7.5 to 1,500 tons.
- Double effect VAM works on relatively high pressure steam in the 40 to 140 psig range directly from boiler or from process cogeneration system. Steam driven units require about 9 to 10 lbs/hr of 114 psig input steam per ton of refrigeration at ARI standard rating conditions.
- The double effect VAM is also available as direct burner-fired (using either gas or oil). Gas fired units require an input of about 10,000 to 12,000 Btuh HHV per ton of cooling at ARI standard rating conditions.
- Double effect VAM requires a higher temperature heat input to operate and therefore they are limited in the type of electrical generation equipment they can be paired with when used in a cogeneration – combine heat and power (CHP) System.

Cost

The capital cost of double effect VAM is high because of special materials required to combat increased corrosion rates associated with high temperature operation. Heat exchanger surface areas are larger and the machine requires complex control mechanism.

WHAT DO YOU NEED TO RUN A VAM?

1. Heat Source
2. Refrigerant-Absorbent Working Pair
3. Cooling Water

HEAT SOURCE

Absorption chillers are classified by the firing method—that is, how the generator is heated and whether it has a single- or a multiple-effect generator.

Indirect Fired Systems

"Indirect-fired" absorption chillers use steam, hot water or hot gases steam from a boiler, turbine or engine generator, or fuel cell as their primary power input. These chillers can be well suited for integration into combined heat and power (CHP) cogeneration system by utilizing rejected heat from gas turbine, steam turbine (non-condensing and extraction type) or engine generator.

COGENERATION – Combine Heat and Power (CHP)

Cogeneration is the sequential generation of two different forms of useful energy from a single primary energy source.

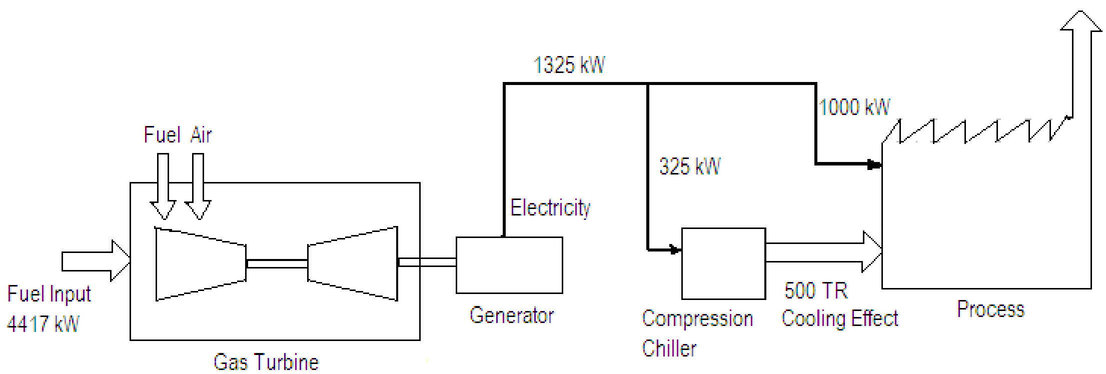
The concept of power and absorption cooling arises from the industries where there is a need for continuous reliable electricity and heating/cooling. As electricity costs rise, producing power at the point of use is far more economical and reliable than generating and transmitting electricity from a remote power plant. In fact, a facility operating a Combined Heating and Power (CHP) system is about three times more efficient, and it reduces greenhouse gases by similar amounts. But to realize these benefits, all the heat by-products of cogeneration must be used all the time. Using the heat from a CHP system is usually straightforward during winter, but this same heat can be used in summer months to drive an absorption chiller to provide chilled water for cooling.

Example

A factory needs 1000 kW of electricity and 500 tons of refrigeration (TR). Consider following scenarios:

Case #1: Open cycle operation - Motor driven 500TR vapor compression chiller is considered.

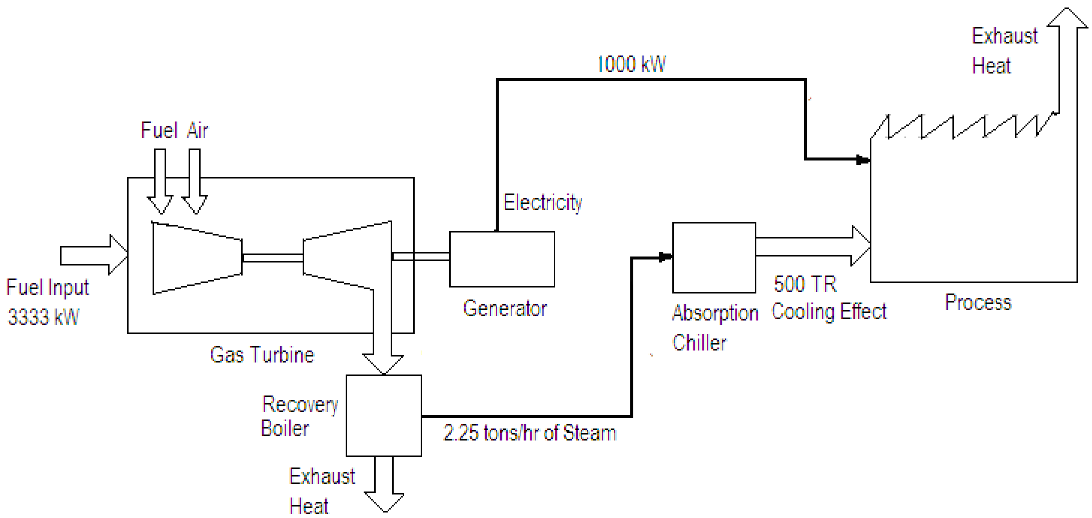
Assuming a COP of 0.65, the compression chiller needs 325 kW of electricity to obtain 500 TR cooling effect. Therefore 1325 kW of electricity must be provided to this factory. If the gas turbine generator has an efficiency of 30%, the primary energy consumption would be 4417 kW.



Schematic Diagram of Power Generation and Cooling with Electricity

Case #2: Combine Heat and Power (CHP) operation - Vapour compression system replaced with absorption chiller.

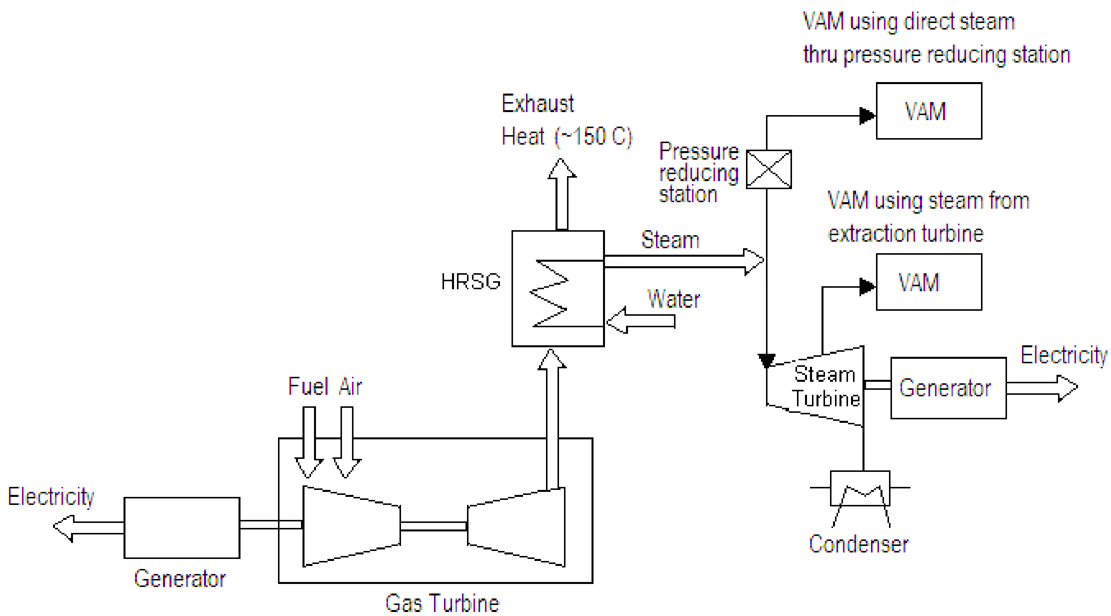
A double effect VAM consumes approximately 4.5 kg/hr per ton of refrigeration. This equates to 2.25 tons/hr for 500 TR machine. When a heat recovery steam generator (HRSG) is added to capture the exhaust heat from gas turbine, the steam generated can be used to run a VAM. This cogeneration system can save about 24.5% of primary energy and provide both power and cooling by consuming only 3333 kW of primary energy. Obviously initial cost will go up because of HRSG, but the payback period shall be less than 3 years.



Schematic Diagram of Power Generation and Absorption Cooling

Gas Turbine cogeneration systems

Gas turbine cogeneration systems can produce all or a part of the energy requirement of the site, and the energy released at high temperature in the exhaust stack can be recovered for various heating and cooling applications. If more power is required at the site, it is possible to adopt a combined cycle that is a combination of gas turbine and steam turbine cogeneration. Steam generated from the exhaust gas of the gas turbine is passed through a backpressure or extraction condensing steam turbine to generate additional power. The exhaust or the extracted steam from the steam turbine provides the required thermal energy.



Gas Turbine Combined Cycle Cogeneration

Gas turbine cogeneration has probably experienced the most rapid development in the recent years due to the greater availability of natural gas, rapid progress in the technology, significant reduction in installation costs, and better environmental performance. Though it has a low heat to power conversion efficiency, more heat can be recovered at higher temperatures. If the heat output is less than that required by the user, it is possible to have supplementary natural gas firing by mixing additional fuel to the oxygen-rich exhaust gas to boost the thermal output more efficiently.

Steam Turbine Cogeneration and VAM

An advantage of the steam turbine cogeneration system is that a wide variety of fuels such as coal, natural gas, fuel oil and biomass can be used. There are 3 types of steam turbines widely used.

1. Condensing turbine ------- {only for power service}
2. Non-condensing turbine ------- { for cogeneration service}
3. Extraction turbine -------- { for cogeneration service}

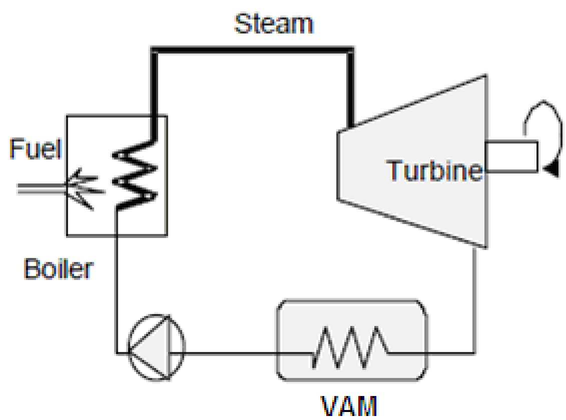
Condensing Turbine

Condensing turbine is primarily used for power generation. These turbines exhaust directly to the condenser maintained under vacuum conditions and result in maximum power generation. These are not recommended for cogeneration systems.

The two types of steam turbines most widely used for cogeneration systems are the backpressure and the extraction condensing types.

Non-Condensing (Back-pressure) Turbine

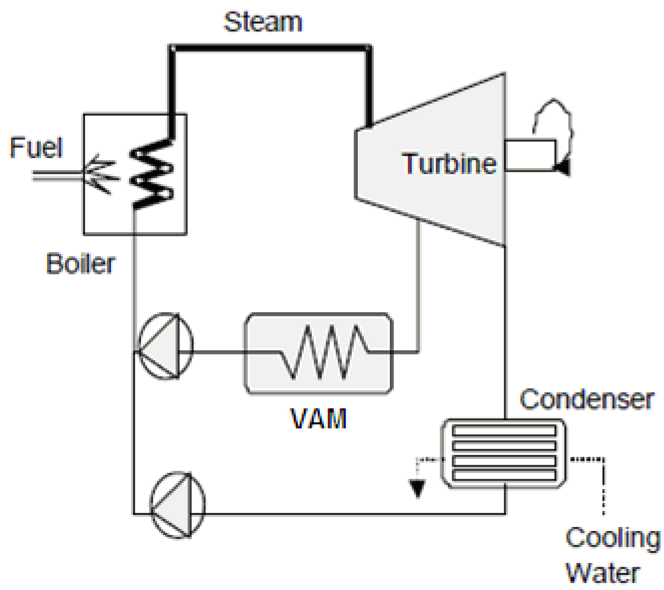
Non-condensing turbine also referred to as a back-pressure turbine exhausts its entire flow of steam at atmospheric pressures and above. Back pressure turbine is generally recommended for single effect absorption system.



Non-Condensing (Back-Pressure) Steam Turbine

Extraction Turbine

In the extraction steam turbine, a portion of the expanded steam is bled off at some intermediate pressure and supplied to the absorption unit, and the remaining steam goes all the way to a condenser and thus higher electricity can be generated. The extraction points of steam from the turbine could be more than one, depending on the temperature levels of heat required by the processes.



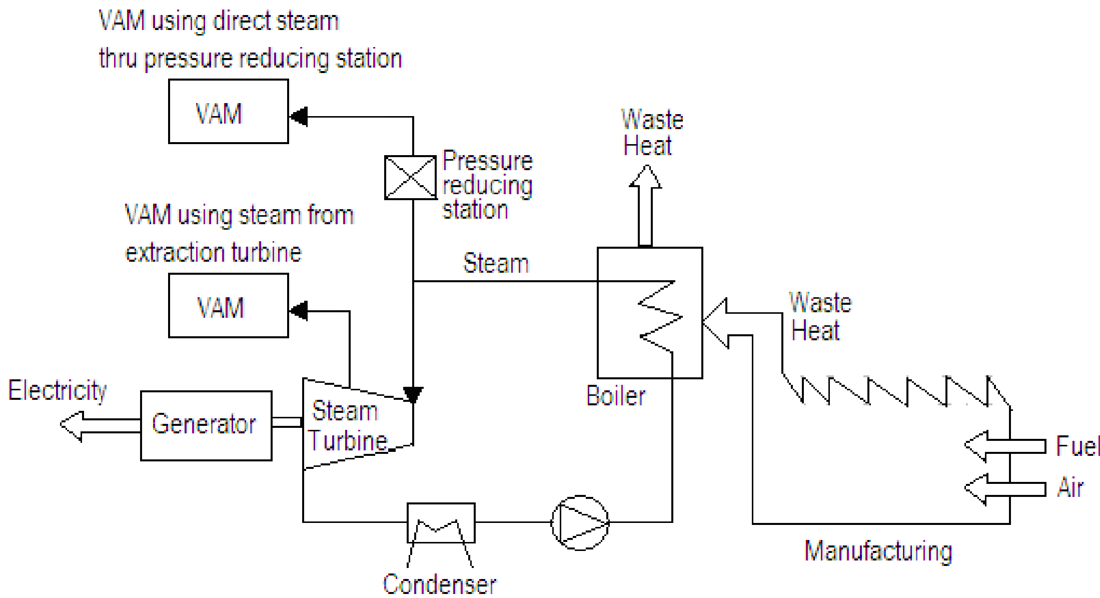
Extraction Steam Turbine

Steam is typically extracted at around 15 psig to drive a single-stage absorption chiller. It however is more advantageous to extract steam at 115 psig to drive a two-stage absorption system. At 115 psig, only half the mass flow of steam is needed as compared to the low-pressure 15 psig extraction for same amount of cooling.

The choice between backpressure turbine and extraction condensing turbine depends mainly on the quantities of power and heat, quality of heat, and economic factors.

Cogeneration Using Waste Heat Recovery

Waster heat recovery process is used to generate power and VAM. This is most suitable for some manufacturing processes which require high temperature heat, for example in furnaces, and reject waste heat at still significantly high temperatures. This waste heat can be used to generate power and cooling in a number of ways.

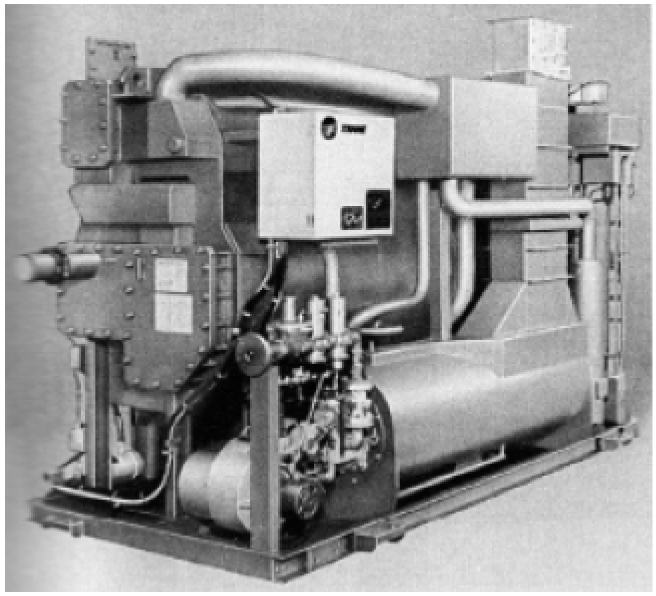


Waste Heat Recovery

Direct Fired Double Effect VAM

Direct fired chillers are heated via the combustion of fossil fuels. Common fuels used are natural gas, number 2 fuel oil, or liquid petroleum (LP). Typical COPs for direct-fired, double-effect chillers are 0.9 to 1.1 (based on the higher heating value, or HHV, of the fuel).

Direct fired absorption chiller operation is virtually identical to the indirect operation with a difference that the heat is generated by the combustion process instead of steam. However, unlike most steam absorption chillers, the direct-fired absorption chiller lend itself fairly readily to "chiller-heater" applications where both cooling and heating are achieved in the same unit. In the direct-fired absorption chiller, an auxiliary heating bundle can be added, allowing the chiller to make hot water as well as chilled water. The auxiliary heating bundle draws in a portion of the refrigerant vapor leaving the high-temperature generator. Water flowing through the tubes absorbs heat from this hot refrigerant vapor, causing the refrigerant to condense on the tube surfaces. This transfer of heat warms the water to a temperature where it can be used for comfort heating, domestic hot water needs, or process heating loads.



Double Effect Direct Fired Vapor Absorption Chiller Machine

In direct fired VAM, since the heat input is at a very high temperature, these achieve a very high efficiency for the absorption cycle...something approaching 12,000 Btu of fuel input for each ton hour of cooling output. When examining gas-fired absorption systems, one has to be sure which heating value was used to determine the published fuel consumption. For example, most chillers that use natural gas are rated using the lower heating value (LHV) of natural gas (typically around 900 Btu/cu ft). However, natural gas is normally purchased and the charge by utilities is based on the higher heating value (HHV) (typically around 1,000 Btu/cu ft). To determine the fuel rate for estimating fuel costs, the published fuel consumption based on the LHV should be divided by the 0.9.

<u>Advantages of Direct Firing</u>

- Since the boiler is eliminated, the cost and space savings can be a significant.
- Direct firing permits unmanned operation.

<u>Disadvantages of Direct Firing</u>

- Require a stack to vent combustion products.
- First cost of direct-fired units is higher than steam driven units.
- Maintenance costs on the heat rejection circuit tend to be higher due to more rapid scaling.

Economics

Direct fired absorption chiller can break even with the cost of an electric chiller when the gas cost is below $4.50/MCF and the electric cost is above $0.08/KWH. Then you can deal with the additional first cost of the units that will be at least 50% higher. Depending on the configuration of a direct-fired system, if a boiler cost is being offset and the tonnage is large enough, first cost may be closer in line with a separate gas boiler and electric chiller plant.

WORKING FLUID

Performance of absorption refrigeration systems is critically dependent on the chemical and thermodynamic properties of the working fluid. A fundamental requirement of absorbent/refrigerant combination is that:

- The difference in boiling point between the pure refrigerant and the mixture at the same pressure should be as large as possible;
- Refrigerant should have high heat of vaporization and high concentration within the absorbent in order to maintain low circulation rate between the generator and the absorber per unit of cooling capacity;
- Transport properties that influence heat and mass transfer, e.g., viscosity, thermal conductivity, and diffusion coefficient should be favorable;
- The mixture should be chemically stable, non-toxic, non-corrosive, environment friendly and non-explosive.

Ammonia-Water Absorption System

Key Characteristics

1. Ammonia is a refrigerant and water is an absorbent;

2. Generally used for applications requiring temperatures in the range of -40ºC to +5ºC. The preferred heat source temperature is 95ºC to 180ºC;
3. Available as very small pump-less systems to large refrigeration capacities in applications ranging from domestic refrigerators to large cold storages;
4. Unlike lithium bromide system, these chillers operate at moderate pressures and NO vacuum is required till -30ºC;
5. Unlike lithium bromide system, these chillers do not suffer from the problem of crystallization.

Cautions:

1. Since water also evaporates when the ammonia water solution is heated in the generator, the ammonia vapor from the generator is mixed with water vapor. If the ammonia vapor mixed with water-vapor reaches the condenser, condensation of water vapor will interfere with the evaporation of the ammonia liquid in the evaporator and reduce the refrigeration capacity. A separate rectifier is generally provided to overcome this problem.
2. Ammonia is not compatible with materials such as copper or brass. Normally the ammonia chiller system is fabricated out of steel.
3. Ammonia is both toxic and flammable.

Lithium Bromide (LiBr) – Water Absorption System

Key Characteristics

1. Lithium bromide is a salt and desiccant (drying agent). The lithium ion (Li+) in the lithium bromide solution and the water molecules have a strong association, producing the absorption essential for the chiller to operate. Water is the refrigerant and LiBr is the absorbent;
2. LiBr system operates under vacuum; the vacuum pumps are needed only for short duration while starting the machine; after that, equilibrium condition is maintained by physical and chemical phenomena;

3. Since water is the refrigerant for the LiBr absorption system, the minimum possible chilled water temperature, at its lowest, is about 44° F; consequently, LiBr absorption chillers are used in large air-conditioning applications;

4. The advantage of the water-LiBr pair includes its stability, safety, and high volatility ratio.

Cautions:

1. At high concentrations, the solution is prone to crystallization.

2. The lithium bromide solution is corrosive to some metals. Corrosion inhibitors may be added to protect the metal parts and to improve heat-mass transfer performance.

COOLING WATER

Cooling water is required to remove the heat that the LiBr solution absorbs from the refrigerant vapor in the absorber and also condenses the refrigerant vapor from the generator. The heat gain in the cooling water is finally rejected in a cooling tower.

Absorption systems require larger cooling tower capacity and greater pump energy than electric chillers due to larger quantities of cooling water needed for the cycle. An absorption refrigeration system that removes 12,000 Btu/hr (does 1 ton of air conditioning) requires heat energy input of approximately 18,000 Btu/hr to drive the absorption process. This means that the heat rejection at the cooling tower approximates 30,000 Btu/hr per ton of refrigeration. With a 15°F (8°C) temperature drop across the tower, the heat rejection of an absorption system requires circulation of approximately 4 gpm of water per ton of air conditioning. [Gpm/ton = Btu/hr / (500 * DT)]. In comparison heat rejection in a compression system is approximately 15,000 Btu/hr per ton of refrigeration [12000 + 3000 Btu/hr per ton of refrigeration due to heat of compression]. The vapor compression system requires approximately 3 gpm of cooling water per ton of refrigeration, with a 10°F temperature drop across the cooling tower.

Key Characteristics

Cooling water in absorption machine passes through both the absorber and condenser. Any deficiency in the cooling water system can affect the cooling capacity and the COP of the machine.

1. **Lower temperature cooling water:** *The absorption power of a LiBr solution is stronger at lower temperatures of cooling water.* When the temperature of the cooling water in the condenser is low, condensing temperature of the refrigerant decreases. Therefore, condenser pressure becomes low. As the boiling temperature (generator temperature) of the LiBr solution decreases when the condensing pressure is low, the calorific value of the driving heat source can decrease. This will result in energy savings.

2. **The cooling water temperature is too low:** It is not acceptable if the temperature of the cooling water is too low. A lithium bromide solution of a given concentration will crystallize at a certain low temperature. For example, at a concentration of 65% LiBr, the absorbent solution crystallizes at a temperature lower than 42°C (108°F), with 60%, at a temperature lower than 17°C (63°F), and with a concentration of 55%, at a temperature lower than 15°C (59°F). As the absorbent crystallizes it become a non-flowing solid, rendering the chiller inoperable. Additionally, crystallization events require cleaning of the entire system.

3. **The cooling water temperature is too high:** Some problems occur when cooling water temperature becomes too high. With the increase of cooling water temperature, the absorption power of the LiBr solution is degraded. This prevents the machine from producing the normal chilled water temperature while a higher amount of fuel is consumed. In order to prevent this, the stability of the cooling water system, preventive maintenance of the cooling tower system/equipment, and proper water treatment are essential.

4. **Water treatment of cooling water:** Water treatment of cooling water is an important factor for the VAM. If the water quality is poor, the heat transfer tubes may form a scale on the interior surfaces in addition to becoming corroded. The heat transfer capability will decrease, causing abrupt changes in chilled water temperature and a waste of source energy.

Note that air-cooled options are not available for absorption chillers in commercial market. Areas having a scarcity of good quality water should be carefully economically evaluated.

VAM's & LEED®

The USGBC LEED for New Construction, Version 2.2, has a mandatory prerequisite to reduce ozone depletion by utilizing no CFC refrigerants in new construction and phasing out CFC refrigerants during renovation of existing facilities. The absorption chillers meet the Energy & Atmosphere Prerequisite 3, Fundamental Refrigerant Management and are entitled for ONE credit.

The USGBC also provides the opportunity for obtaining a credit for Enhanced Refrigerant Management under category the Energy & Atmosphere Credit 4. It works on a formula that weighs a refrigerant's ozone depletion and global warming potentials. If the project's total installed refrigerant has an average atmospheric impact less than a 100, it is eligible for the credit. The credit also recognizes "natural refrigerants" like water, carbon dioxide, ammonia, and propane as having a lower atmospheric damage potential and will allow projects exclusively using natural refrigerants to claim the credit without using the Enhanced Refrigerant Management formula.

(Refer USGBC for further information)

PRACTICAL PROBLEMS

Practical problems typical to water-lithium bromide systems are:

1. Crystallization
2. Air leakage
3. Corrosion

Crystallization

Lithium Bromide absorbent is prone to crystallization. Crystallization is a phenomenon that causes aqueous solution of LiBr to permanently separate into salt at **low** cooling water temperatures. As the absorbent crystallizes, it becomes a non-flowing solid, rendering the chiller inoperable. Currently, modern controls fairly well prevent this from happening; nevertheless, it is important to have an understanding of the concept.

Crystallization is likely to occur when condenser pressure falls and when there is sudden drop in condenser water temperature. While reducing condenser water temperature does improve performance, it could cause a low enough temperature in the heat exchanger to crystallize the concentrate.

Power failures can cause crystallization as well. A normal absorption chiller shutdown uses a dilution cycle that lowers the concentration throughout the machine. At this reduced concentration, the machine may cool to ambient temperature without crystallization. However, if power is lost when the machine is under full load and highly concentrated solution is passing through the heat exchanger, crystallization can OCCUR. The longer the power is out, the greater the probability of crystallization.

Crystallization is avoided by:

- Maintaining artificially high condensing pressures even though the temperature of the available heat sink is low;
- Regulating cooling water flow rate to condenser;
- By adding additives;
- An air purging system is used to maintain vacuum.

Air Leakage and Maintenance Needs

Lithium Bromide absorption systems operate below atmosphere pressure. Any system pressure increase due to leakage of air into the system or the collection of non-condensable gases (NCG) causes a partial pressure that is additive to the vapor pressure of the $LiBr\text{-}H_2O$ solution. As the pressure increases, so does the evaporator temperature.

Air leakage into the machine can be controlled by:

- Designing the machine with hermetic integrity and
- Routinely purging the unit using a vacuum pump.

Corrosion of Components

Lithium Bromide is corrosive to metals. Corrosion can occur inside the chiller due to the nature of the LiBr solution or on exterior components due to the heat source used to drive the system. The corrosive action of the LiBr solution increases with its temperature. In general, as the number of stages in an absorption system increases the temperature at the first generator also increases. This implies that special care must be used to combat corrosion in multiple-stage absorption systems.

As a safeguard, and to have complete protection, a corrosion inhibitor is generally added to the absorbent and the alkalinity is adjusted. Alcohol, namely octyl alcohol, generally is added to the system to increase the absorption effect of the absorbent.

CAPACITY CONTROL

The capacity of any absorption refrigeration system depends on the ability of the absorbent to absorb the refrigerant, which in turn depends on the concentration of the absorbent. To increase the capacity of the system, the concentration of absorbent should be increased, which would enable absorption of more refrigerant. Some of the most common methods used to change the concentration of the absorbent are:

1. Regulating the flow rate of weak solution pumped to the generator through the solution pump;
2. Controlling the temperature of heating fluid to the generator;
3. Controlling the flow of water used for condensing in the condenser, and
4. Re-concentrating the absorbent leaving the generator and entering the absorber.

Method 1 does not affect the COP significantly as the required heat input reduces with reduction in weak solution flow rate, however, since this may lead to the problem of crystallization, many a time a combination of the above four methods are used in commercial systems to control the capacity.

THE ECONOMICS OF ABSORPTION TECHNOLOGY

Cost

The capital cost of installing an absorption chiller is significantly higher than an equivalent vapour compression chiller. Table below compares the cost in dollars per ton for installing several different capacities of electric chillers, single-effect steam heated absorption chillers, and double-effect direct-fired absorption chillers.

Chiller Capital Costs

Chiller Capacity (tons)	300 tons	500 tons	1000 tons
	Installed Chiller Costs ($/ton)		
Electric Centrifugal	340	340	350
Single Effect Steam Heated Absorption	520	430	365
Double Effect Direct Fired Absorption	625	625	625

Both technologies require a condenser and an evaporator of roughly the same size and cost. The cost difference comes from the additional heat exchangers - the generators, the absorber, the solution heat exchangers and the high-pressure condenser. In addition, the cooling tower for an absorption machine is larger - and more expensive - than that of a comparable- vapor compression machines.

While the cost of absorption equipment is higher in the short term the operating costs can be noticeably lower depending on the application and relative energy costs. Below is a case study comparison for a facility in Japan.

An example of two 120 Tons machines located within MetroGAS Headquarters “Ombú”		Electric Screw Compressor System	Absorption System
Heat Power Required	Ton	240	240

An example of two 120 Tons machines located within MetroGAS Headquarters "Ombú"			Electric Screw Compressor System	Absorption System
Heat Power Required		**Ton**	**240**	**240**
Electric Power				
Equipment	Maximum	kW	192	5
Ancillary Equipment	Maximum	kW	32	40
Annual Full Load Operating Hours		hrs/year	1000	1000
Consumed Electric Power				
Power	Contract - Not Peak Load	kW	224	45
	Contract - Peak Load	kW	224	45
Electric Power		kWh/yr	224,000	45,000
Consumed Electric Power		Nm^3/yr	0	76,800
Charges/Tariffs Applied				
Electric Power	Tariff No 3 -MT			
Power	Not Peak Load	$/kW	2.92	2.92
	Peak	$/kW	4.67	4.67
Energy		$/kWh	0.0365	0.0365
Taxes	Capital		6.38%	6.38%
Natural Gas	S.G.P. Tariff			

An example of two 120 Tons machines located within MetroGAS Headquarters “Ombú”			Electric Screw Compressor System	Absorption System
Heat Power Required		**Ton**	**240**	**240**
	Up to 1000Nm^3	\$/Nm^3		0.13430
	The Next 8000 Nm^3	\$/Nm^3		0.12548
	Remainder	\$/Nm^3		0.11667
	Bill Charge	$		12.7288
	Average	\$/Nm^3		0.12455
Taxes	Capital			2.60%
Annual Operating Costs				
Electric Power		$/year	$30400	$6100
Natural Gas		$/year	0	$9600
Annual Total Cost		$/year	$30400	$15700
Annual Operating Savings		$/year		$14700

Further, when viewed in context of life cycle analysis, the cost may be comparable:

- Reduced electrical service size, transformer, switchgear, cabling and other electrical auxiliaries;
- No need for an equipment room;
- The Electric Peak demand is reduced thereby providing recurring savings on the tariff;

- No need for installing emergency back-up power such as DG sets for critical applications;
- Direct-fired machines do not require boilers or waste heat recovery investments;
- Where waste heat is effectively tapped, chilling is essentially free; operating costs reduce drastically;
- Machines are silent and do not require acoustic protection;
- Machines are environmental friendly.

Their exact economics must be worked out on a project-by-project basis.

AVAILABLE CAPACITIES OF VAM

The chiller ratings are typically given at 100 percent design capacity. The units are rated according to ARI standards. The ARI standard specifies the condenser water inlet temperature (85 °F) and the chilled water exit temperature (44 °F). The actual unit capacity will vary as the above conditions change. The capacity and performance will decrease with higher condenser water or lower chilled water temperatures and vice-versa.

Commercially proven absorption cooling systems, ranging in size from 90 tons to 2,000 tons are widely available. These systems come as stand-alone chillers or as chillers with integral heating systems. Currently there are only single stage and two stage machines in production. There are several patents for 3 stage machines but they are not very common in the market.

Equipment Manufacturers

The following commercially proven absorption cooling systems, ranging in size from 20TR to 2500TR are widely available in the market. These systems come as stand-alone chillers or as chillers with integral heating systems.

- Yazaki LiBr Double-Effect, 20 to 100 ton
- McQuay LiBr Double-Effect, 20 to 100 ton
- Carrier Absorption Chillers, 100 to 1,700 ton

- Trane Absorption Chillers, 100 to 2,500 ton
- Daikin (McQuay) Absorption Chillers, 100 to 1,500 ton
- York Absorption Chillers, 100 to 1,500 ton
- Dunham-Bush, 100 to 1,400 tons

Is VAM Right for You?

Absorption cooling may be worth considering if your site requires cooling, and if at least one of the following applies:

1. You have a combined heat and power CHP) unit and cannot use all of the available heat, or if you are considering a new CHP plant;
2. Waste heat is available;
3. A low-cost source of fuels is available;
4. Your boiler efficiency is low due to a poor load factor;
5. Your site has an electrical load limit that will be expensive to upgrade;
6. Your site needs more cooling, but has an electrical load limitation that is expensive to overcome, and you have an adequate supply of heat.

In short, absorption cooling may fit when a source of free or low-cost heat is available, or if objections exist to using conventional refrigeration. Essentially, the low-cost heat source displaces higher-cost electricity in a conventional chiller. Absorption units are typically economical at 500 tons and above (on a first cost per ton basis).

Recent Improvements to absorption chillers

Since the 1960's, several improvements have been made to absorption chiller, which include:

1. Automatic purge systems eliminating the need for manual purging and lowering the potential for corrosion.
2. Faster system response due to the use of electronic controls and solution concentration sensing

3. Electronic controls and sensors that make crystallisation of the chiller far less likely than in the past.
4. Lower water flow requirements.
5. Absorption chillers can provide water temperature as low as 3.5 Deg C allowing for the use of reduced air flow and duct size in delivery systems.

Course Summary

The absorption cycle uses a heat-driven concentration difference to move refrigerant vapours (usually water) from the evaporator to the condenser. The high concentration side of the cycle absorbs refrigerant vapours (which, of course, dilute that material). Heat is then used to drive off these refrigerant vapours thereby increasing the concentration again. Lithium bromide is the most common absorbent used in commercial cooling equipment, with water used as the refrigerant. Smaller absorption chillers sometimes use water as the absorbent and ammonia as the refrigerant. The LiBr absorption chiller must operate at very low pressures (about l/l00th of normal atmospheric pressure) for the water to vaporize at a cold enough temperature (e.g., at ~ 40°F) to produce 44°F chilled water.

Absorption chillers are available in two types:

Single Effect (Stage) Units using low pressure (20 psig or less) as the driving force. These units typically have a COP of 0.7 and require about 18pph per ton of 9 psig steam at the generator flange (after control valve) at ARI standard rating conditions.

Double Effect (2-Stage) Units are available as gas-fired (either direct gas firing, or hot exhaust gas from a gas-turbine or engine) or steam-driven with high pressure steam (40 to 140 psig). These units typically have a COP of 1.0 to 1.2. Steam driven units require about 9 to 10 pph per ton of 114 psig input steam at ARI standard rating conditions. Gas-fired units require an input of about 10,000 to 12,000 Btuh HHV per ton of cooling at ARI standard rating conditions. To achieve this improved performance they have a second generator in the cycle and require a higher temperature energy source.

Cost is the primary constraint on the widespread adoption of absorption chiller systems. Although absorption chillers can be quite economical in the right situation, their exact economics must be worked out on a project-by-project basis.

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