OVERVIEW OF VAPOR ABSORPTION CHILLING SYSTEMS

Course Content

One of the oldest methods to mechanically cool a space is with absorption technology. A vapor absorption chiller (VAM) is a machine to produce chilled water using heat source such as steam, hot water, gas, and oil. It seems unreasonable to achieve cooling with heat, but that is what happens inside an absorption chiller.

A fluid pair lithium bromide and water is used in commercial VAM. The refrigerant used is actually water, as that is the working medium that experiences a phase change and causes the cooling affect. The second fluid that drives the process is a salt, generally lithium bromide. Heat is used to separate the two fluids; when they are mixed in a near vacuum environment.

For low temperature applications ammonia based absorption machines are used that utilize ammonia as refrigerant and water as an absorbent.

These machines use only small fraction of electricity as compared to the conventional vapor compression chillers. Vapor absorption systems work with non-CFC environmentally friendly refrigerants such as water or ammonia.

The capital cost of VAM is higher compared to compression systems, but when viewed in totality of reduced electrical service size, transformer, switchgear, cabling and lack of need for an equipment room, the VAM becomes comparable to compression systems.

Today's modern absorption chillers range from around 90 tons to 2000 tons. Currently there are only single stage and two stage machines in production. There are several patents for 3 stage machines but they are not currently in the market.

What you need to run a VAM?

Heat Source

Waste heat from the exhaust of a gas turbine, or from the exhaust and water jackets of a reciprocating engine is recovered for use through heat exchangers. The heat from the flue gases of furnaces, dryers, kilns and boilers can be utilized to drive the hot water or steam run chillers.

In the case of dual effect absorption chillers, high-pressure steam or direct firing from natural gas or oil, is the energy source.

Refrigerant

Vapor absorption systems work with non-CFC refrigerants such as water or ammonia.

Refrigerant of Li Br Absorption Machine is pure (distilled) water. The refrigerant water flows in a closed loop and is re-circulated. These systems find acceptability in the commercial air-conditioning or process cooling.

The ammonia based absorption system that uses ammonia as a refrigerant, finds use in low temperature applications.

Absorbent

Absorbent is a material that has great affinity with water. It is well known that when salt (such as Na Cl) is left in a high-humidity atmosphere, it becomes sticky. This is because it absorbs moisture in the atmosphere. You might have noticed a pack of silica gel in a shoebox. The purpose is to remove the dampness.

The vapor absorption machine uses an aqueous absorbent; Lithium Bromide (Li Br). We can easily relate that the lithium bromide and the sodium chloride have similar features because they are of the same element, that is, lithium (*Li*) and sodium (*Na*) are alkali while bromide (*Br*) and chlorine (*Cl*) are halogen. Li Br has the same characteristics of a salt and its absorption power is stronger than that of salt. The higher is the concentration and the lower its temperature, the stronger is the absorption power. The chemical details of Li Br are as follows:

- Chemical Formula: *Li Br*
- Molecular Weight: 86.856
- Component: *Li* = 7.99% / Br = 92.01%
- Specific Gravity: 3.464 at 25°C (77°F)
- Melting Point: 549°C (1,020.2 °F)
- Boiling Point: 1,265°C (2,309°F)

Li Br is a non-toxic aqueous solution but very corrosive in oxygen.

Absorbent in the ammonia based absorption machine is water.

Inhibitor

Li Br has a corrosive action to metals in oxygen. But, as the absorption chiller is a vacuum vessel, almost no oxygen is present in it. However, to safeguard and have a complete protection, corrosion inhibitor is added in the absorbent and alkalinity is adjusted. Alcohol namely octyle alcohol is generally added into the system to increase the absorption effect of the absorbent.

Cooling Water

Cooling water is required to cool the absorbent and the refrigerant vapor. The cooling water flows through the Absorber and the Condenser items of the VAM. The heat gain in the cooling water is rejected in a cooling tower and thus is an open loop. Around 2% of water is lost as a result of evaporation, drift and blow down in the cooling tower that needs make-up.

Vapor Absorption Refrigeration Principle

Do you know water boils at 89°C at the summit of 2750m mountains?

The fundamental truth is that the water boils at 100°C (212°F) in the atmospheric pressure and when the pressure is higher than the atmospheric pressure, water boils at a temperature higher than 100°C (212°F) while when the pressure is lower (vacuum), water boils at a temperature lower than 100°C (212°F).

The pressure less than atmospheric pressure is called vacuum. Two basic principles underlying the operation of absorption systems are as follows:

1. *The first principle is that water boils at 5deg C at low-pressure vacuum conditions of 6.5mmwg.*
2. The second principle is *"Evaporation results in cooling."*

Lets examine the above closely.

Consider a closed vessel placed under vacuum of say 6.5mmHg (refer figure below). Imagine the closed vessel contain a dry silica gel, which is high quality absorbent material and also a heat transfer tube through which water is circulated. Now drop water on the outer wall of the heat transfer tube. The following phenomenon shall occur:

1. The water droplets under vacuum conditions get evaporated at 5°C (41°F) taking an evaporation heat from running water in the heat transfer tube. Such a liquid is called a refrigerant.
2. The vapors so produced, as a result of evaporation shall immediately be absorbed by the silica gel. This ensures the vacuum is kept inside the vessel.
3. The running water in the heat transfer tube become cool because the heat equivalent to the evaporation heat is taken.

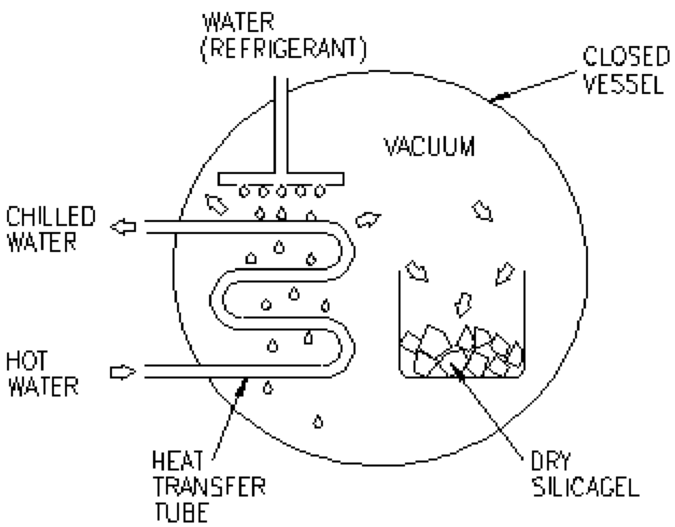


Figure – Vapor Absorption System with Silica Gel Absorbent

When the silica gel reaches the limit of its absorbing capacity, the process continuity cannot be maintained. Therefore some means of converting the absorbent to original concentration is necessary, to ensure continuous cooled water supply.

In commercial practice silica gel is replaced with aqueous solution of lithium bromide (Li Br). Li Br is much easy to handle than a solid, silica gel absorbent and exhibits great affinity to water.

Continuing with the same explanation, Li Br after absorbing water vapors gets diluted. It reaches a stage when it can no longer hold vapors and it is necessary to enrich it again to the original level of concentration.

To recover the absorbent power, the weak diluted absorbent is heated that causes the solution to release the absorbed vapor. The mixture is separated and the concentrated absorbent is recycled back to the vessel. The released refrigerant vapor is condensed in a separate vessel and sent back for evaporation. The figure below reflects the scheme.

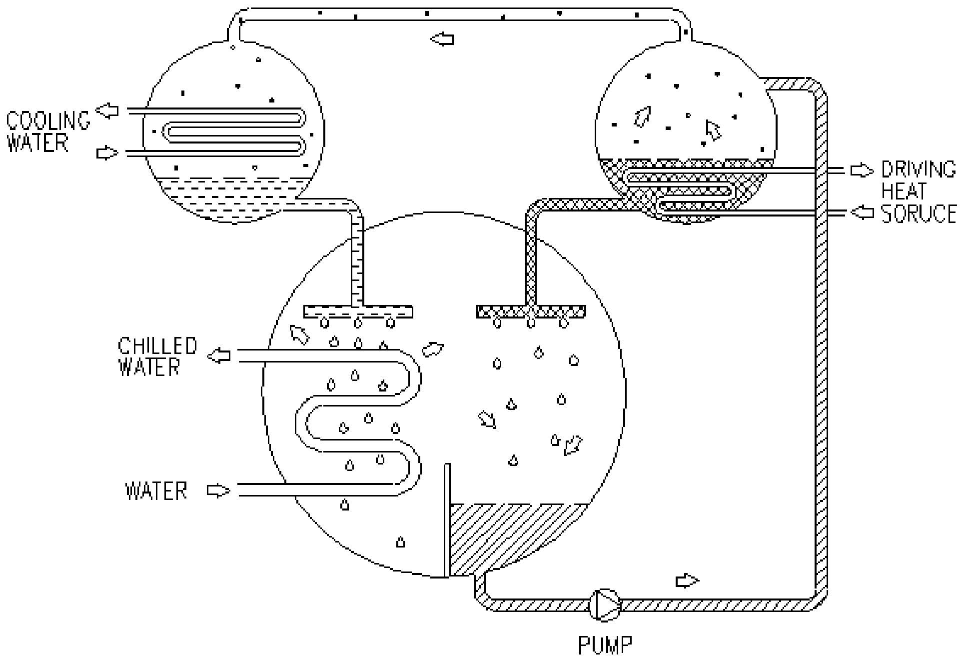
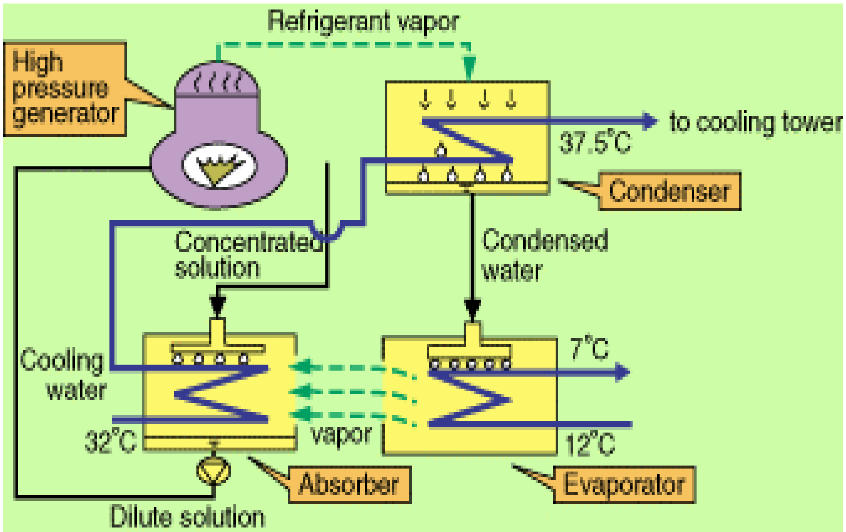


Figure – Vapor Absorption System with Aqueous Li Br Absorbent

How does the absorption chiller works?

The inside of the absorption machine is always kept in vacuum. There are 4 main components of the VAM namely:

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



EVAPORATOR

The evaporator functions to cool the water flowing though a coil.

The condensed refrigerant (water) droplets falling on the heat transfer tubes evaporate over the tubes. The water running through the heat transfer tubes of evaporator is cooled by the latent heat of vaporized refrigerant.

The evaporator is maintained under vacuum of around 6.5mmHg to which the refrigerant water boils at around 5°C.

Table below shows the relationship between the pressure and evaporation temperature.

	Gauge Pressure (kg/cm² G)	Absolute Pressure (kg/cm² G)	Temp. (°C)	Remarks
Pressure	10	11	183.2	
	8	9	174.5	Driving pressure for double effect type
	5	6	158.1	
	1	2	119,6	Driving pressure for single effect type
	0.5	1.5	110.8	
1 atm.		760 mmHg	100	Atmospheric Pressure
Vacuum		650.0	95.5	High Temp. Generator Pressure
		525.9	90.0	
		167.6	62.6	
		92.5	50.0	
		61.0	41.5	Condenser Pressure
		31.8	30.0	
		29.4	28.6	
		9.2	10.0	
		6.54	5.0	Evaporator Pressure
		5.68	3.0	

ABSORBER

The absorber functions to maintain the pressure of the evaporator in the vacuum by absorbing the refrigerant vapor evaporated in the evaporator.

The refrigerant vapor from the evaporator is drawn into "absorber " vessel containing the "absorbent" solution. The vapor gets readily absorbed into the absorbent, due to its strong affinity for the refrigerant.

The cooling water flowing through the cooling coils within the absorber absorbs the heat load from the evaporator and, unavoidably, some of the residual heat from the concentrated solution. This heat is dissipated through the cooling tower.

When the refrigerant vapors are absorbed, a vacuum is created which allows the refrigerant from the condenser to expand into the evaporator causing the refrigerating effect.

GENERATOR

The generator functions to enrich the Li Br solution to its original concentration.

As lithium bromide solution is diluted, the effect to absorb the refrigerant vapor reduces. The diluted solution of Li Br absorbent flows to the Generator to regain its concentration.

It is a vessel where the diluted solution of absorbent is heated by means of steam, hot water or direct gas/oil firing. The diluted solution releases the refrigerant vapor and becomes concentrated solution.

The hot concentrated solution, which has now regained its strong affinity for absorbing more refrigerant, returns back to the ‘absorber’.

A heat exchanger is generally provided for heat exchange between the cold dilute solution before entering the generator and the hot concentrated solution leaving the generator. This improves the ‘cycle efficiency’ as preheating of the dilute solution prior to entering the generator reduces the heat-energy input to the generator and the simultaneous pre-cooling of the concentrated solution returning to the 'absorber' will reduce the extent of cooling water flow in the absorber.

CONDENSER

The refrigerant vapors that are released from the generator are cooled and liquefied in a condenser.

The hot refrigerant vapors leaving the generator flows through eliminators or separator (which prevent carry over of Li Br) to the condenser. The cooling water from a cooling tower circulates through the condenser removing the heat from the vapors. The low temperature steam vapor is condensed into a liquid refrigerant where it passes through an orifice into the evaporator, which operates under a vacuum. This performs the same function as the condenser in a conventional compression refrigeration system.

The cooling water is the same water that has been previously used to cool the absorber.

Single – Double Effect Absorption Chillers

Without getting technical, the number of "effects" in a chiller reflects the number of times energy is used. The single effect absorption cycle uses a single generator for concentrating the diluted solution.

Single Effect Units use low- pressure (20 psig or less) steam or hot water at (85 deg C to 95 deg. C) as the driving force. These units typically require about 18pph per ton of 9-psig steam at the generator flange (after control valve) at ARI standard rating conditions.

The Coefficient of performance (i.e. useful refrigeration effect in the evaporator divided by the heat input in generator) of single effect absorption chillers is low (ranging between 0.68 to 0.75)

However, a single-effect vapor absorption system offers the unique benefits of obtaining useful refrigeration for air-conditioning or process chilling through heat recovery from low-pressure and temperature waste steam in certain industrial processes or power plants using condensing back-pressure turbines, as well as heat recovery from a relatively lower-temperature flue-gas (such as a diesel engine/ gas engine exhaust) to produce hot water for operating the single effect vapor absorption cycle.

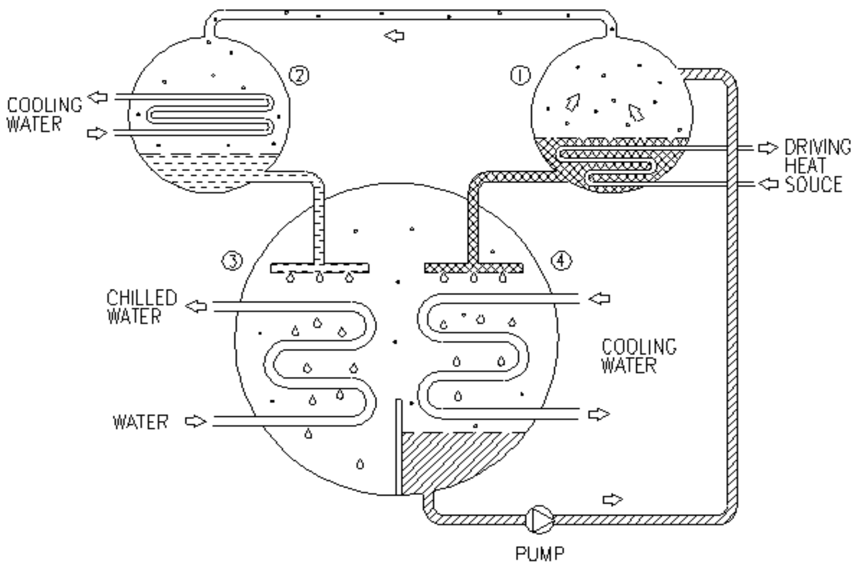


Figure - Basic Cycle of Single Effect Chiller

Double Effect (2-Stage) Units

The double effect units are available as direct burner-fired (using either gas or oil) or steam-driven with high-pressure steam (40 to 140 psig).

The Double Effect Type Absorption Machine adopts a higher heat efficiency of condensation. The Generator section is divided into a High Temperature Generator and a Low Temperature Generator. The refrigerant vapor produced by the High Temperature generator is used to heat the *Li Br* solution in the low temperature generator in which the pressure (hence the boiling point) is lower.

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.

The improved performance over single effect machine is due to second generator in the cycle and higher temperature energy source.

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

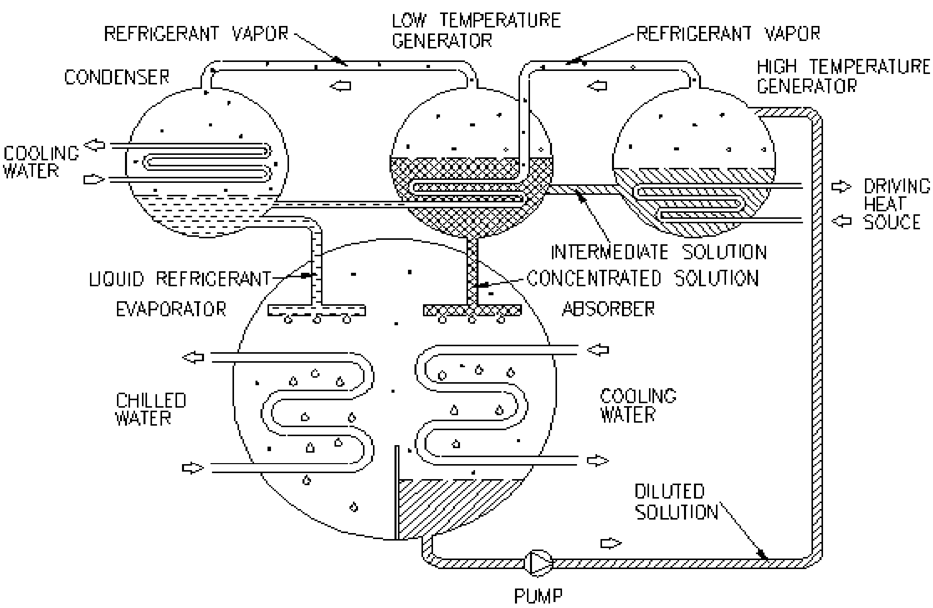
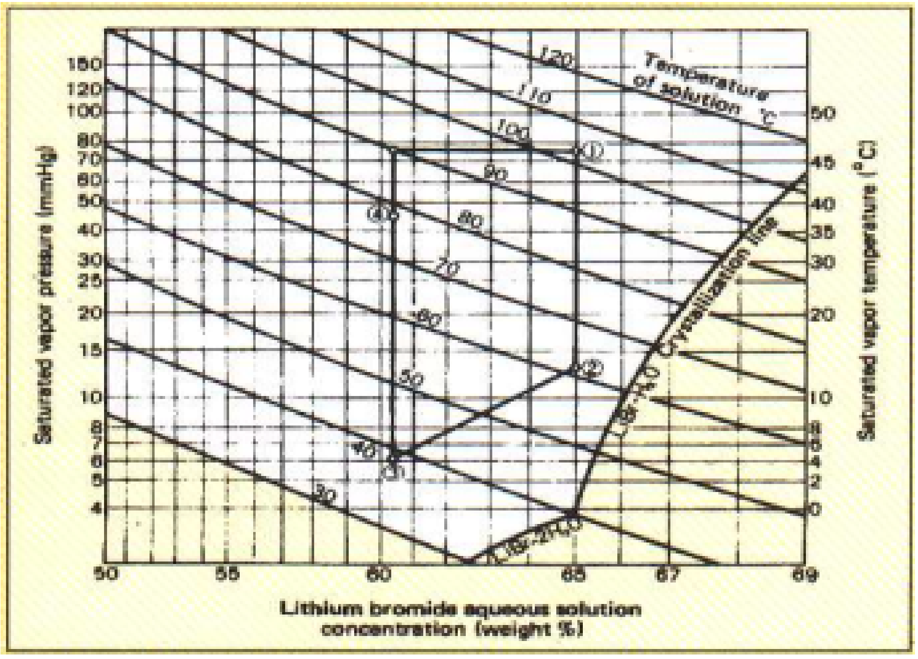


Figure - Basic Cycle of Double Effect Type Chillers

Performance Analysis of Li Br System

The absorption cycle's performance can be read in Figure below which depicts the temperature pressure concentration relation for the lithium bromide aqueous solution in the entire cycle.



The explanation is as follows:

1. At Generator Outlet: shows concentrated and heated state of lithium bromide solution (65% lithium bromide by weight) and temperature 103 deg. C and corresponding vapor pressure of 75 mm mercury Absolute.

2. At Absorber Inlet: Lithium bromide concentration remaining unchanged i.e. 65% but solution temperature coming down to 61 deg C (after passing through heat-exchanger) and vapor pressure 13 mm mercury Absolute.

3. At Absorber Outlet: Lower solution concentration of 60.3% reached after dilution and cold solution temperature of approx 38.5 deg C.

4.Inlet of Generator: Solution concentration remaining unchanged i.e. 60.3% (as in 3 above) but higher solution temperature of approx. 78 deg C attained due to pre-heating in the heat-exchanger.

Operation Issues and Precautions

Li Br absorbent is prone to "crystallization". If something goes wrong in the cycle, the salt and water would permanently separate, and the aqueous solution of Li Br shall crystallize on the walls of the absorber. Modern controls pretty much make that impossible to happen now, but for understanding, it is important to have the concept.

The cooling water influences the operation of VAM. Cooling water flows through the Absorber and the Condenser. The cooling water takes the heat, which the *Li Br* solution absorbs from the refrigerant vapor in the Absorber. This means the cooling water-cools the absorbent and the refrigerant vapor from the Generator.

1) The lower temperature of cooling water

The absorption power of *Li Br* solution is stronger at lower temperature of the 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 *Li Br* solution decreases when the condensing pressure is low, 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 that the temperature of cooling water is too low. The lithium bromide solution of certain concentration becomes crystallized under the temperature lower than certain degree. For example, at a concentration of Li Br of 65% this absorbent solution crystallizes at a temperature lower than 42°C(108°F), with concentration of 60% at a temperature lower than 17°C(63°F) and with concentration of 55% at the temperature lower than 15 deg C. As the absorbent crystallizes, it become a solid, thus unable to flow therefore chiller cannot operate. Plus it leaves a messy maintenance work of cleaning the whole system.

3) The cooling water temperature becomes high

The Machine has some problems when cooling water temperature becomes too high. With increase of cooling water temperature, the absorption power of the *Li Br* solution is degraded. The Machine cannot produce the normal chilled water temperature and higher fuel is consumed. Therefore, to prevent this, the stability of cooling water system, preventive maintenance of cooling tower system/ equipment and water treatment is essential.

4) Water treatment of cooling water

The water treatment of the cooling water is an important factor for the Machine. If the water quality is not good, the heat transfer tubes may form a scale on the interior surfaces besides it may become corroded. The heat transfer capability shall decrease, causing abrupt changes in chilled water temperature and a waste of the driving source energy.

CAPACITY CONTROL

Capacity of the unit is automatically controlled to meet the load variation, by varying the rate of re-concentration of the dilute solution in the generator by regulating the steam supply to the unit with a control valve at the steam condensate outlet getting a command for opening or closing from the 'sensor' sensing the outlet chilled water temperature.

VAM FOR HEATING

The absorption process described can also be used for heating applications by passing the hot refrigerant (water) vapors directly from the high temperature generator to the evaporator where the chilled water coils become heating coils. This is the function of the conventional gas fired "Chiller/Heater.

Some units can optionally heat and cool at the same time (for multi-zoned applications that have both a heated and chilled water loop).

Choice of Refrigerant- Absorption Pairs

Lithium Bromide – Water Absorption System

A fluid pair comprising lithium bromide salt solution as 'absorbent ' and water as refrigerant is commonly used for air-conditioning applications.

The characteristics are:

At the operating temperatures and pressures encountered, water as refrigerant is much more volatile compared to lithium bromide which is practically non-volatile. Hence it is feasible to separate the refrigerant from the absorbent for proper evaporation of the refrigerant in the evaporator.

A concentrated lithium bromide solution has great affinity for water.

Since the operating pressures are low in the lithium bromide-water absorption system, the pumping cost is low and also the wall thickness of the shell gets reduced compared to the ammonia-water fluid combination. The ammonia-water absorption system is now used mainly for low-temperature applications.

The precautions are:

Since water is used as refrigerant, evaporation temperature must be kept above the freezing point of water and hence the temperature of chilled water from such a system cannot be less than 5 deg C (41 deg. F)

Lithium bromide solution is corrosive. Therefore inhibitors need to be added to the system to protect the metal parts of the system against corrosion.

Coolant temperatures must not be too low to avoid crystallization of the lithium bromide.

Ammonia-Water Absorption System

A fluid pair comprising ammonia as refrigerant and water as absorbent is mainly used for low temperature refrigeration applications.

The characteristics are:

Ammonia water as working media has following advantages:

- High affinity
- High stability
- Moderate operating pressure, No vacuum up to -30°C
- Absence of solid phase
- Non-corrosive to carbon steel

Water has great affinity for ammonia and can dissolve enormous amounts of ammonia vapor and there is no solidification problem encountered with ammonia refrigerant over a very wide range of evaporating temperatures even up to very low temperature applications.

The precautions are:

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 of the ammonia liquid in the evaporator and reduce the refrigeration capacity. A separate rectifier is generally provided to overcome this problem.

Cost Economics

The absorption systems with a COP of 1.0 burn 12,000 BTUs of gas for each ton-hour of cooling, or at $4.50 per MCF, $0.054/ton-hour. There is an electric load on the absorbers for pumps (in addition to cooling towers and chilled water loops) that must be considered as well.

Therefore, before an absorption machine can break even with the cost of electric equipment, the gas cost must be below $4.50/MCF and electric above $0.08/KWH. Then you can deal with the additional first cost of the units

Find below is a case study comparison for one of the facility in Japan. This illustration provides useful format to perform life cycle analysis on new projects.

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			
	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

S.G.P. Tariff - General Small Supply Tariff

While the cost of absorption pieces of equipment is higher than the same power compressor ones, the lower operating cost balances the difference in the short term.

Other General Facts and Economics

1. From the Li Br absorption system, since water is the refrigerant, the minimum possible chilled water temperature at its lowest is about 46° F. Therefore, absorbers cannot be used in a refrigeration application. The ammonia –water absorption systems find usage in low temperature cold storages and refrigeration applications.

2. The coefficient of performance (COP) of the absorption machine is low generally around 1 as compared to around 3 for modern vapor compression systems. The VAM however offer great savings where there is possibility of tapping waste heat in industrial applications or where the energy pricing electricity v/s fuel oil/gas tip the scale in favor of fuel/gas. Typically, the life cycle analysis on various projects indicate that the dual effect absorption chillers shall operate more economically in

most geographical areas, due to the differential in the cost between gas and electric energy.

3. The energy and environmental norms are becoming more and more stringent in all countries. The concept of energy consumption and CO_2 emission tax is becoming reality in many western countries. On international scale many countries have started identifying VAM as an energy & environmentally friendly device. The ozone depletion issues associated with compression systems and the green house/ acid rain issues associated with power generation favors induction of VAM. Absorption chillers do not use CFCs or HCFCs.

4. Many of the smaller sizes of absorption chillers up to 100 tons are designed for outside installations and require no equipment rooms as compared with larger size absorption chillers, which do.

5. The absorption systems do require cooling water. Air-cooled options are not available in commercial market. The areas having scarcity of good quality water should carefully evaluate the economics.

6. VAM uses only small fraction of electricity to drive the solution pumps as compared to the conventional vapor compression chillers.

7. The capital cost of VAM is higher by at least by 50% as compared to equivalent compression systems. But when the following items are considered for 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 that shall provide recurring savings on the tariff
   - No need for installing an emergency back up power such as DG sets for critical applications
   - The direct-fired machines do not require any boilers or waste heat recovery investments

- Where waste heat is effectively tapped the chilling is for the free; operating costs reduce drastically
- Machines are silent and do not require acoustic protection
- Machines are environmental friendly
- Some states and utility companies provide subsidies and incentives such as higher depreciation for VAM