# CHAPTER 41

# ABSORPTION COOLING, HEATING, AND REFRIGERATION EQUIPMENT

THIS chapter surveys and summarizes the types of absorption equipment that are currently manufactured and/or commonly encountered. The equipment can be broadly categorized by whether it uses water or ammonia as refrigerant. The primary products in the water refrigerant category are large commercial chillers, which use lithium bromide (LiBr) as absorbent. There are three primary products in the ammonia refrigerant category: (1) domestic refrigerators, (2) residential chillers, and (3) large industrial refrigeration units.

This chapter focuses on the hardware (i.e., the cycle implementation), not on the cycle thermodynamics. Cycle thermodynamic descriptions and calculation procedures are presented in Chapter 1 of the *ASHRAE Handbook—Fundamentals* along with a tabulation of the types of absorption working pairs and a glossary.

Absorption units provide two major advantages: (1) they are activated by heat, and (2) no mechanical compression of vapor is required. They also do not use atmosphere-harming halogenated refrigerants, and reduce summer electric peak demand. No lubricants, which are known to degrade heat and mass transfer, are required. The various equipment can be direct-fired by combustion of fuel, can be directly heated by various waste fluids, or can be heated by steam or hot water (from either direct combustion or from hot waste fluids). Figure 1 illustrates the similarities between absorption and vapor compression systems.

With natural gas firing, absorption chilling units level the year-round demand for natural gas. From an energy conservation perspective, the combination of a prime mover plus a waste-heat-powered absorption unit provides unparalleled overall efficiency.

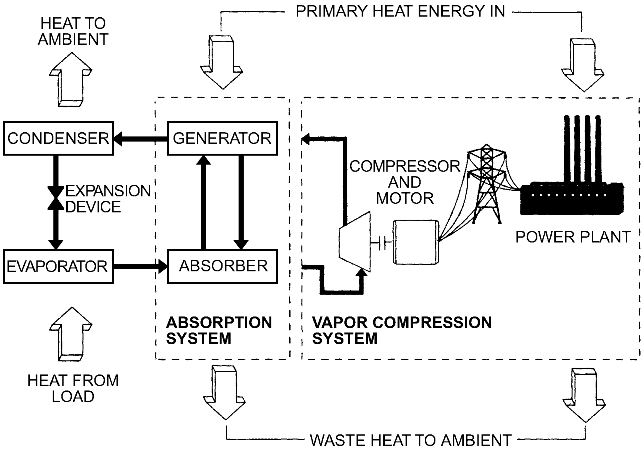

**Fig. 1 Similarities Between Absorption and Vapor Compression Systems**

## WATER-LITHIUM BROMIDE ABSORPTION TECHNOLOGY

### Components and Terminology

Absorption equipment using water as the refrigerant and lithium bromide as the absorbent is classified by the method of heat input to the primary generator (the firing method) and whether the absorption cycle is single- or multiple-effect.

Machines using steam or hot liquids as a heat source are **indirect-fired**, and those using direct combustion of fossil fuels as a heat source are **direct-fired**. Machines using hot waste gases as a heat source are also classified as indirect-fired but are often referred to as **heat recovery chillers**.

**Solution recuperative heat exchangers**, also referred to as **economizers**, are typically shell-and-tube or plate heat exchangers. They transfer heat between hot and cold absorbent solution streams, thus recycling energy. The material of construction is mild steel or stainless steel.

**Condensate subcooling heat exchangers**, a variation of solution heat exchangers, are used on steam-fired, double-effect machines and on some single-effect, steam-fired machines. These heat recovery exchangers use the condensed steam to add heat to the solution entering the generator.

**Indirect-fired generators** are usually of the shell-and-tube type, with the absorbent solution either flooded or sprayed outside the tubes, and the heat source (steam or hot fluid) inside the tubes. The absorbent solution boils outside the tubes, and the resulting intermediate- or strong-concentration absorbent solution flows from the generator through an outlet pipe. The refrigerant vapor evolved passes through a vapor/liquid separator consisting of baffles, eliminators, and low-velocity regions and then flows to the condenser section. Ferrous materials are used for absorbent containment; copper, copper-nickel alloys, stainless steel, or titanium are used for the tube bundle.

**Direct-fired generators** consist of a fire-tube section, a flue-tube section, and a vapor/liquid separation section. The fire tube is typically a double-walled vessel with an inner cavity large enough to accommodate a radiant or open-flame fuel oil or natural gas burner. Dilute solution flows in the annulus between the inner and outer vessel walls and is heated by contact with the inner vessel wall. The flue-tube section is typically a tube or plate heat exchanger connected directly to the fire tube.

Heated solution from the fire-tube section flows on one side of the heat exchanger, and flue gases flow on the other side. Hot flue gases further heat the absorbent solution and cause it to boil. The flue gases leave the generator, while the partially concentrated absorbent solution and refrigerant vapor mixture pass to a vapor/liquid separator chamber. This chamber separates the absorbent solution from the refrigerant vapor. Materials of construction are mild steel for the absorbent containment parts and mild steel or stainless steel for the flue gas heat exchanger.

**Secondary** or **second-stage generators** are used only in double- or multistage machines. They are both a generator on the low-

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pressure side and a condenser on the high-pressure side. They are usually of the shell-and-tube type and operate similarly to indirect-fired generators of single-effect machines. The heat source, which is inside the tubes, is high-temperature refrigerant vapor from the primary generator shell. Materials of construction are mild steel for absorbent containment and usually copper-nickel alloys or stainless steel for the tubes. Droplet eliminators are typically stainless steel.

**Evaporators** are heat exchangers, usually of the shell-and-tube type, over which liquid refrigerant is dripped or sprayed and evaporated. The liquid to be cooled passes through the inside of the tubes. Evaporator tube bundles are usually copper or a copper-nickel alloy. Refrigerant containment parts are mild steel. Mist eliminators and drain pans are typically stainless steel.

**Absorbers** are tube bundles over which strong absorbent solution is sprayed or dripped in the presence of refrigerant vapor. The refrigerant vapor is absorbed into the absorbent solution, thus releasing heat of dilution and heat of condensation. This heat is removed by cooling water that flows through the tubes. Weak absorbent solution leaves the bottom of the absorber tube bundle. Materials of construction are mild steel for the absorbent containment parts and copper or copper-nickel alloys for the tube bundle.

**Condensers** are tube bundles located in the refrigerant vapor space near the generator of a single-effect machine or the second-stage generator of a double-effect machine. The water-cooled tube bundle condenses refrigerant from the generator on the surface of the tubes. Materials of construction are mild steel, stainless steel, or other corrosion-resistant materials for the refrigerant containment parts and copper for the tube bundle. For special waters, the condenser tubes can be copper-nickel, which derates the performance of the unit.

**High-stage condensers** are found only in double-effect machines. This type of condenser is typically the inside of the tubes of the second-stage generator. Refrigerant vapor from the first-stage generator condenses inside the tubes, and the resulting heat is used to concentrate absorbent solution in the shell of the second-stage generator when heated by the outside surface of the tubes.

**Pumps** move absorbent solution and liquid refrigerant in the absorption machine. Pumps can be configured as individual (one motor, one impeller, one fluid stream) or combined (one motor, multiple impellers, multiple fluid streams). The motors and pumps are hermetic or semihermetic. Motors are cooled and bearings lubricated either by the fluid being pumped or by a filtered supply of liquid refrigerant. Impellers are typically brass, cast iron, or stainless steel; volutes are steel or impregnated cast iron, and bearings are babbitt-impregnated carbon journal bearings.

**Refrigerant pumps** (when used) recirculate liquid refrigerant from the refrigerant sump at the bottom of the evaporator to the evaporator tube bundle in order to effectively wet the outside surface and enhance heat transfer.

**Dilute solution pumps** take dilute solution from the absorber sump and pump it to the generator.

**Absorber spray pumps** recirculate absorbent solution over the absorber tube bundle to ensure adequate wetting of the absorber surfaces. These pumps are not found in all equipment designs. Some designs use a jet eductor for inducing concentrated solution flow to the absorber sprays. Another design uses drip distributors fed by gravity and the pressure difference between the generator and absorber.

**Purge systems** are required on lithium bromide absorption equipment to remove noncondensables (air) that leak into the machine or hydrogen (a product of corrosion) that is produced during equipment operation. Even in small amounts, noncondensable gases can reduce chilling capacity and even lead to solution crystallization. Purge systems for larger sizes above 100 tons of refrigeration typically consist of these components:

- Vapor pickup tube(s), usually located at the bottom of large absorber tube bundles
- Noncondensable separation and storage tank(s), located in the absorber tube bundle or external to the absorber/evaporator vessel
- A vacuum pump or valving system using solution pump pressure to periodically remove noncondensables collected in the storage tank

Some variations include jet pumps (eductors), powered by pumped absorbent solution and placed downstream of the vapor pickup tubes to increase the volume of sampled vapor, and water-cooled absorbent chambers to remove water vapor from the purged gas stream.

Because of their size, smaller units have fewer leaks, which can be more easily detected during manufacture. As a result, small units may use variations of solution drip and entrapped vapor bubble pumps plus purge gas accumulator chambers.

**Palladium cells**, found in large direct-fired and small indirect-fired machines, continuously remove the small amount of hydrogen gas that is produced by corrosion. These devices operate on the principle that thin membranes of heated palladium are permeable to hydrogen gas only.

**Corrosion inhibitors**, typically lithium chromate, lithium nitrate, or lithium molybdate, protect machine internal parts from the corrosive effects of the absorbent solution in the presence of air. Each of these chemicals is used as a part of a corrosion control system. Acceptable levels of contaminants and the correct solution pH range must be present for these inhibitors to work properly. Solution pH is controlled by adding lithium hydroxide or hydrobromic acid.

**Performance additives** are used in most lithium bromide equipment to achieve design performance. The heat and mass transfer coefficients for the simultaneous absorption of water vapor and cooling of lithium bromide solution have relatively low values that must be enhanced. A typical additive is one of the octyl alcohols.

## Single-Effect Lithium Bromide Chillers

Figure 2 is a schematic diagram of a commercially available single-effect, indirect-fired liquid chiller, showing one of several configurations of the major components. Table 1 lists typical characteristics of this chiller. During operation, heat is supplied to tubes

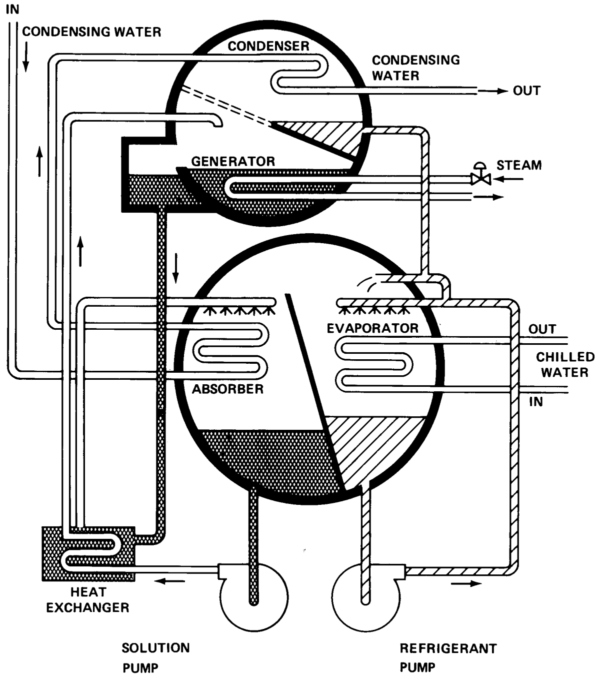

**Fig. 2 Two-Shell Lithium Bromide Cycle Water Chiller**

**Table 1 Characteristics of Typical Single-Effect, Indirect-Fired, Water-Lithium Bromide Absorption Chiller**

| Performance Characteristics | |
|---|---|
| Steam input pressure | 9 to 12 psig |
| Steam consumption | 18.3 to 18.7 lb/ton·h |
| Hot-fluid input temp. | 240 to 270°F, with as low as 190°F for some smaller machines for waste heat applications |
| Heat input rate | 18,100 to 18,500 Btu/ton·h, with as low as 17,100 Btu/ton·h for some smaller machines |
| Cooling water temp. in | 85°F |
| Cooling water flow | 3.6 gpm/ton, with up to 6.4 gpm/ton for some smaller machines |
| Chilled water temp. off | 44°F |
| Chilled water flow | 2.4 gpm/ton, with 2.6 gpm/ton for some smaller international machines |
| Electric power | 0.01 to 0.04 kW/ton with a minimum of 0.004 kW/ton for some smaller machines |
| **Physical Characteristics** | |
| Nominal capacities | 50 to 1660 tons, with 5 to 10 tons for some smaller machines |
| Length | 11 to 33 ft, with as low as 3 ft for some smaller machines |
| Width | 5 to 10 ft, with 3 ft minimum for some smaller machines |
| Height | 7 to 14 ft, with 6 ft for some smaller machines |
| Operating weight | 11,000 to 115,000 lb, with 715 lb for some smaller machines |

of the **generator** in the form of a hot fluid or steam, causing dilute absorbent solution on the outside of the tubes to boil. This desorbed refrigerant vapor (water vapor) flows through eliminators to the **condenser**, where it is condensed on the outside of tubes that are cooled by a flow of water from a heat sink (usually a cooling tower). Both the boiling and condensing processes take place in a vessel that has a common vapor space at a pressure of about 0.9 psia.

The condensed refrigerant passes through an orifice or liquid trap in the bottom of the condenser and enters the evaporator. In the **evaporator**, the liquid refrigerant boils as it contacts the outside surface of tubes that contain a flow of water from the heat load. In this process, the water in the tubes is cooled as it releases the heat required to boil the refrigerant. Refrigerant that does not boil is collected at the bottom of the evaporator, flows to a **refrigerant pump**, is pumped to a distribution system located above the evaporator tube bundle, and is sprayed over the evaporator tubes again.

The dilute (weak in absorbing power) absorbent solution that enters the generator increases in concentration (percentage of sorbent in the water) as it is boiled and releases water vapor. The resulting strong absorbent solution leaves the generator and flows through one side of a **solution heat exchanger** where it cools as it heats a stream of weak absorbent solution passing through the other side of the solution heat exchanger on its way to the generator. This increases the efficiency of the machine by reducing the amount of heat from the primary heat source that must be added to the weak solution before it begins to boil in the generator.

The cooled, strong absorbent solution then flows (in some designs via a jet eductor or solution spray pumps) to a solution distribution system located above the **absorber tubes** and drips or is sprayed over the outside surface of the absorber tubes. The absorber and evaporator share a common vapor space at a pressure of about 0.1 psia. This allows refrigerant vapor, which is evaporated in the evaporator, to be readily absorbed into the absorbent solution flowing over the absorber tubes. This absorption process releases heat of condensation and heat of dilution, which are removed by cooling water flowing through the absorber tubes. The resulting weak absorbent solution flows off the absorber tubes and then to the absorber sump and **solution pump**. The pump and piping convey the weak absorbent solution to the heat exchanger, where it accepts heat from the strong absorbent solution returning from the generator. From there, the weak solution flows into the generator, thus completing the cycle.

These machines are typically fired with low-pressure steam or medium-temperature liquids. Several manufacturers in the United States and elsewhere have machines with capacities ranging from 50 to 1660 tons of refrigeration. Machines of 5 to 10 ton capacities are also available from international sources.

Typical coefficients of performance (COPs) for large single-effect machines at Air Conditioning and Refrigeration Institute (ARI) rating conditions are 0.7 to 0.8.

## Single-Effect Heat Transformers

Figure 3 shows a schematic of a single-effect heat transformer (or Type 2 heat pump). All major components are similar to the single-effect, indirect-fired liquid chiller. However, the absorber/evaporator is located above the desorber (generator)/condenser due to the higher pressure level of the absorber and evaporator compared to the desorber/condenser pair, which is the opposite of a chiller.

High-pressure refrigerant liquid enters the top of the evaporator, and heat released from a waste hot water stream converts it to a vapor. The vapor travels to the absorber section, where it is absorbed by the incoming rich solution. The heat released during this process is used to raise the temperature of a secondary fluid stream to a useful level.

The diluted solution leaves the bottom of the absorber shell and flows through a solution heat exchanger. There it releases heat in counterflow to the rich solution. After the solution heat exchanger, the dilute solution flows through a throttling device, where its pressure is reduced before it enters the generator unit. In the generator, heat from a waste hot-water system generates low-pressure refrigerant vapor. The rich solution leaves the bottom of the generator shell and a solution pump sends it to the absorber.

The low-pressure refrigerant vapor flows from the generator to the condenser coil, where it releases heat to a secondary cooling fluid and condenses. The condensate flows by gravity to a liquid storage sump and is pumped into the evaporator. Unevaporated refrigerant collects at the bottom of the evaporator and flows back into the storage sump below the condenser. Measures must be taken to control the refrigerant pump discharge flow and to prevent vapor from blowing back from the higher-pressure evaporator into the condenser during start-up or during any other operational event that causes low condensate flow. Typically, a column of liquid refrigerant is used to seal the unit to prevent blowback, and a float-operated valve controls the refrigerant flow to the evaporator. Excess refrigerant flow is maintained to adequately distribute the liquid with only fractional evaporation.

## Double-Effect Chillers

Figure 4 is a schematic of a commercially available, double-effect indirect-fired liquid chiller. Table 2 lists typical characteristics of this chiller. All major components are similar to the single-effect chiller except for an added generator (first-stage or primary generator), condenser, heat exchanger, and optional condensate subcooling heat exchanger.

Operation of the double-effect absorption machine is similar to that for the single-effect machine. The primary generator receives heat from the external heat source, which boils dilute absorbent solution. The pressure in the vapor space of the primary generator is about 15 psia. This vapor flows to the inside of tubes in the second-effect generator. At this pressure the refrigerant vapor has a condensing temperature high enough to boil and concentrate absorbent solution on the outside of these tubes, thus creating additional refrigerant vapor with no additional primary heat input.

The extra solution heat exchanger (high-temperature heat exchanger) is placed in the intermediate and dilute solution streams

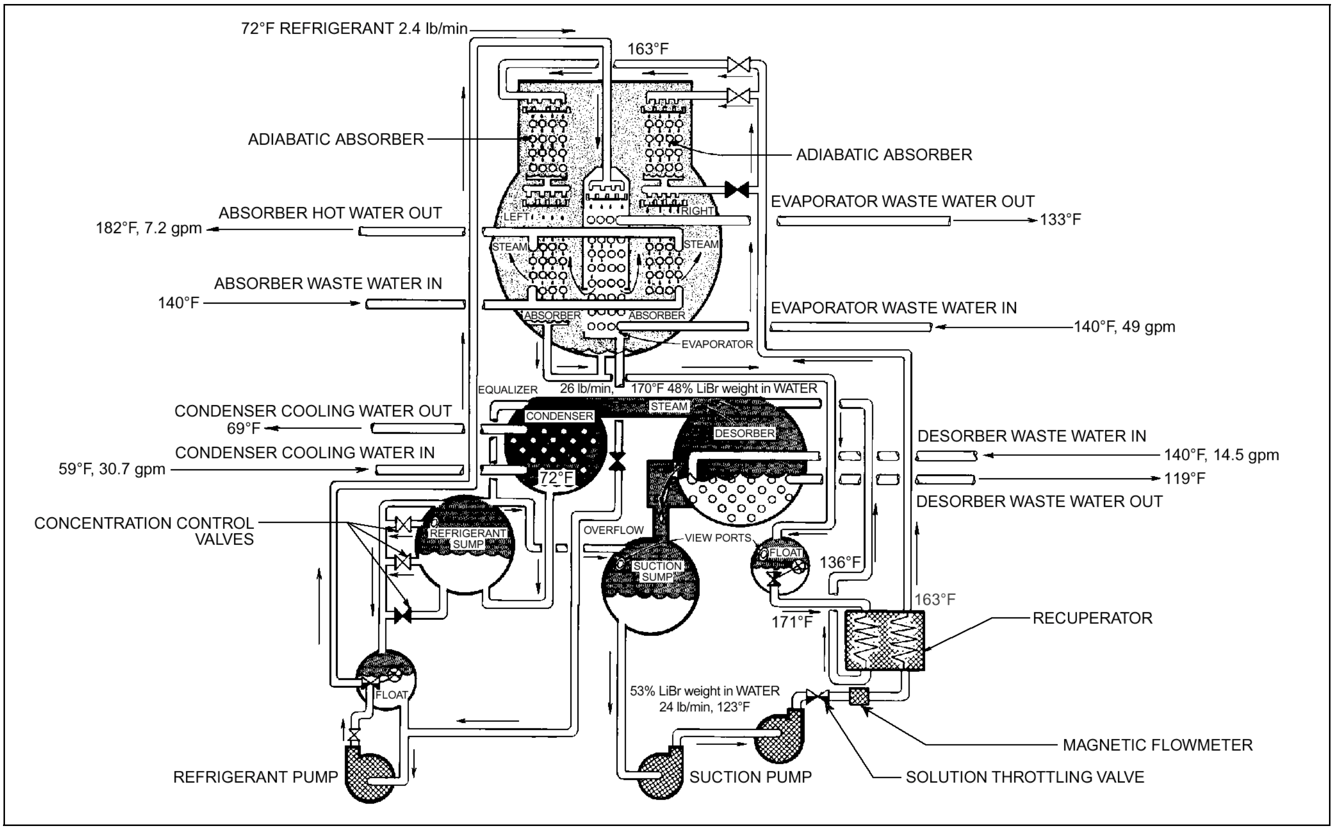

**Fig. 3 Single-Effect Heat Transformer**

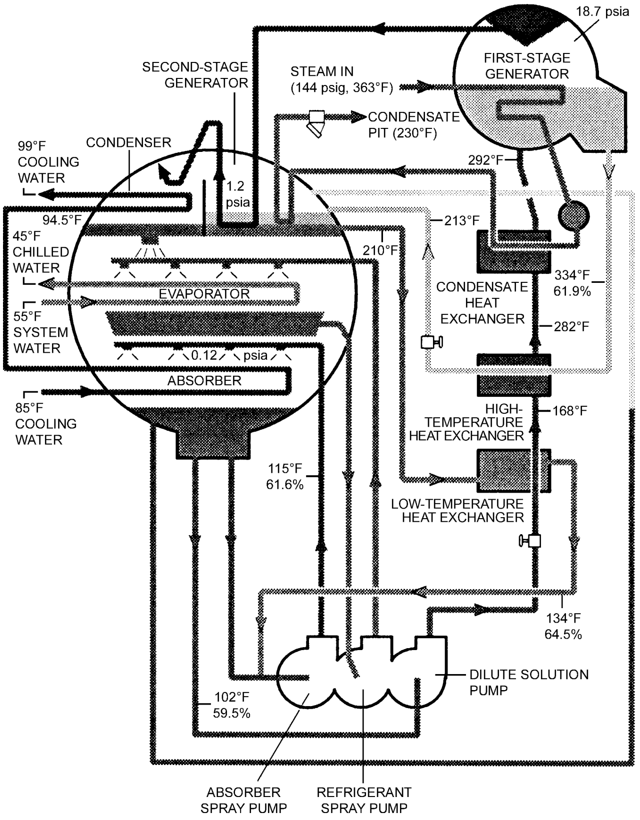

**Fig. 4 Double-Effect Indirect-Fired Chiller**

**Table 2 Characteristics of Typical Double-Effect, Indirect-Fired, Water-Lithium Bromide Absorption Chiller**

| Performance Characteristics | |
|---|---|
| Steam input pressure | 115 psig |
| Steam consumption (condensate saturated conditions) | 9.7 to 10 lb/ton·h |
| Hot-fluid input temperature | 370°F |
| Heat input rate | 10,000 Btu/ton·h |
| Cooling water temperature in | 85°F |
| Cooling water flow | 3.6 to 4.5 gpm/ton |
| Chilled water temperature off | 44°F |
| Chilled water flow | 2.4 gpm/ton |
| Electric power | 0.01 to 0.04 kW/ton |
| **Physical Characteristics** | |
| Nominal capacities | 100 to 1700 tons |
| Length | 10 to 31 ft |
| Width | 6 to 12 ft |
| Height | 8 to 14 ft |
| Operating weight | 15,000 to 132,000 lb |

flowing to and from the primary generator to preheat the dilute solution. Because of the relatively large pressure difference between the vapor spaces of the primary and secondary generators, a mechanical solution flow control device is required at the outlet of the high-temperature heat exchanger to maintain a liquid seal between the two generators. A valve at the heat exchanger outlet that is controlled by the liquid level leaving the primary generator can maintain this seal.

One or more condensate heat exchangers may be used to remove additional heat from the primary heat source steam by subcooling the steam condensate. This heat is added to the dilute or intermediate solution flowing to one of the generators. The result is a reduction in the quantity of steam required to produce a given refrigeration effect; however, the required heat input remains the same. The COP is not improved by condensate exchange.

As with the single-effect machine, the strong absorbent solution flowing to the absorber can be mixed with dilute solution and pumped over the absorber tubes or can flow directly from the low-temperature heat exchanger to the absorber. Also, as with the single-effect machines, the four major components can be contained in one or two vessels.

The following solution flow cycles may be used:

**Series flow.** All solution leaving the absorber runs through a pump and then flows sequentially through the low-temperature heat exchanger, high-temperature heat exchanger, first-stage generator, high-temperature heat exchanger, second-stage generator, low-temperature heat exchanger, and absorber, as show in Figure 4.

**Parallel flow.** Solution leaving the absorber is pumped through appropriate portions of the combined low- and high-temperature solution heat exchanger and is then split between the first- and second-stage generators. Both solution flow streams then return to appropriate portions of the combined solution heat exchanger, are mixed together, and flow to the absorber.

**Reverse parallel flow.** All solution leaving the absorber is pumped through the low-temperature heat exchanger and then to the second-stage generator. Upon leaving this generator, the solution flow is split, with a portion going to the low-temperature heat exchanger and on to the absorber. The remainder goes sequentially through a pump, the high-temperature heat exchanger, the first-stage generator, and the high-temperature heat exchanger. This stream then rejoins the solution from the second-stage generator; both streams flow through the low-temperature heat exchanger and to the absorber, as shown in Figure 5.

These machines are typically fired with medium-pressure steam of 80 to 144 psig or hot liquids of 300 to 400°F. Typical operating COPs are 1.1 to 1.2. These machines are available commercially from several manufacturers and have capacities ranging from 100 to 1700 tons of refrigeration.

Figure 5 is a schematic of a commercially available double-effect, direct-fired chiller with a reverse parallel flow cycle. Table 3

**Table 3 Characteristics of Typical Double-Effect, Direct-Fired, Water-Lithium Bromide Absorption Chiller**

| Performance Characteristics | |
|---|---|
| Fuel consumption (high heating value of fuel) | 12,000 to 13,044 Btu/ton·h |
| COP (high heating value) | 0.92 to 1.0 |
| Cooling water temperature in | 85°F |
| Cooling water flow | 4.4 to 4.5 gpm/ton |
| Chilled water temperature off | 44°F |
| Chilled water flow | 2.4 gpm/ton |
| Electric power | 0.01 to 0.04 kW/ton |
| **Physical Characteristics** | |
| Nominal capacities | 100 to 1500 tons |
| Length | 10 to 34 ft, with minimum of 5 ft for some machines |
| Width | 5 to 21.3 ft, with minimum of 4 ft for some machines |
| Height | 7 to 12 ft |
| Operating weight | 11,000 to 174,600 lb, with a minimum of 3300 lb for some machines |

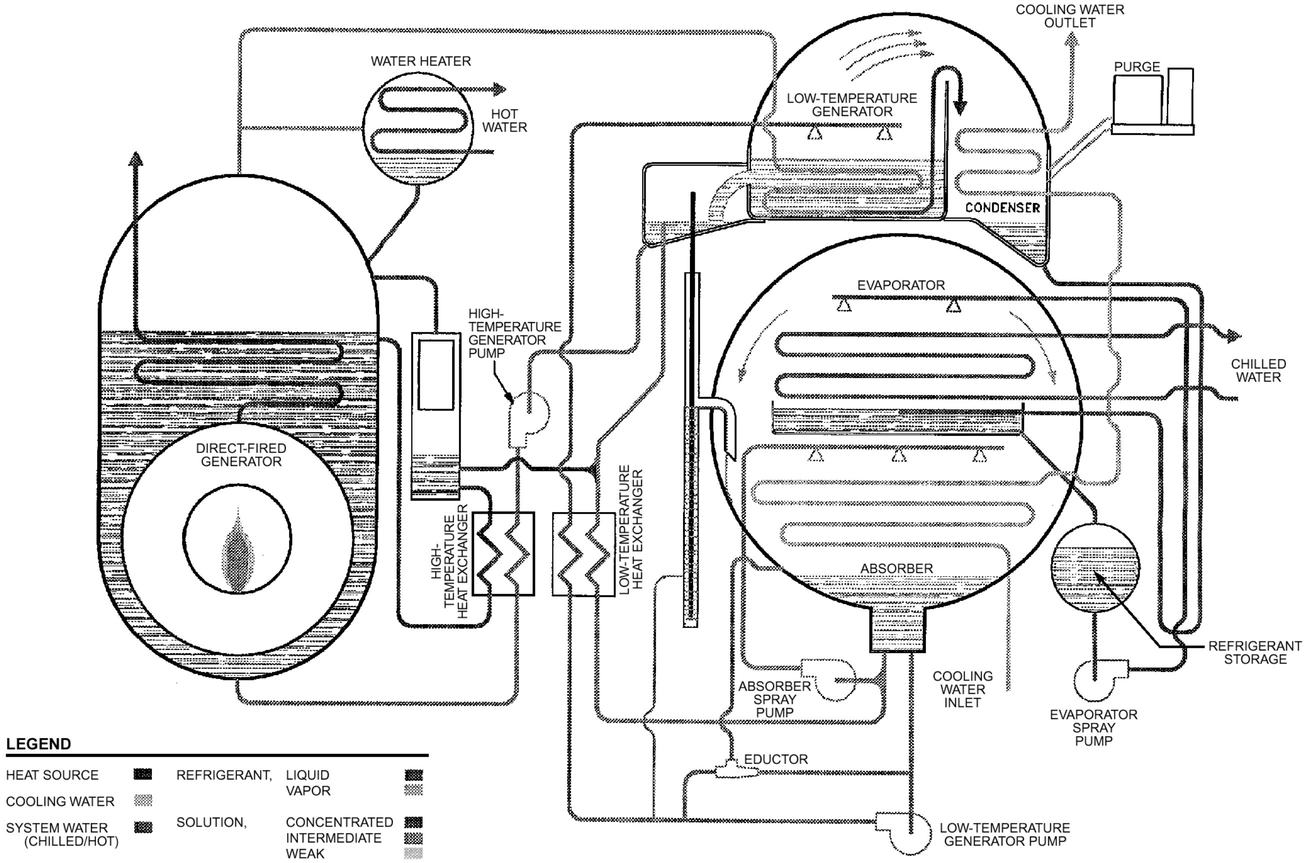

Fig. 5 Double-Effect, Direct-Fired Chiller

lists typical characteristics of this chiller. All major components are similar to the double-effect indirect-fired chiller except for substitution of the direct-fired primary generator for the indirect-fired primary generator and elimination of the steam condensate subcooling heat exchanger. Operation of these machines is identical to that of the double-effect indirect-fired machines. The typical direct-fired, double-effect machines can be ordered with a heating cycle. Also available on some units is a simultaneous cycle. This cycle provides about 180°F water, via a heat exchanger, and chilled water, simultaneously. The combined load is limited by the maximum burner input.

These machines are typically fired with natural gas or fuel oil (most have dual fuel capabilities). Typical operating COPs are 0.92 to 1.0 on a fuel input basis. These machines are available commercially from several manufacturers and have capacities ranging from 100 to 1500 tons. Machine capacities of 20 to 100 tons are also available from international sources.

## Operation

Modern water-lithium bromide chillers are trouble-free and easy to operate. As with any equipment, careful attention should be paid to operational and maintenance procedures recommended by the manufacturer. The following characteristics are common to all types of lithium bromide absorption equipment.

**Operational Limits.** Chilled water temperature leaving the evaporator should normally be between 40 and 60°F. The upper limit is set by the pump lubricant and is somewhat flexible. The lower limit exists because the refrigerant (water) freezes at 32°F.

Cooling water temperature entering the absorber tubes is generally limited to between 55 and 110°F, although some machines limit the entering cooling water temperatures to between 70 and 95°F. The upper limit exists because of hydraulic and differential pressure limitations between the generator-absorber, the condenser-evaporator, or both, and to reduce absorbent concentrations and corrosion effects. The lower temperature limit exists because, at excessively low cooling water temperature, the condensing pressure drops too low and excessive vapor velocities carry over solution to the refrigerant in the condenser. Sudden lowering of cooling water temperature at high loads will also promote crystallization; therefore, some manufacturers will dilute the solution with refrigerant liquid to help prevent crystallization. The supply of refrigerant is limited, however, so this dilution is done in small steps.

**Operational Controls.** Modern absorption machines are equipped with electronic control systems. The primary function of the control system is to safely operate the absorption machine and modulate its capacity in order to satisfy the load requirements placed upon it.

Refrigerant flow control between condensers and evaporators is typically achieved with orifices (suitable for high- or low-stage condensers) or liquid traps (suitable for low-stage condensers only).

For solution flow control between generators and absorbers, flow control valves (primary generator of double-effect machines), variable-speed solution pumps, or liquid traps are used. Refrigerant flow control between condensers and evaporators is accomplished with orifices (suitable for high- or low-stage condensers) or liquid traps (suitable for low-stage condensers only).

Solution flow control between generators and absorbers typically requires flow control valves (primary generator of double-effect machines), variable-speed solution pumps, or liquid traps. The temperature of the chilled water leaving the evaporator is set at a desired value. Deviations from this set point indicate that the machine capacity and the load applied to it are not matched. Machine capacity is then adjusted as required by modulation of the heat input control device. Modulation of heat input results in changes to the concentration of absorbent solution supplied to the absorber if the pumped solution flow remains constant.

Some equipment uses solution flow control to the generator(s) in combination with capacity control. The solution flow may be reduced with modulating valves or solution pump speed controls as the load decreases (which reduces the required sensible heating of solution in the generator to produce a given refrigeration effect), thereby improving part-load efficiency.

Operation of lithium bromide machines with low entering cooling water temperatures or a rapid decrease in cooling water temperature during operation can cause liquid carryover from the generator to the condenser and possible crystallization of absorbent solution in the low-temperature heat exchanger.

For these reasons, most machines have a control that limits heat input to the machine based on entering cooling water temperature. Because colder cooling water enhances machine efficiency, the ability of machines to use colder water, when available, is important.

Use of electronic controls with advanced control algorithms has improved part-load and variable cooling water temperature operation significantly, compared to older pneumatic or electric controls. Electronic controls have also made chiller setup and operation simpler and more reliable.

These steps are involved in a typical start-run-stop sequence of an absorption chiller with chilled and cooling water flows preestablished (this sequence may vary from one product to another):

1. Cooling required signal is initiated by building control device or in response to rising chilled water temperature.
2. All chiller unit and system safeties are checked.
3. Solution and refrigerant pumps are started.
4. Heat input valve is opened or burner is started.
5. Chiller begins to meet the load and controls chilled water temperature to desired set point by modulation of heat input control device.
6. During operation, all limits and safeties are continually checked. Appropriate action is taken, as required, to maintain safe chiller operation.
7. Load on chiller decreases below minimum load capabilities of chiller.
8. Heat input device is closed.
9. Solution and refrigerant pumps continue to operate for several minutes to dilute the absorbent solution.
10. Solution and refrigerant pumps are stopped.

**Limit and Safety Controls.** In addition to capacity controls, these chillers require several protective devices. Some controls keep the units operating within safe limits and others stop the unit before damage occurs due to a malfunction. Each limit and safety cutout function usually uses a single sensor when electronic controls are used. The following limits and safety features are normally found on absorption chillers:

*Low-temperature chilled water control/cutout.* Allows the user to set the desired temperature for chilled water leaving the evaporator. Control then modulates the heat input valve to maintain this set point. This control incorporates chiller start and stop by water temperature. A safety shutdown of the chiller is invoked if a low-temperature limit is reached.

*Low-temperature refrigerant limit/cutout.* A sensor in the evaporator monitors refrigerant temperature. As the refrigerant low-limit temperature is approached, the control limits further loading, then prevents further loading, then unloads, and finally invokes a chiller shutdown.

*Chilled water, chiller cooling water, and pump motor coolant flow.* Flow switches trip and invoke chiller shutdown if flow stops in any of these circuits.

*Pump motor over-temperature.* A temperature switch in the pump motor windings trips if safe operating temperature is exceeded and shuts down the chiller.

*Pump motor overload.* Current to the pump motor is monitored, and the chiller shuts down if the current limit is exceeded.

*Absorbent concentration limit.* Key solution and refrigerant temperatures are sensed during chiller operation and used to determine the temperature safety margin between solution temperature and solution crystallization temperature. As this safety margin is reduced, the control first limits further chiller loading, then prevents further chiller loading, then unloads the chiller, and finally invokes a chiller shutdown.

In addition to this type of control, most chiller designs incorporate a built-in overflow system between the evaporator liquid storage pan and the absorber sump. As the absorbent solution concentration increases in the generator/absorber flow loop, the refrigerant liquid level in the evaporator storage pan increases. The initial charge quantities of solution and refrigerant are set such that liquid refrigerant will begin to overflow the evaporator pan when maximum safe absorbent solution concentration has been reached in the generator/absorber flow loop. The liquid refrigerant overflow goes to the absorber sump and prevents further concentration of the absorbent solution.

*Burner fault.* Operation of the burner on direct-fired chillers is typically monitored by its own control system. A burner fault indication is passed on to the chiller control and generally invokes a chiller shutdown.

*High-temperature limit.* Direct-fired chillers typically have a temperature sensor in the liquid absorbent solution near the burner fire tube. As this temperature approaches its high limit, the control first limits further loading, then prevents further loading, then unloads, and finally invokes a chiller shutdown.

*High-pressure limit.* Double-effect machines typically have a pressure sensor in the vapor space above the first-stage generator. As this pressure approaches its high limit, the control first limits further loading, then prevents further loading, then unloads, and finally invokes a chiller shutdown.

The performance of lithium bromide absorption machines is affected by the operating conditions and the heat transfer surface chosen by the manufacturer. Manufacturers can provide detailed performance information for their equipment at specific alternative operating conditions.

### Machine Setup and Maintenance

Large-capacity lithium bromide absorption water chillers are generally put into operation by factory-trained technicians. Proper procedures must be followed in order to ensure that the machines will function as designed and continue to function in a trouble-free manner for their intended design life (20+ years). Steps required to set up and start a lithium bromide absorption machine include the following:

1. Level the unit so that internal pans and distributors can function properly.
2. Isolate the unit from foundations with pads if it is located near noise-sensitive areas.
3. Confirm that factory leaktightness has not been compromised.
4. Charge the unit with refrigerant water (distilled or deionized water is required) and lithium bromide solution.
5. Add corrosion inhibitor to the absorbent solution if required.
6. Calibrate all control sensors and check all controls for proper function.
7. Start the unit and bring it slowly to design operating condition while adding performance additive (usually one of the octyl alcohols).
8. If necessary to obtain design conditions, adjust absorbent and/or refrigerant charge levels. This procedure is known as trimming the chiller, and, if done correctly, will allow the chiller to operate safely and efficiently over its entire operating range.
9. Fine-tune control settings.
10. Check purge operation.

Recommended periodic operational checks and maintenance procedures typically include the following:

- Purge operation and air leaks. Confirm that the purge system operates correctly and that the unit does not have chronic air leaks. Continued leakage of air into an absorption chiller will deplete the corrosion inhibitor, cause corrosion of internal parts, contaminate the absorbent solution, reduce chiller capacity and efficiency, and may cause crystallization of the absorbent solution.
- Sample absorbent and refrigerant periodically and check for contamination, pH, corrosion-inhibitor level, and performance additive level. Use these checks to adjust the levels of additives in the solution and as an indicator of internal machine malfunctions.

Mechanical systems such as the purge, solution pumps, controls, and burners all have periodic maintenance requirements recommended by the manufacturer.

## AMMONIA-WATER ABSORPTION EQUIPMENT

### Residential Chillers and Components

In the 1950s, under sponsorship from natural gas utilities, three companies undertook the development of a gas-fired, air-cooled residential chiller. Manufacturing volume reached 150,000 units per year in the 1960s, but only a single manufacturer remains at the start of the twenty-first century; the product line is now being changed over to the GAX cycle, described later.

Figure 6 shows a typical schematic of an ammonia-water machine, which is available as a direct-fired, air-cooled liquid chiller in capacities of 3 to 5 tons. Table 4 lists physical characteristics of this chiller. Ammonia-water equipment varies from water-lithium bromide equipment in three main ways:

- Water (the absorbent) is also volatile, so the regeneration of weak absorbent to strong absorbent is a fractional distillation process.
- Ammonia (the refrigerant) causes the cycle to operate at condenser pressures of about 280 psia and at evaporator pressures of approximately 70 psia. As a result, vessel sizes are held to a diameter of 6 in. or less to avoid construction code requirements on small systems, and positive-displacement solution pumps are used.

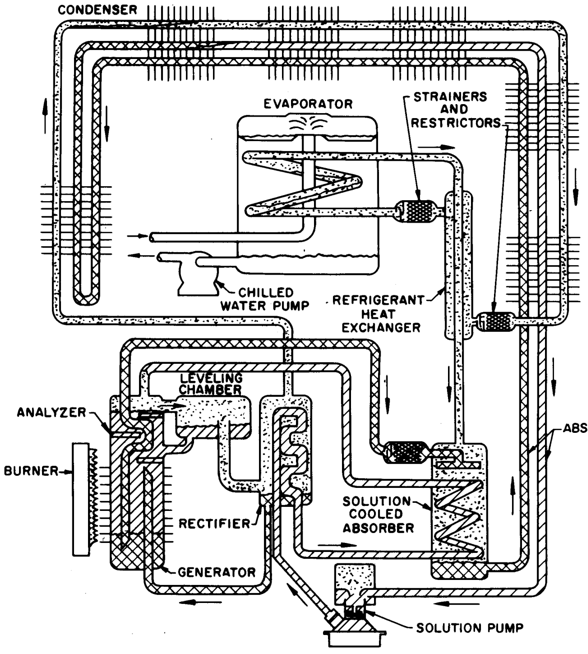

**Fig. 6 Ammonia-Water Direct-Fired Air-Cooled Chiller**

**Table 4 Physical Characteristics of Typical Ammonia-Water Absorption Chiller**

| | |
|---|---|
| Cooling capacities | 36,000 to 60,000 Btu/h |
| Length | 40 to 48.5 in. |
| Width | 29.1 to 33.5 in. |
| Height | 37.6 to 46 in. |
| Weight | 550 to 775 lb |

- Air cooling requires condensation and absorption to occur inside the tubes so that the outside can be finned for greater air contact.

The vertical vessel is finned on the outside to extract heat from the combustion products. Internally, a system of analyzer plates creates intimate counterflow contact between the vapor generated, which rises, and the absorbent, which descends. Atmospheric gas burners depend on the draft of the condenser air fan to sustain adequate combustion airflow to fire the generator. The exiting flue products mix with the air that has passed over the condenser and absorber.

Heat exchange between strong and weak absorbents takes place partially within the generator-analyzer. A tube bearing strong absorbent (nearly pure water) spirals through the analyzer plates, releasing heat to the generation process. Strong absorbent, metered from the generator through the solution capillary, passes over a helical coil bearing weak absorbent, called the solution-cooled absorber. The strong absorbent absorbs some of the vapor from the evaporator, thus releasing the heat of absorption within the cycle to improve the COP. The strong absorbent and unabsorbed vapor continue from the solution-cooled absorber into the air-cooled absorber, where absorption is completed and the heat of absorption is rejected to the air.

The **solution-cooled rectifier** is a spiral coil through which weak absorbent from the solution pump passes on its way to the absorber and generator. Some type of packing is included to assist counterflow contact between condensate from the coil (which is refluxed to the generator) and the vapor (which continues on to the air-cooled condenser). The function of the rectifier is to concentrate the ammonia in the vapor from the generator by cooling and stripping out some of the water vapor.

**Absorber and Condenser.** These finned-tube air exchangers are arranged so that most of the incoming air flows over the condenser tubes and most of the exit air flows over the absorber tubes.

**Evaporator.** The liquid to be chilled drips over a coil bearing evaporating ammonia, which absorbs the refrigeration load. On the chilled-water side, which is at atmospheric pressure, a pump circulates the chilled liquid to the load source. Refrigerant to the evaporator is metered from the condenser through restrictors. A tube-in-tube heat exchanger provides the maximum refrigeration effect per unit mass of refrigerant. The tube-in-tube design is particularly effective in this cycle because water present in the ammonia produces a liquid residue that evaporates at increasing temperatures as the amount of residue decreases.

**Solution Pumps.** The reciprocating motion of a flexible sealing diaphragm moves solution through suction and discharge valves. Hydraulic fluid pulses delivered to the opposite side of the diaphragm by a hermetic vane or piston pump at atmospheric suction pressure impart this motion.

**Capacity Control.** A thermostat usually cycles the machine on and off. A chilled-water switch shuts the burners off if the water temperature drops close to freezing. Units may also be underfired by 20% to derate to a lower load.

**Protective Devices.** Typical protective devices include (1) flame ignition and monitor control, (2) a sail switch that verifies airflow before allowing the gas to flow to the burners, (3) a pressure relief valve, and (4) a generator high-temperature switch.

**Equipment Performance and Selection.** Ammonia absorption equipment is built and rated to meet ANSI *Standard* Z21.40.1, Gas-Fired Absorption Summer Air Conditioning Appliances, Sixth Edition, for outdoor installation. The rating conditions are ambient air at 95°F dry bulb and 75°F wet bulb and chilled water delivered at the manufacturer's specified flow at 45°F. A COP of about 0.5 is realized, based on the higher heating value of the gas.

Although most units are piped to a single furnace, duct, or fan coil and operated as air conditioners, multiple units supplying a multicoil system for process cooling and air conditioning are also encountered. Also, chillers can be packaged with an outdoor boiler and can supply chilled or hot water as the cooling or heating load requires.

## Domestic Absorption Refrigerators and Controls

Domestic absorption refrigerators use a modified absorption cycle with ammonia, water, and hydrogen as working fluids. Wang and Herold (1992) reviewed the literature on this cycle. These units are popular for recreational vehicles because they can be dual-fired by gas or electric heaters. They are also popular for hotel rooms because they are silent. The refrigeration unit is hermetically sealed. All spaces within the system are open to each other and, hence, are at the same total pressure, except for minor variations caused by fluid columns used to circulate the fluids.

The key elements of the system shown in Figure 7 include a generator (1), a condenser (2), an evaporator (3), an absorber (4), a rectifier (7), a gas heat exchanger (8), a liquid heat exchanger (9), and a bubble pump (10). The following three distinct fluid circuits exist in the system: (I) an ammonia circuit, which includes the generator, condenser, evaporator, and absorber; (II) a hydrogen circuit, which includes the evaporator, absorber, and gas heat exchanger; and (III) a solution circuit, which includes the generator, absorber, and liquid heat exchanger.

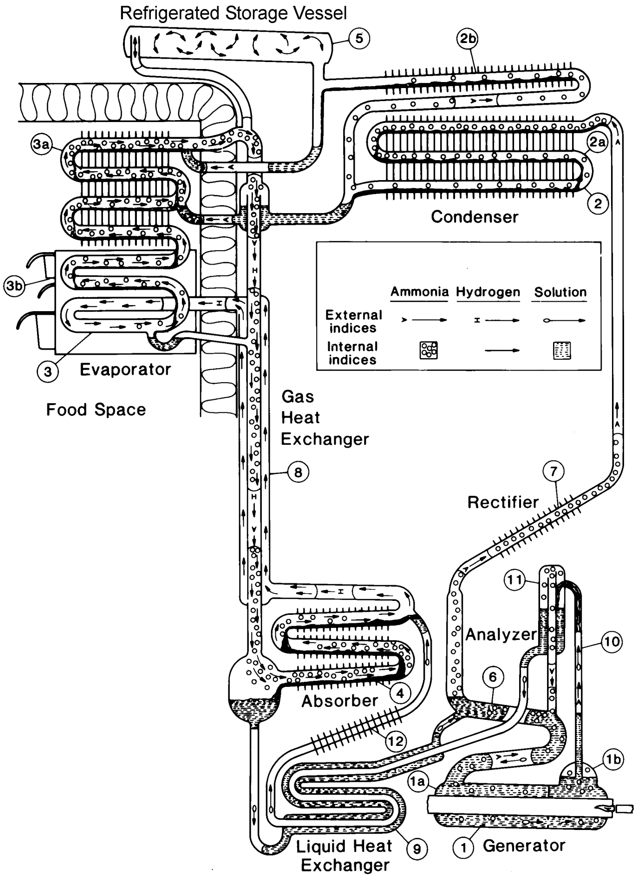

Fig. 7 Domestic Absorption Refrigeration Cycle

Starting with the generator, a gas burner or other heat source applies heat to expel ammonia from the solution. The ammonia vapor generated then flows through an analyzer (6) and a rectifier (7) to the condenser (2). The small amount of residual water vapor in the ammonia is separated by atmospheric cooling in the rectifier and drains to the generator (1) through the analyzer (6).

The ammonia vapor passes into section (2a) of the condenser (2), where it is liquified by air cooling. Fins on the condenser increase the cooling surface. The liquified ammonia then flows into an intermediate point of the evaporator (3). A liquid trap between the condenser section (2a) and the evaporator prevents hydrogen from entering the condenser. Ammonia vapor that does not condense in the condenser section (2a) passes to the other section (2b) of the condenser and is liquified. It then flows through another trap into the top of the evaporator.

The evaporator has two sections. The upper section (3a) has fins and cools the freezer compartment directly. The lower section (3b) cools the refrigerated food section.

Hydrogen gas, carrying a small partial pressure of ammonia, enters the lower evaporator section (3) and, after passing through a precooler, flows upward and counterflow to the downward-flowing liquid ammonia, increasing the partial pressure of the ammonia in the vapor as the liquid ammonia evaporates. While the total pressures in the evaporator and the condenser are the same, typically 20 bar, substantially pure ammonia is in the space where condensation takes place, and the vapor pressure of the ammonia essentially equals the total pressure. In contrast, the ammonia partial pressures entering and leaving the evaporator are typically 1 and 3 bars, respectively.

The gas mixture of hydrogen and ammonia leaves the top of the evaporator and passes down through the center of the gas heat exchanger (8) to the absorber (4). Here, ammonia is absorbed by liquid ammonia-water solution, and hydrogen, which is almost insoluble, passes up from the top of the absorber, through the external chamber of the gas heat exchanger (8), and into the evaporator. Some ammonia vapor passes with the hydrogen from the absorber to the evaporator. Because of the difference in molecular mass of ammonia and hydrogen, the gas circulation is maintained between the evaporator and absorber by natural convection.

Countercurrent flow in the evaporator permits placing the box cooling section of the evaporator at the top of the food space, which is the most effective location. Also, the gas leaving the lower-temperature evaporator section (3b) can pick up more ammonia at the higher temperature in the box cooling evaporator section (3a), thus increasing capacity and efficiency. In addition, the liquid ammonia flowing to the lower temperature evaporator section is precooled in the upper evaporator section. The dual liquid connection between the condenser and the evaporator permits extending the condenser below the top of the evaporator to provide more surface, while maintaining gravity flow of liquid ammonia to the evaporator. The two-temperature evaporator partially segregates the freezing function from the box cooling function, thus giving better humidity control.

In the absorber, the strong absorbent flows counter to and is diluted by direct contact with the gas. From the absorber, the weak absorbent flows through the liquid heat exchanger (9) to the analyzer (6) and then to the weak absorbent chamber (1a) of the generator (1). Heat applied to this chamber causes vapor to pass up through the analyzer (6) and to the condenser. The solution passes through an aperture in the generator partition into the strong absorbent chamber (1b). Heat applied to this chamber causes vapor and liquid to pass up through the small-diameter bubble pump (10) to the separation vessel (11). While liberated ammonia vapor passes through the analyzer (6) to the condenser, the strong absorbent flows through the liquid heat exchanger (9) to the absorber. The finned air-cooled loop (12) between the liquid heat exchanger and the absorber precools the solution further. The heat of absorption is rejected to the surrounding air.

The refrigerant storage vessel (5), which is connected between the condenser outlet and the evaporator circuit, is a reservoir for the refrigerant to compensate for changes in load and the heat rejection air supply temperature.

The following controls are normally present on the refrigerator:

**Burner Ignition and Monitoring Control.** These controls are either electronic or thermomechanical. Electronic controls ignite, monitor, and shut off the main burner as required by the thermostat. For thermomechanical control, a thermocouple monitors the main flame. The low-temperature thermostat then changes the input to the main burner in a two-step mode. A pilot is not required because the main burner acts as the pilot on low fire.

**Low-Temperature Thermostat.** This thermostat monitors the temperature in the cabinet and controls the gas input.

**Safety Device.** Each unit has a fuse plug to relieve pressure in the event of fire. Gas-fired installations require a flue exhausting to outside air. Nominal operating conditions are as follows:

| | |
|---|---|
| Ambient temperature | 95°F |
| COP | 0.22 |
| Freezer temperature | 10°F |
| Heat input | 100 $\text{Btu/h}\cdot\text{ft}^3$ of cabinet interior |

## Industrial Absorption Refrigeration Units

Industrial absorption refrigeration units (ARUs) were pioneered by the Carre brothers in France in the late 1850s. They were first used in the United States for gunpowder production during the Civil War. The technology was placed on a firm footing some 20 years later, when the principles of rectification became known and applied. Rectification is necessary in ammonia-water cycles because the absorbent (water) is volatile.

Industrial ARUs are essentially custom units, since each application varies in capacity, chilling temperature, driving heat, heat rejection mode, or other key parameters. They are almost invariably waste-heat-fired, using steam, hot water, or process fluids. The economics improve relative to mechanical vapor compression at lower refrigeration temperatures and at higher utility rates. These units can produce refrigeration temperatures as low as –70°F, although are more commonly rated for –20 to –50°F.

Industrial ARUs are rugged, reliable, and suitable for demanding applications. For example, they have been directly integrated into petroleum refinery operations. In one early example, the desorber contained hot gasoline, and the evaporator directly cooled lean oil for the oil refinery sponge absorbers. In a recent example, 280°F reformate heated the shell side of the desorber, and the evaporator directly chilled trat gas to –20°F to recover LPG (Erickson and Kelly 1998).

# SPECIAL APPLICATIONS AND EMERGING PRODUCTS

## Systems Combining Power Production with Waste-Heat-Activated Absorption Cooling

Most prime movers require relatively high-temperature heat to operate efficiently. They also reject large amounts of low-temperature heat. In contrast, absorption cycles are uniquely capable of operating at high second law efficiency with low-temperature heat input. Accordingly, it is not surprising that many combination systems comprised of fuel-fired prime mover and a waste-heat-powered absorption unit have been demonstrated.

These systems can assume many forms, usually in ad hoc, one-of-a-kind custom systems. Examples include (1) engine rejects heat to a heat recovery steam generator, and steam powers the absorption cycle; (2) steam boiler powers a steam turbine, and turbine extraction steam powers the absorption cycle; (3) hot engine exhaust directly heats the absorption unit generator; (4) engine jacket cooling water powers the absorption unit.

Recent programs are under way to better integrate and standardize these combined systems to make them more economical and replicable.

A related technology is derived from the effect of cooling on the inlet air to a compressor. When the compressor supplies a prime mover, the power output is similarly benefitted. Hence, applications are found where combustion turbine waste heat supplies an absorption refrigeration unit, and the cooling in turn chills the inlet air.

## Triple-Effect Cycles

Triple-effect absorption cooling can be classified as single-loop or dual-loop cycles. Single-loop triple-effect cycles are basically double-effect cycles with an additional generator and condenser. The resulting system with three generators and three condensers operates similarly to the double-effect system. Primary heat (from a natural gas or fuel oil burner) concentrates absorbent solution in a first-stage generator at about 400 to 450°F. A fluid pair other than water-lithium bromide must be used for the high-temperature cycle. The refrigerant vapor produced is then used to concentrate additional absorbent solution in a second-stage generator at about 300°F. Finally, the refrigerant vapor produced in the second-stage generator concentrates additional absorbent solution in a third-stage generator at about 200°F. The usual internal heat recovery devices (solution heat exchangers) can be used to improve cycle efficiency. As with the double-effect cycles, several variations of solution flow paths through the generators are possible.

Theoretically, the COP obtainable with these triple-effect cycles is about 1.7 (not taking into account burner efficiency). Difficulties with these cycles include the following:

- High solution temperatures pose problems to solution stability, performance additive stability, and material corrosion.
- High pressure in the first-stage generator vapor space requires costly pressure vessel design and high-pressure solution pump(s).

A double-loop triple-effect cycle consists of two cascaded single-effect cycles. One cycle operates at normal single-effect operating temperatures and the other at higher temperatures. The smaller high-temperature topping cycle is direct-fired with natural gas or fuel oil and has a generator temperature of about 400 to 450°F. A fluid pair other than water-lithium bromide must be used for the high-temperature cycle. Heat is rejected from the high-temperature cycle at 200°F and is used as the energy input for the conventional single-effect bottoming cycle. Both the high- and low-temperature cycles remove heat from the cooling load at about 44°F.

Theoretically, the overall COP obtainable with this triple-effect cycle is about 1.8 (not taking into account burner efficiency).

As with the single-loop triple-effect cycle, high temperatures create problems with solution and additive stability and material corrosion. Also, the use of a second loop requires additional heat exchange vessels and additional pumps. However, both loops operate below atmospheric pressure and, therefore, do not require costly pressure vessel designs.

## GAX (Generator-Absorber Heat Exchange) Cycle

The air-cooled absorption air-conditioning equipment presently available operates at gas-fired cooling COPs of just under 0.5 at ARI rating conditions. The absorber heat exchange cycle of past air conditioners had a COP of about 0.67 at the rating conditions. In recent years, several projects have been initiated around the world to develop generator-absorber heat exchange (GAX) cycle systems. The best-known programs have been directed toward cycle COPs of about 0.9.

The GAX cycle is a heat-recovering cycle in which absorber heat is used to heat the lower-temperature section of the generator as well as the rich ammonia solution being pumped to the generator. This cycle, like others capable of higher COPs, is more difficult to develop than the ammonia single-stage and absorber heat exchange cycles, but its potential gas-fired COPs of 0.7 in cooling mode and 1.5 in heating mode make it capable of significant annual energy savings. In addition to providing a more effective use of heat energy than the most efficient furnaces, the GAX heat pump is able to supply all the heat a house requires to outdoor temperatures below 0°F without the use of supplemental heat.

## Solid-Vapor Sorption Systems

Solid-vapor heat pump technology is being developed for zeolite, silica-gel, activated-carbon, and coordinated complex adsorbents. The cycles are periodic in that the refrigerant is transferred periodically between two or more primary vessels. Several concepts providing quasi-continuous refrigeration have been developed. One advantage of solid-vapor systems is that no solution pump is needed. The main challenge in designing a competitive solid-vapor heat pump is to package the adsorbent in such a way that good heat and mass transfer are obtained in a small volume. A related constraint is that good thermal performance of periodic systems requires that the thermal mass of the vessels be small to minimize cyclic heat transfer losses.

## Liquid Desiccant-Absorption Systems

In efforts to reduce a building's energy consumption, designers have successfully integrated liquid desiccant equipment with standard absorption chillers. These applications have been building specific and are sometimes referred to as application hybrids. In a more general approach, the absorption chiller is modified so that rejected heat from its absorber can be used to help regenerate the liquid desiccant. Only liquid desiccants are appropriate for this integration because they can be regenerated at lower temperatures than solid desiccants.

The desiccant dehumidifier dries ventilation air sufficiently that, when it is mixed with return air, the building's latent load is satisfied. The desiccant drier is cooled by cooling tower water so that a significant amount of the cooling load is transferred directly to the cooling water. Consequently, the absorption chiller size is significantly reduced, potentially to as little as 60% of the size of the chiller in a conventional installation.

Because the air handler is restricted to sensible load, the evaporator in the absorption machine will run at higher temperatures than normal. Consequently, a machine operating at normal concentrations in its absorber will reject heat at higher temperatures. To permit convenient regeneration of the liquid desiccant, only moderate increases in solution concentration are required. These are subtle but significant modifications to a standard absorption chiller.

Such combined systems seem to work best when about one-third of the supply air comes from outside the conditioned space. These systems do not require 100% outside air for ventilation, so they should be applicable to conventional buildings as newly mandated ventilation standards are accommodated. Because they always operate in a form of economizer cycle, they are particularly effective during shoulder seasons (spring and fall). As lower-cost liquid desiccant systems become available, reduced first costs may join the advantages of decreased energy use, better ventilation, and improved humidity control.

# INFORMATION SOURCES

The are four modern textbooks on absorption: Niebergall (1981), Bogart (1981), Alefeld and Radermacher (1994), and Herold et al. (1995). Other sources of information include conference proceedings, journal articles, newsletters, trade association publications, and manufacturers' literature.

The only recurring conference that focuses exclusively on absorption technology is the triennial Absorption Experts conference, most recently identified as the "International Sorption Heat Pump Conference." Proceedings from these conferences are available from Berlin (1982), Paris (1985), Dallas (1988), Tokyo (1991), New Orleans (1994), Montreal (1996), and Munich (1999).

Technical Committee 8.3 of ASHRAE sponsors symposia on absorption technology at least annually, and the papers appear in the *Transactions*.

The Advanced Energy Systems Division of ASME sponsors heat pump symposia approximately annually, with attendant proceedings.

The International Congress of Refrigeration is held quadrennially, under auspices of the International Institute of Refrigeration (IIR). IIR publishes the conference proceedings, and also the *International Journal of Refrigeration*, both of which include articles on absorption.

These in one newsletter covering absorption topics: the *International Energy Agency Heat Pump Center Newsletter.*

The American Gas Cooling Center publishes a comprehensive *Natural Gas Cooling Equipment and Services Guide* plus a periodic journal, *Cool Times*.

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