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Review of Liquid Desiccant Technology for HVAC Applications

Andrew Lowenstein, PhD
Member ASHRAE

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A thermally driven air conditioner that uses liquid desiccants as the working fluid may be an attractive alternative to the compressor-based technology that is now used in most HVAC applications. The operation of a liquid-desiccant air conditioner is first explained and several basic concepts are reviewed. This review focuses on the development of liquid-desiccant conditioners and regenerators that are better suited to comfort conditioning (as opposed to industrial dehumidification). This includes work on conditioners and regenerators that use low flow rates of desiccants and have internal heat exchange. These conditioners and regenerators will have lower pump and fan power than packed-bed units, and will be much less likely to introduce desiccant droplets into the process air. Work to identify and develop regenerators that have COPs over 1.0 and research on alternative liquid desiccants is also reviewed.

INTRODUCTION

In the 20th century, the HVAC industry brought air conditioning out of the lab and into millions of homes and commercial buildings. What was once a luxury is now a necessity in many countries. However, this success now presents the industry with new challenges.

If the air conditioner is to improve the quality of life for billions more people in a rapidly developing world, we face many potential problems. The source of many of these problems is the air conditioner's heavy reliance on electricity. Tremendous amounts of fossil fuels are converted to carbon dioxide each year to produce the power needed by air conditioners. A rapidly growing demand for air conditioning could accelerate global climate change at a time when the world is struggling to reduce it. Air and water pollution could also increase as more power plants are built to meet the demand for electricity. Areas with limited water resources will find these resources overtaxed by the need to cool the new power plants. The reliability of electric systems could be compromised as air conditioning creates high peak demands for power.

Indoor air quality is another challenge to the HVAC industry, particularly in more humid climates. Sick Building Syndrome is a problem that can be corrected through better ventilation. For many types of buildings, ASHRAE's standards have tripled the ventilation rates over those that were common following the energy crisis of the 1970s. However, in humid climates, the increased ventilation can raise indoor humidity to levels that are both uncomfortable and unhealthy.

The vapor-compression cycle is now the foundation of the HVAC industry and will remain so for many years. The following problems are being addressed through a number of approaches including: (1) more efficient designs for air conditioners, (2) more efficient buildings that require less cooling, (3) the conversion of power generation from fossil fuels to sustainable resources, (4) the development of air conditioners that provide more dehumidification, or latent

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Andrew Lowenstein is president of AIL Research, Inc., Princeton, NJ.

cooling, more efficiently, and (5) a wider implementation of energy storage technologies. Solutions do exist using only vapor-compression technology, but these solutions will increase the cost for air conditioning. Alternatives to the vapor-compression air conditioner may be better able to meet the growing demand while meeting the new economic, environmental, and performance requirements.

THE BASICS OF LIQUID-DESICCANT AIR CONDITIONERS

Although far less mature than vapor-compression technology, air conditioners based on liquid desiccants are one of the more promising new alternatives. Two characteristics of liquid-desiccant air conditioners (LDAC) will be critical to their wider use:

- The LDAC runs mostly on heat; its electric demand is typically one-fourth that of a vapor-compression air conditioner.
- The LDAC is exceptionally good at dehumidifying air; almost all of the cooling it provides can be latent cooling.

The primary objectives of this article are to present a summary of current R&D on LDACs and identify areas where further development will improve the competitiveness of the technology. However, since liquid-desiccant technology is not yet commonly part of HVAC systems, several basic concepts are first presented.

A desiccant is a material that has a strong attraction for water vapor. It is common to classify desiccants as either solid or liquid depending on their normal physical state (although a material such as lithium chloride can be both, absorbing water vapor both as a solid, hydrated salt, or as an aqueous solution). Both solid and liquid desiccants are commonly used in industrial applications where low dew-point air is needed. Solid desiccants are also increasingly being used in HVAC systems to either increase an air conditioner's latent cooling or recover total energy from the building exhaust.

The strength of a desiccant can be measured by its equilibrium vapor pressure (i.e., pressure of water vapor that is in equilibrium with the desiccant). This equilibrium vapor pressure increases roughly exponentially with the temperature of the desiccant/water system. It also increases as the desiccant absorbs water (a dilute liquid desiccant will have a higher equilibrium vapor pressure than a concentrated liquid desiccant).

When the absolute humidity of air that has come into equilibrium with a liquid desiccant of fixed concentration is plotted on a psychrometric chart, the equilibrium line closely follows a line of constant relative humidity. Figure 1 illustrates this behavior for solutions of lithium chloride. A liquid desiccant that is alternately exposed to two environments that are at different relative humidities will move moisture from high to low relative humidity.

A liquid desiccant can enhance heat transfer by a mechanism that is the inverse of evaporative cooling. When air flows over a surface wetted with water, evaporation from the film of water will lower the temperature of the water-air interface toward the wet-bulb temperature of the air. This wet-bulb temperature is a function of the air's initial temperature and humidity. A line of constant enthalpy that passes through the air's state point intersects the saturation line on a psychrometric chart at approximately the wet-bulb temperature. As shown in Figure 2, the wet-bulb temperature for air at 80°F (26.7°C) and 50% RH is 66.7°F (19.3°C).

When air flows over a surface that is wetted with a desiccant, the desiccant can either absorb or desorb water, depending on whether the desiccant's equilibrium relative humidity is above or below the air's relative humidity. If the desiccant absorbs water from the air, heat will be released and the desiccant's temperature will increase. This heating is the inverse of evaporative

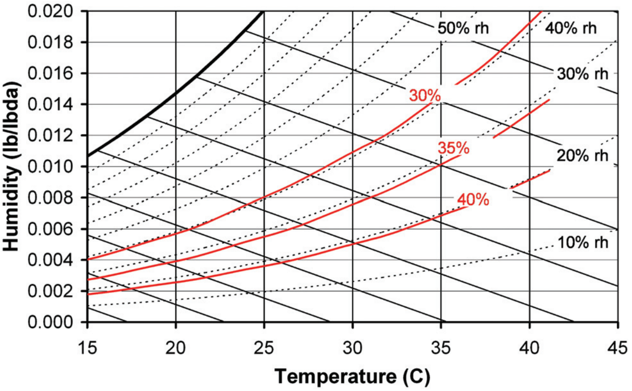

Figure 1. Psychometric performance of lithium chloride at different concentrations.

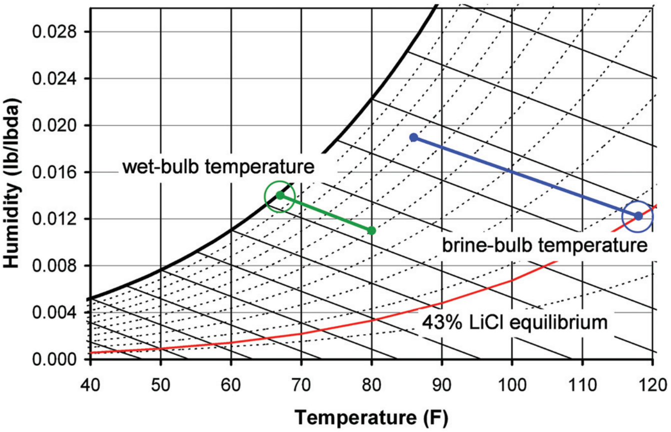

Figure 2. Examples of the wet-bulb temperature and the brine-bulb temperature.

cooling. By analogy to evaporative cooling, one can define a brine-bulb temperature as the temperature that the desiccant-air interface approaches.

The brine-bulb temperature is a function of a liquid desiccant's concentration and the air's temperature and humidity. As shown in Figure 2, the brine-bulb temperature will always be slightly higher than the temperature at which a line of constant enthalpy from the air state point intersects the equilibrium relative humidity curve for the desiccant. This is because the heat that is released as the desiccant absorbs the water vapor includes the chemical heat of mixing between the desiccant and water, in addition to the vapor-liquid latent heat for the water vapor.

As shown in Figure 2, the brine-bulb temperature for a 43% solution of lithium chloride and air at 86/78°F (30.0/25.6°C) dry-bulb/wet-bulb will be 118°F (47.8°C). With an ambient wet-bulb temperature of 78°F (25.6°C), a typical cooling tower might supply water at 85°F (29.4°C). It's impractical to cool the ambient air using this cooling water in a conventional heat exchanger, because the cooling water is only one degree below the air temperature. However, a strong cooling effect could be achieved by wetting the surfaces of the heat exchanger with the 43% lithium chloride.

Of course, one does not get this enhanced cooling for free. If the cooling process is to be continuous, energy must be expended to regenerate the desiccant back to its original concentration.

If ambient air from the preceding example is brought into equilibrium with 43% lithium chloride at 85°F (29.4°C), the air will have a dew point of 33.5°F (0.8°C), a wet-bulb of 57.8°F (14.3°C), and its enthalpy will be reduced from 41.5 Btu/lb (96.3 kJ/kg) to 24.9 Btu/lb (57.8 kJ/kg). This large cooling effect, both in terms of latent cooling and total cooling, and low dew point—both of which are achieved without a compressor—demonstrate the potential for liquid desiccants to become an important part of HVAC systems.

Liquid desiccants have been successfully used to produce dry air for a surprisingly long time. Dr. Russell Bichowsky, working for the Frigidaire Division of General Motors, first used solutions of lithium chloride to dry air in the 1930s. Frigidaire sold the technology to Surface Combustion Corporation (SCC) in the mid-1930s. A residential liquid-desiccant dehumidifier was field tested by SCC shortly after they acquired the technology, but no product was introduced into the market (Griffiths 2007).

Also in the 1930s, the Niagara Blower Company introduced a liquid desiccant technology that used glycol solutions to prevent frost from forming on low-temperature evaporators. Both lithium chloride and glycol continue to be used today in liquid-desiccant dehumidifiers, but their use is limited primarily to industrial applications.

An important objective of this review is to identify the current technology base and R&D needs for moving liquid-desiccant systems into HVAC applications. The state of the art for industrial applications is a useful starting point, but typically, its cost, maintenance, and performance characteristics are not suitable for HVAC applications.

A typical industrial application of a liquid-desiccant system is shown in Figure 3. The conditioner (also commonly called an *absorber*) is the component that cools and dries the process air. As shown in this figure, the conditioner is a bed of structured contact media, similar to the corru-

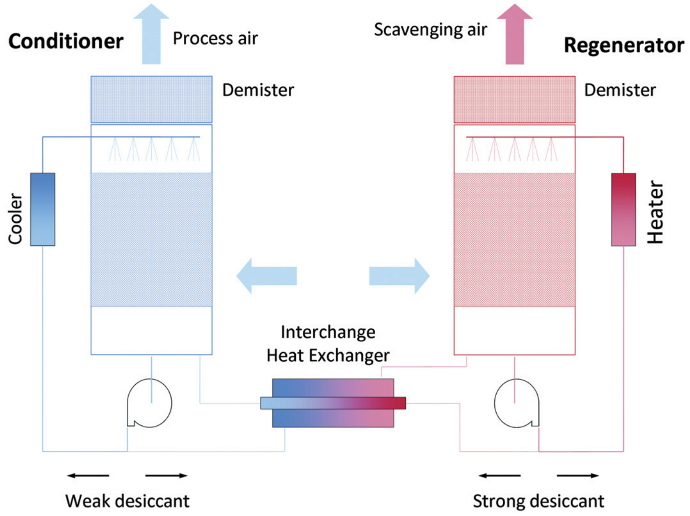

Figure 3. Schematic of a packed-bed liquid-desiccant dehumidifier and cooler.

gated fill that might be used in a cooling tower. Liquid desiccant is first cooled in a heat exchanger and then sprayed onto the contact media. The desiccant flow rate must be sufficiently high to ensure complete wetting of the media, meaning it should be about 5 gpm per square foot of face area. The process air is cooled and dried as it comes in contact with the desiccant-wetted surfaces of the contact media. Heat is released as the desiccant absorbs water from the air, but the high flow rate of the desiccant limits its temperature rise to a few degrees.

The regenerator removes the water that the desiccant has absorbed in the conditioner. The desiccant is regenerated by first heating it to raise its equilibrium vapor pressure. The hot desiccant, typically between 160°F (71.1°C) and 200°F (93.3°C), is sprayed over a bed of random fill (e.g., Raschig rings). Flooding rates are again sufficiently high to ensure complete wetting of the media. The hot desiccant desorbs water to the air that flows through the bed. This moisture-laden air is typically exhausted to ambient.

Both the regenerator and conditioner require droplet filters (also referred to as mist eliminators) to ensure that the desiccant is not entrained in either the supply air to the building or the exhaust from the regenerator. Droplet formation is fundamental to both the spray distributor and the highly flooded beds of contact media used in industrial equipment. Droplet filters can suppress desiccant carryover to parts per billion of airflow, but these filters do increase air-side pressure drops and require maintenance (Kathabar 1998).

An interchange heat exchanger (IHX) can be used to preheat the weak desiccant that flows to the regenerator using the hot, concentrated desiccant that leaves the regenerator. The IHX reduces both the thermal energy use of the regenerator and the cooling requirements of the conditioner.

An industrial liquid-desiccant system that processed 6000 cfm (10,200 m^3/h) typically would recirculate 75 to 100 gpm (283 to 377 l/min) of desiccant in the conditioner and half that amount in the regenerator using 2.0 HP and 1.5 HP pumps, respectively. Airflow through the regenerator would be 1500 cfm (2550 m^3/h), requiring a 3.0 HP blower (Kathabar 1998). A conventional roof-top air conditioner that processes 6000 cfm (10,200 m^3/h) might have 15 HP of combined compressor and condenser fan motors. This comparison points to an important R&D need for liquid-desiccant technology. The industrial system in this comparison has a motor load only 57% lower than the conventional unit; liquid-desiccant technology must further reduce electrical loads if it is to become competitive in the HVAC market.

Most industrial liquid-desiccant systems use packed-bed contact media, as described above; some have also used conditioners and regenerators with internal heat exchange. For the conditioner, the contact surface between the desiccant and process air is a bank of water-cooled tubes. The desiccant is dripped or sprayed onto the tubes and the process air is drawn past them. For an industrial conditioner that uses a halide salt solution, the tubes would typically be a copper-nickel alloy to limit corrosion to acceptable levels. Although an internally cooled conditioner no longer relies on the thermal capacitance of the desiccant flow to limit the temperature rise of the desiccant as absorption occurs, flooding rates are still comparable to those used in a packed-bed conditioner to ensure complete wetting of the tubes. Coil-type or tube-type conditioners are now rarely used in halide salt liquid-desiccant systems because of the very high cost for the corrosion resistant coils.

PAST R&D ON LIQUID-DESICCANT TECHNOLOGY

Past work on liquid-desiccant technologies can be categorized as follows:

- search for advanced desiccants
- development of conditioners for HVAC service
- development of high-efficiency regenerators

- design of systems for specific applications such as solar thermal and combined cooling, heat, and power

This review focuses on the first three points: development of the essential components of a liquid-desiccant system.

Advanced Desiccants

The choice of desiccant will have a profound effect on the design of the LDAC. Glycols and solutions of halide salts are routinely used in industrial equipment, each having important advantages and disadvantages. Halide salts such as lithium chloride and lithium bromide are very strong desiccants: a saturated solution of lithium bromide can dry air to 6% relative humidity and lithium chloride to 11%. Unfortunately, prices for both lithium salts have increased significantly in the last two years. Recent quotes from an Asian source for large amounts of anhydrous salt for lithium bromide and chloride ran $3 and $4.40 per pound ($6.60 and $9.68 per kilogram), respectively. A 25 ton (88 kW) liquid-desiccant air conditioner might be charged with 200 lb (91 kg) of salt.

Unfortunately, halide salts are corrosive to most ferrous and nonferrous metals. Aqueous solutions of lithium bromide are commonly used in absorption chillers. But these systems are closed, so oxygen levels can be kept low and corrosion inhibitors can be used. Titanium is one of the few metals that could be used in the high-temperature heat exchanger that supplies hot desiccant to the regenerator shown in Figure 3. However, prices for titanium have dramatically increased in the past few years, and the heat exchanger for a 25 ton (88 kW) LDAC might cost $2,500.

Glycols are the second class of liquid desiccants now used in industrial equipment. Both triethylene and propylene glycol have low toxicity, and their compatibility with most metals has led several researchers to use them in LDACs designed for HVAC applications (Elsarrag 2006, Meckler et al. 1993, Oberg and Goswami 1998A).

However, all glycols have one undesirable characteristic: they are volatile. A mixture of 96% triethylene glycol (TEG) and 4% water will dry air to the same dew point as a 42% lithium chloride solution. However, at equilibrium, the molar concentration of the glycol in the air will be on the order of 1% that of the water vapor. In an HVAC application where a 6000 cfm (10,200 m^3/h) LDAC operates for 2000 hours per year, the annual loss of TEG in the conditioner would be more than 10,000 lb (4500 kg). Both the economic penalty and the environmental impact of this loss would be unacceptable in an HVAC system.

Salts of weak organic acids, such as potassium or sodium formate and acetate, have been explored as less corrosive alternatives to halide salts that are also not volatile. Formate salts have the advantage of being significantly less viscous than acetate salts at concentrations with equivalent equilibrium relative humidities. Although several companies market potassium formate as a low-viscosity heat transfer fluid and biodegradable de-icing solution, the property data that they provide on their Web sites is for concentrations too low to be useful in LDACs (Dynalene 2001). (Suppliers of potassium formate for heat transfer applications provide property for solutions up to 50% concentration by weight. At this concentration, potassium formate would perform in a LDAC similar to a 27% lithium chloride solution: equilibrium relative humidity would be about 50%.) A 70% solution of potassium formate has a viscosity of about 10 cP at 68°F (20°C) and an equilibrium relative humidity of 26% (Atkinson 2003). Although it is a significantly weaker desiccant than lithium bromide or lithium chloride, the ability to dry air below 30% relative humidity could make potassium formate a good alternative desiccant in some applications. However, questions such as, "Will it react with trace contaminants that may be present in the process air? Can it promote biological growth?" and "Can it be a source of offensive odors?" need to be answered before it can be determined if it is acceptable in HVAC applications.

The cost of lithium-based desiccants can also be an obstacle to their use, particularly in applications where the storage of concentrated desiccant is important (e.g. a solar cooling system that must provide cooling during hours when solar insolation is low or zero). At the cost of $4.40 per pound ($9.68 per kilogram) for lithium chloride and a concentration swing from 43% to 37%, the desiccant can store latent cooling at $132 per ton-hour ($37.50 per kWh). Although the tank for desiccant storage (e.g., an uninsulated, plastic tank) is relatively inexpensive, the cost of the lithium chloride alone would discourage desiccant storage of more than a fraction of an hour.

Ertas et al. (1992) studied mixtures of lithium chloride and calcium chloride as a lower-cost alternative to lithium chloride. The cost for calcium chloride is approximately one-twentieth that of the lithium salt. By itself, calcium chloride is a moderately strong desiccant, with a 29% equilibrium relative humidity for a saturated solution at 77°F (25°C). Ertas' study examines a solution in which the combined salt content totals 20% by weight at 80°F (26.7°C). As the fraction of calcium chloride to lithium chloride increases from 0% to 50%, the equilibrium vapor pressure for the solution more closely matches the value for pure lithium chloride. The equilibrium vapor pressure for the 50/50 mixture is a 71/29 weighted average of the values for solutions of pure lithium chloride and pure calcium chloride. If this weighted average holds at higher solution concentrations, then 43% solutions of calcium chloride, lithium chloride and a 50/50 mixture at 85°F (29.4°C) would have equilibrium dew points of 52.1°F (11.2°C), 33.5°F (0.8°C), and 40.2°F (4.6°C), respectively. The 43% solution of the 50/50 mixture would behave in the LDAC the same as a 40% solution of pure lithium chloride (whereas, a 43% calcium chloride solution behaves like a 34% lithium chloride solution). A complete design study of the LDAC and its performance would be needed to decide whether the LDAC operating with the 50/50 mixture is an attractive alternative.

Of the possible halide salts that could be used as a liquid desiccant, lithium chloride has by far been the most widely applied. This preference has persisted despite the fact that lithium bromide can work at concentrations at which it is a significantly stronger desiccant. Indeed, lithium bromide is almost exclusively used in absorption chillers that use water as the refrigerant.

It has been difficult to document the decision-making process that led to lithium chloride as the prevailing liquid desiccant in industrial dehumidifiers. Anecdotes suggest that both lithium chloride and lithium bromide were tested in the 1930s, but the bromide salt sometimes produced offensive odors in the process air. Since lithium chloride was significantly less expensive at that time, it became the preferred desiccant.

The bromide ion in the solution is more easily ionized than is the chlorine ion. In slightly acidified solutions, the bromide ion can be oxidized to bromine, which even in trace amounts can cause odor problems. In open dehumidifiers, trace gases in the process air, such as nitric oxides, can turn the solution acidic. Those doing early work with lithium bromide may have encountered this problem. However, it may be possible to control the pH of the liquid desiccant to avoid this problem.

An LDAC that used a stronger desiccant than lithium chloride might have one important advantage: it might lead to a practical air-cooled LDAC that does not need cooling water. As noted earlier, a 43% lithium chloride solution that processes air at 86°F (30°C) dry-bulb and 78°F (25.6°C) wet-bulb temperatures has a brine-bulb temperature of 118°F (47.8°C). If a 62% lithium bromide solution processes the same air, the brine-bulb temperature will be 136°F (57.8°C). This 18°F (10°C) increase in the temperature that drives the heat transfer would compensate for the higher temperature of the cooling sink without evaporative cooling.

An LDAC with dry air cooling of the conditioner would not need a cooling tower or other source of evaporative cooling. In addition to being a simpler system to install and maintain, it would place minimal demands on water resources. Not only would the LDAC use no water for cooling, but by switching air conditioning loads from electricity to mostly thermal energy, the water demands at the power plant would be greatly reduced.

Development of Conditioners for HVAC Service

Despite the limitations previously noted, the packed-bed conditioner has been the focus of many R&D projects on LDACs. Comprehensive reviews of packed-bed heat and mass exchangers using liquid desiccants are reported by Oberg and Goswami (1998B) and Elsarrag (2006).

More recent R&D on packed-bed heat and mass exchangers includes the work of Gommed, Grossman, and Ziegler (2004) in which the performance of packed-bed heat and mass exchangers flooded with lithium chloride solutions were experimentally measured. The researchers first implemented their conditioner and regenerator as internally cooled units using either copper tubes or polypropylene tubes as the contact surface. However, the copper tubes were too easily corroded by the desiccant, and the polypropylene tubes were too difficult to wet. Adiabatic packed beds with volumetric surface area of 285 m^2 per m^3 were finally used. The researchers reported that "the LiCl solution should not be sprayed, but rather dripped over the packing, with the drops large enough not to be carried away by the air stream." A 16 kWt LDAC was field tested by Gommed and Grossman (2006). With thermal energy for regeneration provided by solar collectors, the LDAC had an average coefficient of performance (COP) of 0.8.

Fumo and Goswami (2002) modeled and experimentally measured the performance of packed-bed, lithium chloride heat, and mass exchangers that used a random, polypropylene packing with a volumetric surface area of 210 m^2 per m^3. They reported that the lithium chloride solution did not uniformly wet the packing because of its high surface tension. Good agreement between measured and modeled performance was achieved after an empirical formula was used to estimate the fraction of wetted surface area in the bed.

Liu et al. (2006) experimentally measured the performance of a cross-flow liquid-desiccant conditioner that used structured packing flooded with a solution of lithium bromide. Performance is reported in terms of the moisture removal rate for the conditioner and its dehumidification effectiveness (i.e., the change in the humidity ratio of the air expressed as a percentage of the theoretical maximum change) at varying desiccant flow rates, airflow rates, desiccant inlet temperature, desiccant inlet concentration, air inlet temperature, and air inlet humidity ratio.

Liu and Jiang (2008) and Liu et al. (2007) presented analytical solutions for the coupled heat and mass transfer within liquid-desiccant packed-bed systems under assumptions that included minimal change in desiccant concentration through the packed bed and a Lewis number of one. Both groups of researchers showed that their analytical solutions closely agree with more exact numerical solutions and with experimental data from other studies.

Chen et al. (2005) reported on a field test of a LDAC that uses cross-flow packed-bed heat and mass exchangers. For this field test, each of five conditioners processed approximately 1300 cfm (2200 m^3/h) of ventilation air using four packed beds arranged so that the air flowed through all four in series. Each of the four beds was flooded with a solution of lithium bromide between 42% and 48% by weight. The desiccant was circuited so that the air flowed through packed beds of increasing desiccant concentration (i.e., the air and desiccant flowed quasi-counter-flow). Packed-bed evaporative coolers provided water that cooled the desiccant in heat exchangers. Exhaust air from the building was the heat and moisture sink for the evaporative coolers. Water was removed from the desiccant in a packed-bed regenerator whose heat source was hot water at between 69°C and 73°C. Chen et al. (2005) reported that the regenerator's average COP was 0.82 and the average COP for the overall cooling process was 1.50.

Flooding rates in packed-bed conditioners must be high, both to ensure complete wetting of the packing and to prevent heating of the desiccant. Although the first objective—complete wetting—might be realized at low flow rates by adding surfactants to the desiccant or treating the surface of the packing to increase its surface energy, the second—keep the desiccant cool—will always require a high flooding rate.

Figure 4 shows the temperature rise that occurs when a 43% solution of lithium chloride initially at 85°F (29.4°C) adiabatically absorbs water vapor. If the quantity of absorbed water decreases the desiccant's concentration to 42% and the desiccant is not cooled, the temperature of the desiccant will increase to 130°F (54.4°C). Whereas, initially the desiccant has an equilibrium dew point of 52.1°F (11.2°C), the 42% solution at the higher temperature has an equilibrium dew point of 96.8°F (36.0°C)—a value much too high to be useful. If the more dilute desiccant is cooled to 85°F (29.4°C), its equilibrium dew point would be 53.8°F (12.1°C), and the desiccant could continue to dehumidify air.

Conditioners that are internally cooled do not have to operate at the high flooding rates of packed-bed units. As noted earlier, industrial liquid-desiccant conditioners have used water-cooled banks of metal tubes as the contacted area between the desiccant and the process air. However, when operating with halide salt solutions, this type of internally cooled conditioner is too expensive to implement (at least if it is to compete in HVAC applications).

Two approaches to internally cooled conditioners for use with halide salts are now being pursued. In both approaches the conditioner is a plate-type heat exchanger with air flowing on one side of the heat exchanger and a coolant on the other. The surfaces of the air passages are wetted with the liquid desiccant. The desiccant absorbs water from the air, but instead of getting warmer, the desiccant's temperature stays close to that of the coolant on the other side of the heat exchanger.

The more difficult of the two configurations to implement, but the one that has the potential to produce the greatest cooling effect, is similar to a conventional indirect evaporative cooler. Indirect evaporative coolers function similarly to the plate-type air-to-air heat exchanger that is shown in Figure 5. In this figure, the cooling air (secondary air) flows upward through one set of passages, and the process air (primary air) flows horizontally through the alternate passages.

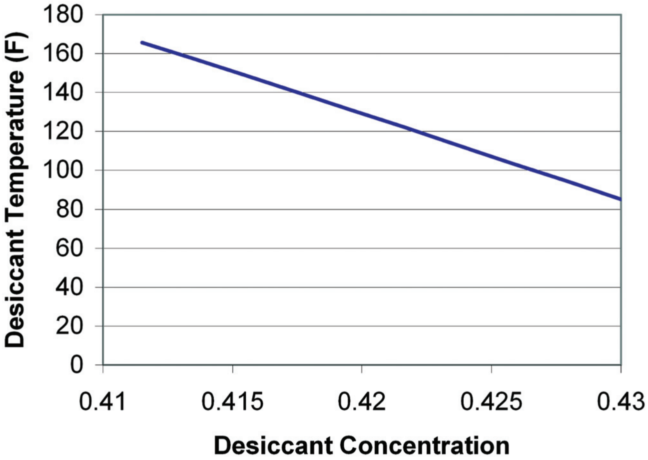

Figure 4. Temperature rise in an adiabatic absorption process by 43% lithium chloride solution.

This air-to-air heat exchanger becomes an indirect evaporative cooler by spraying, dripping, or wicking water onto the walls of the cooling-air passages.

At least two researchers have attempted to convert an indirect evaporative cooler into a liquid-desiccant conditioner by wetting the walls of the process-air passages with solutions of lithium chloride or other halide salts. Lowenstein et al. (1988) used a commercially available cross-flow, air-to-air heat exchanger that had plastic-coated aluminum plates as the desiccant conditioner. A thin nonwoven fiberglass wick was applied to the plate surfaces to promote wetting by the water and desiccant. Initial tests with 3 mm gaps between the plates produced pressure drops that were too high, and the gaps were increased to 4 mm. The evaporatively cooled conditioner was packaged for field testing as a 500 cfm residential dehumidifier. The nominal desiccant flow was 3 gpm (11.4 l/min) (with a 0.83 L/G mass flow ratio). Bartz et al. (1989) reported on the field performance of two of these 500 cfm prototypes. The better performing of the two delivered its design 1 ton of cooling when the ambient wet-bulb temperature was 60°F. Although not reported, the plastic coatings did not adequately protect the aluminum plates, and several parts of the LDAC were seriously corroded by the desiccant. It is also noted that the 0.83 L/G mass flow ratio is about one-third the value for a typical packed-bed conditioner, which is a fairly high desiccant flow for an internally cooled conditioner. This work has not led to a commercial product.

Saman and Alizadeh (2002) built and tested an evaporatively cooled, liquid-desiccant conditioner that used a plastic-plate, cross-flow, air-to-air heat exchanger as its contact surface. The plastic plates were 0.2 mm thick and 600 mm square. Dimples on the plates kept at a 3 mm gap between plates. Approximately 190 plates were stacked to form a 600 mm wide conditioner. The maximum process airflow was 1800 m^3/hr (1060 cfm), which corresponded to a 1.4 m/s (275 fpm) face velocity and 3.0 m/s (590 fpm) velocity in the gap. Water was sprayed into the cooling-air passages counter-flow to the cooling air and at 4.6 l/min (1.2 gpm). A 40% calcium chloride solution was sprayed into the process-air passages counter-flow to the process air and at 2.6 l/min (0.7 gpm). At the maximum process airflow, the conditioner operated with a 0.1 desiccant-to-air (L/G) mass flow ratio. The stack of conditioner plates was tilted so that the two liquid flows tended to flow down over the surfaces of the plates. When the conditioner was oriented so that the diagonal of the plates was vertical (i.e., the cooling air

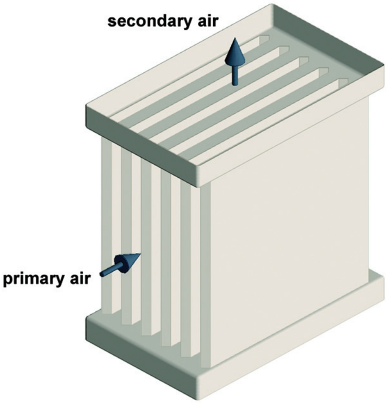

Figure 5. Cross-flow air-to-air heat exchanger.

and process air flowed cross-wise up through the conditioner, each flow at 45° from the horizontal), a 0.75 heat/mass effectiveness could be achieved at a process airflow of 0.3 kg/s (where the heat/mass effectiveness is the measured enthalpy change for the process air divided by the maximum theoretical limit).

Although simple in theory, an evaporatively cooled conditioner can be difficult to implement. The biggest challenge is preventing leaks between the desiccant and water that flow on opposite sides of the heat exchanger.

A simpler alternative to implement is to configure the conditioner as a heat exchanger with water-cooled plates. This approach is illustrated in the conditioner shown in Figure 6. The outer surfaces of the conditioner plates are wetted with desiccant and the process air flows in the gaps between the plates.

In most applications, the source for cooling water would be a conventional cooling tower. The ambient wet-bulb temperature would be the temperature of the cooling sink—as it is for the evaporatively cooled conditioner—but in this configuration the plates are no longer directly cooled by evaporation. The additional temperature drop that this introduces slightly reduces the cooling capacity of the conditioner.

Laevemann et al. (2006) described a water-cooled conditioner that is made from twin-wall polypropylene plates (i.e., a hollow extrusion that has two parallel walls with thin webs maintaining the space between the walls and creating a multitude of internal passages). Cooling water flows within the plates' internal passages. A low flow of desiccant is directly delivered to the outer surfaces of the plates. A polypropylene fleece on the outer surfaces of the plates evenly spreads the desiccant. A more detailed description of the conditioner is presented by Peltzer and Laevemann (2003).

As reported by Laevemann et al. (2006), a 128-plate conditioner is designed to cool and dry 3200 m^3/h (1900 cfm) of air from 27.5°C and 0.0120 kg/kg to 25.3°C and 0.0062 kg/kg when it is cooled with 23.4°C water. At this operating conditioner, the desiccant-to-air mass flow ratio (L/G) is 0.04 and the desiccant is a 39.7% lithium chloride solution. The sensible and latent

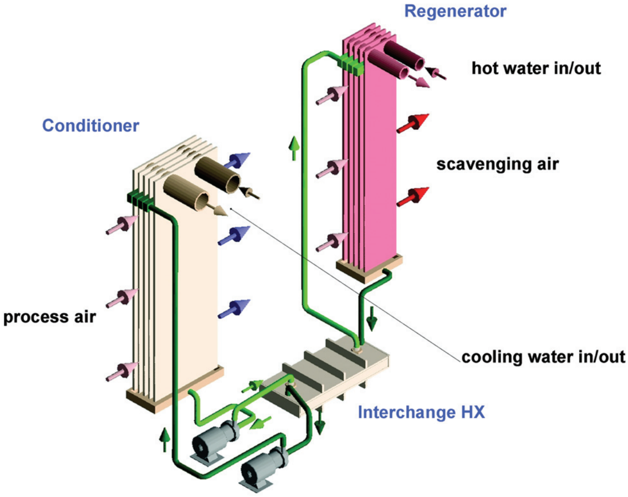

Figure 6. A liquid-desiccant air conditioner that uses a water-cooled conditioner and water-heated regenerator.

cooling is 3.0 kW and 15.4 kW. In one field test of this conditioner, complete wetting of the plate surfaces was not achieved and the delivered latent cooling was only 55% of the design value (Laevemann et al. 2006).

Lowenstein et al. (2006) described an alternative design of a plastic-plate water-cooled conditioner. In this second design, the plates are made from a PVC extrusion. The cross section of each plate, which is shown in Figure 7, is 0.1 in. by 12 in. (2.5 mm by 305 mm), with 110 cooling passages running the 4 ft length of the plate. The plates have a thin—approximately 0.020 mil (0.5 mm)—wick covering their surfaces to ensure even wetting by the desiccant. Then each plate is bonded to an upper and lower end-piece. The upper end-piece has a desiccant distributor that can deliver very low flows of desiccant directly to the top of the plate. When the plate/end-piece assemblies are stacked, they form separate circuits for the cooling water and the liquid desiccant. They also create a 0.1 in. (2.5 mm) air gap between the plates. Lowenstein et al. (2004) presents a much more detailed description of the construction of this conditioner.

At nominal operating conditions, the preceding water-cooled conditioner operates with a face velocity of 375 fpm (1.91 m/s) and a velocity of 900 fpm (4.57 m/s) in the gap between the plates. At these conditions, the pressure drop across a 12 in. (30.5 cm) deep conditioner is 0.3 in. w.c. (75 Pa). The nominal desiccant flow for a conditioner that processes 6000 cfm (10,200 m^3/hr) is between 3 and 5 gpm (11.3 and 18.9 l/min), with an L/G between 0.067 and 0.111. When operating with 43% lithium chloride and 85°F (29.4°C) cooling water, this conditioner will process air from 85°F/0.0192 lb/lb (29.4°C/0.0192 kg/kg) to 90°F/0.0089 lb/lb (32°C/0.0089 kg/kg). The latent and total cooling is 288,000 Btu/h (84.4 kW) and 267,000 Btu/h (78.2 kW), respectively. Monitored operation of this conditioner has confirmed that the design performance can be achieved in field operation (Miller and Lowenstein, 2008).

The potential for droplet carryover from liquid-desiccant conditioners and regenerators that use halide salts has seriously discouraged their use in all but the most carefully maintained industrial applications. Internally cooled conditioners and regenerators that can work at very low flooding rates can eliminate carryover. The conditioners of Laevemann et al. (2006) and Lowenstein et al. (2006) directly deliver the desiccant onto the surfaces of the cooled conditioner plates. Sprays and drip pans are not used, avoiding droplet formation. Once on the plates, the desiccant flows within a thin wick. At the gap air velocities in these conditioners (i.e., less than 4.57 m/s), desiccant is not entrained in the airflow.

Slayzak (2005) verified that a low-flow conditioner could operate without the entrainment of desiccant droplets into the air. Figure 8 shows the particle densities in five size ranges at the inlet and outlet of a low-flow conditioner as measured by a laser particle counter. Twelve measurements were made, half at the inlet and half at the outlet. The x axis in this figure is the time at which the measurements were made. As shown in this figure the particle densities in each size range are

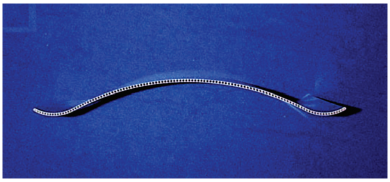

Figure 7. Cross section of a water-cooled conditioner plate.

essentially the same at the inlet and outlet. From this measurement it is concluded that the conditioner is neither removing particles nor adding particles to the air.

Several researchers have modeled internally cooled conditioners. Saman and Alizadeh (2001) developed a model for the evaporatively cooled cross-flow conditioner that they tested (Saman and Alizadeh 2002). Their model performs energy and mass balances on incremental control volumes using heat and mass transfer coefficients for laminar flows. The Nusselt theory for laminar falling films is used to calculate the thickness of the liquid films. The model predicts the measured performance of the conditioner reasonably well with most data falling within 15% of the model's predictions.

Mesquita et al. (2004) modeled a water-cooled conditioner in which the air and desiccant flows are counter-current and the flows are laminar. Three models were developed. The simplest model performed mass and energy balances on discrete control volumes using published data for heat and mass transfer coefficients to calculate the heat and mass exchange between the desiccant and the air. The most sophisticated model calculated the temperature and concentration gradients across the desiccant and air films and calculated the thickness of the film. At desiccant-to-air (L/G) mass ratios greater than 0.10, the dehumidification efficiency predicted by the three models agreed to within 9%. The model that included a calculation of the liquid film thickness, predicted experimentally, measured dehumidification rates to within 5% when L/G ratios were less than 0.015. At an L/G ratio of 0.05, the deviation between the model and the experiment was about 9%.

An important difference between published models of internally cooled conditioners and the physical systems previously described occurs in the desiccant films. The models assume classical, Nusselt falling films, meaning that in the physical systems, the desiccant flows within thin wicks that cover the contact surface.

The wicks are an essential part of an internally cooled conditioner. With halide salts remaining the most practical liquid desiccant for HVAC applications, the conditioner will most likely have plastic walls. Since high surface-tension halide salt solutions will not easily wet low surface-energy plastic walls, wicks must be used to uniformly spread the desiccant. Furthermore, the air is much less likely to entrain desiccant droplets if the desiccant flow is entirely within the wick. At the operating conditions of a conditioner, the Nusselt theory predicts film thicknesses

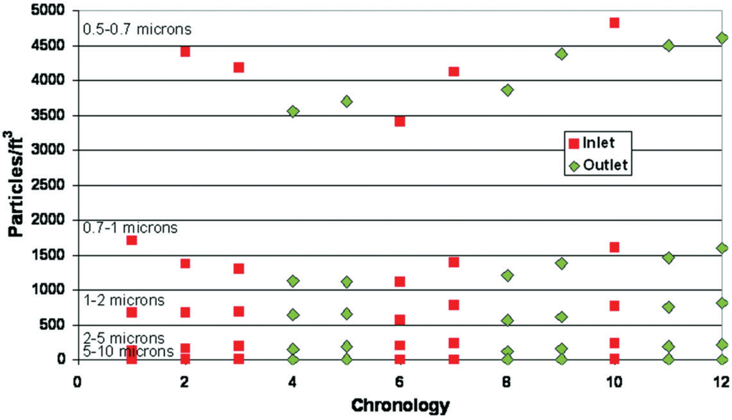

Figure 8. Particle counts at the inlet and outlet of a low-flow conditioner.

that are much thinner than practical wicks. Also, depending on the structure of the wick, the desiccant may be mixed as it flows through the fibers of the wick. Future models of liquid-desiccant conditioners should include the effect of the wick on performance.

Development of Regenerators for HVAC Service

The regeneration of a salt-based liquid desiccant is similar to thermal separation processes that are common in the chemical industry. Techniques such as multiple-effect boilers and vapor-compression distillation, which are frequently used to remove water from aqueous solutions, can greatly reduce the energy needed to regenerate a desiccant.

Packed-bed scavenging-air regenerators are the dominant technology for industrial liquid-desiccant dehumidifiers that use halide salts. These regenerators operate similarly to packed-bed conditioners, except that now the porous bed of contact media is flooded with hot desiccant. Air is drawn either across the bed or up through the bed. The equilibrium vapor pressure of the hot desiccant is much higher than the partial pressure of water vapor in the air, so water evaporates from the desiccant into the air. After scavenging water from the desiccant, the humid air is typically exhausted to ambient.

A packed-bed regenerator will have the limitations previously noted for this type of heat and mass exchangers. The desiccant flooding rates must be high so that the change in desiccant concentration as it flows through the bed is small. The desiccant's equilibrium vapor pressure, which is the driving potential for regeneration, is an exponential function of temperature. For a 39% lithium chloride solution at regeneration conditions, the equilibrium vapor pressure will drop by a factor of two with a 26°F (14.4°C) to 28°F (15.5°C) decrease in temperature. However, regeneration is an endothermic reaction that, in a packed-bed regenerator, is sustained by the thermal energy of the desiccant flow. The dependence of temperature on the change in concentration that was discussed for conditioners (Figure 4) also applies to packed-bed regenerators. Even a one point increase in concentration would produce an unacceptable drop in desiccant temperature. The high flooding rates for packed-bed regenerators require large pumps with correspondingly large power requirements.

Droplets will be created as the desiccant is sprayed onto the packed bed and as it flows down through the bed. Droplet filters must be used to suppress droplet carryover. These droplet filters increase fan power and can be a source of maintenance problems.

Despite their limitations, packed-bed regenerators have been more thoroughly tested and modeled than other types of regenerators. The previously cited reviews of packed-bed heat and mass exchangers by Oberg and Goswami (1998B) and Elsarrag (2006) summarize past work on this type of regenerator.

An internally heated scavenging-air regenerator can overcome many of the limitations inherent in a packed-bed unit. Since the temperature of the desiccant is no longer coupled to its flow rate, it can be decreased by more than an order of magnitude. Pumping power can be reduced, and the regenerator can operate without creating desiccant droplets.

The relatively large concentration changes that are possible in an internally heated scavenging-air regenerator lead to additional system benefits. When a low-flow and high-flow scavenging-air regenerator operate so that they supply strong desiccant at the same concentration, the low-flow unit is operating with an average desiccant concentration that can be two to four points lower (the inlet desiccant concentration to the low-flow regenerator can be four to eight points lower). For lithium chloride at 180°F (82.2°C), a 40% solution has an equilibrium vapor pressure that is 25% higher than a 43% solution. This higher equilibrium vapor pressure will lead to a correspondingly smaller regenerator.

Low-flow internally heated regenerators have been built and tested by Krause et al. (2005) and Lowenstein et al. (2006). Both of these regenerators are made from extruded plastic plates.

Internal passages are formed within the plates as part of the extrusion. As shown conceptually in Figure 6, the desiccant is delivered to the outer surfaces of the plates and hot water flows within the plates. The scavenging air flows in gaps between the plates.

The plates for the regenerator of Krause et al. (2005) are polypropylene. The plates are 5 mm thick and the air gap between them is 6 mm. A thin cotton coating covers the plate surfaces to promote wetting by the desiccant. Both the hot water within the plates and the air between the plates flow upward counter to the desiccant. Computer modeling of this regenerator predicted that at a desiccant-to-air mass ratio (L/G) of 0.028 and with hot water entering the plates at 85°C, the regenerator would concentrate a lithium chloride solution from 30% to 38%. If the water temperature decreased to 60°C, the same flow of desiccant would be regenerated to 33%.

Lowenstein et al. (2006) tested a 21-plate regenerator that had a nominal water-removal capacity of 18 lb/h (8.2 kg/h). The plates were 0.12 in. thick, 4.5 in. wide, and 24 in. long (3 mm × 11.4 cm × 61 cm) and extruded from a polymer in the polysulphone family. A thin layer of fibers was adhered to the plate surfaces to promote uniform wetting by the desiccant. The desiccant flowed down the length of the plates and air flowed horizontally in the gaps between the plates (similar to the regenerator shown in Figure 6).

A regenerator's COP—defined as the ratio of the phase-change enthalpy of the desorbed water (its latent heat) divided by the thermal input to the regenerator—strongly affects the LDAC's competitiveness with alternative technologies for cooling and dehumidification. As shown in Figure 9, Lowenstein et al. (2006) reported that when regenerating a lithium chloride solution from 36% to 40%, the COP of the preceding internally-heated scavenging-air regenerator increases from 0.624 to 0.732 as the temperature of the hot water supplied to the regenerator increases from 160°F to 200°F. Over the same temperature range, the regenerator's water removal capacity more than doubles from 11.2 lb/h (5.1 kg/h) to 23.2 lb/h (10.5 kg/h).

The improvement in COP produced by higher temperatures in scavenging-air regenerators results from the exponential dependence of the desiccant's equilibrium water vapor pressure. The hot desiccant that flows down the contact surfaces loses energy through both heat and mass exchange with the air. The convective heat exchange is a parasitic loss that cools the desiccant without increasing its concentration. Since the driving potential for mass exchange—the desiccant's equilibrium vapor pressure—increases exponentially with its temperature, but the driving potential for heat exchange increases linearly, a greater fraction of the input thermal energy will produce useful mass exchange when the regenerator operates at higher temperatures.

The COP of a scavenging-air regenerator can be increased by preheating the air through heat exchange with the hot exhaust. In laboratory tests, Slayzak (2006) reported that an internally heated regenerator operating at 200°F (93.3°C) and processing 40% lithium chloride has a COP of 0.72 without heat recovery, and 0.83 with heat recovery by a 70% effective heat exchanger.

A simple boiler can also be used to regenerate a desiccant. The boiling point of a 43% lithium chloride solution is 290°F (143.3°C). At this temperature, boiling water requires approximately 1060 Btu/lb (2.46 MJ/kg) of removed water. (The phase change energy for pure water at this temperature is 918 Btu/lb [2.13 MJ/kg]. Additional heat is required because of the stronger bonding of the water to the desiccant —the chemical heat of mixing.)

In addition to the heat for phase change, heat is required to raise the temperature of the weak desiccant to its boiling point. If a heat exchanger is used to preheat the weak desiccant by recovering energy from the strong desiccant that leaves the boiler, then this ideal boiler will have a COP of 0.92. In a more realistic system with an 80% recovery of thermal energy and a four point increase in desiccant concentration to 43%, the boiler's COP will be 0.71—a value comparable to a scavenging-air regenerator without heat recovery from the exhaust air. (All COPs presented so far have not accounted for possible inefficiencies in the heat source. For example, a gas-fired boiler might have a flue efficiency of 80%.)

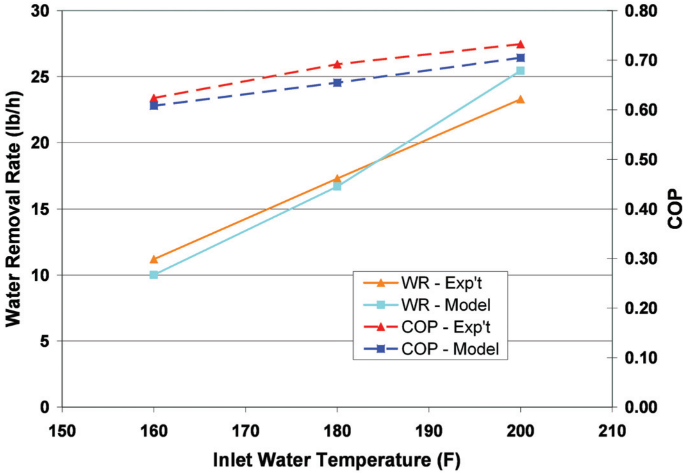

Figure 9. COP and water removal capacity of an internally heated regenerator.

An LDAC’S COP will strongly influence its competitiveness against other air conditioners. In applications that convert thermal energy into cooling (i.e., those that either run the air conditioner on heat provided by solar thermal collectors or recovered from an engine-generator) the LDAC will compete with other heat-driven cooling technologies. However, the LDAC may also compete in the growing market for dedicated outdoor air systems (DOAS) and other high-latent cooling systems. In this market, the LDAC will most likely be competing against vapor-compression air conditioners that have been modified so that a higher fraction of their cooling is latent. Kosar (2006) discusses the alternatives for high latent air conditioners based on a conventional vapor-compression cycle. These advanced air conditioners typically add a heat and/or mass exchanger in the airstream to lower the sensible heat ratio (SHR) of the cooling process. These modified vapor-compression air conditioners have lower energy efficiency ratios (EER) than conventional units because of the additional air-side pressure drops across the added heat/mass exchangers.

At what COP does an LDAC’s operating costs equal those of a high-latent vapor-compression air conditioner? This breakeven COP will depend on both utility rates and the EERs of the two cooling systems. If one assumes that the EER for a commercial vapor-compression air conditioner is 9.5 and for the LDAC is 45 (based on the electrical power for pumps and fans in the LDAC and its cooling tower), and that the cost for gas and electricity are the 2007 U.S. averages for commercial customers—$0.0967 per kWh and $11.31 per million Btu ($10.72 per GJ)—then the breakeven gas-based COP will be 1.41. Clearly, an LDAC will have trouble competing with a high-latent electric system if it uses a simple scavenging-air regenerator.

Most of the thermal input to a simple desiccant boiler appears as latent heat in the exiting superheated steam. Multiple-effect boilers can greatly improve the efficiency of a separation process by using this steam as the thermal source for a second boiler stage. However, this second stage must operate at a temperature that is lower than the steam’s saturation temperature. If the first boiler stage operates at atmospheric pressure, the latent heat of the steam is available at 212°F (100°C). The second boiler stage would have to operate under a vacuum if the desiccant is to boil at a temperature lower than 212°F (100°C). Absorption chillers have successfully used double-effect boilers to increase their gas-fired COPs from approximately 0.6 to 1.0 or slightly greater.

A liquid-desiccant regenerator can realize the high efficiency of a double-effect boiler without using a second stage that operates under a vacuum. Albers and Beckman (1992) described a two-stage regenerator in which the first stage is a simple boiler. The steam from this first stage heats a tube that is the contact surface for a second-stage scavenging-air regenerator. A regenerator that has a first-stage atmospheric boiler and a second-stage, internally heated, scavenging-air regenerator can have a 1.10 COP when operating with an 80% effective interchange heat exchanger and concentrating lithium chloride from 39% to 43%.

A second approach to recovering the thermal energy in the steam that leaves a boiler is to compress the steam to a pressure at which its saturation temperature is higher than the operating temperature of the boiler. This approach is commonly referred to as vapor-compression distillation (VCD) or vapor recompression. As reported by Slayzak et al. (1998), a VCD regenerator will have its best performance when the compressor is driven by a gas-fired engine and rejected heat from the engine is returned to the boiler. The COP of a VCD regenerator will decrease as the concentration of the desiccant it delivers increases. The more concentrated desiccant has a higher boiling point elevation, and so the compressor must operate at a higher pressure ratio. A VCD regenerator that supplies a lithium chloride solution at 35% would have a 2.3 COP. The COP would decrease to 1.6 at a desiccant supply concentration of 41%.

RESEARCH NEEDS

Important advances must still be made in liquid-desiccant technology if it is to be widely used for comfort conditioning. Several research needs have previously been identified as part of the review of current R&D. These needs, plus additional ones, are as follows:

The Identification of a Noncorrosive Desiccant

The halide salt solutions now commonly used in LDACs are nontoxic, but corrosive. Although developers of halide-based LDACs may be confident that they have engineered their systems to work with the halide salt solutions and that the desiccant will be completely contained within the system, many potential users won't accept the technology until these claims have been proven in many applications over many years. A noncorrosive, nontoxic desiccant that did not compromise the LDAC's performance would accelerate the adoption of the technology. Assuming that low-flow liquid desiccant technology will dominate in HVAC applications, alternative desiccants must have relatively low surface tensions so that they easily wet the contact surfaces of the conditioner and regenerator. They also must not be too viscous so that pumping power stays low. Finally, they must be chemically stable in open systems where they are exposed to air that may have trace contaminants such as ozone, oxides of nitrogen, and volatile organic compounds.

The Development of an Air-Cooled Conditioner

Owners of smaller HVAC systems tend to avoid cooling towers, which require more maintenance than they will accept. In some applications, the advantages offered by the LDAC will overcome any possible reluctance to use a cooling tower. However, market acceptance of LDACs would be hastened by the development of an air-cooled unit. An air-cooled LDAC would have the added benefit of greatly reducing the high demand for water created by air conditioning, whether the demand is at the site or at the power plant.

Wetting and Rewetting of Contact Surface

As illustrated by the experience of Laevemann et al. (2006), incomplete wetting of the contact surfaces within an LDAC will degrade the unit's performance. Although the higher surface tension of common desiccants compared to water impedes wetting, desiccants do have the advantage that once the contact surface is thoroughly wetted with desiccant, it won't dry out. Robust contact surfaces that are easily and completely wetted by low flows of a desiccant must be proven over a wide range of operating conditions.

High-Efficiency Regenerators

Simple, scavenging-air regenerators—the type of regenerator that has been used in almost all LDAC demonstrations—are limited to COPs less than one. Several approaches to increasing the COP of regenerators have been previously discussed. These approaches include multiple-effect boilers and vapor-compression distillation. If these technologies are to become part of a high-efficiency LDAC, they must be developed and demonstrated in long-term operation. Other high-efficiency separation processes should also be explored.

Enhanced Heat and Mass Transfer

In the internally cooled conditioners developed by Saman and Alizadeh (2002), Lowenstein et al. (2004), and Laevemann et al. (2006), the process air flows between parallel contact surfaces at laminar Reynolds numbers. The open parallel passages may be interrupted by spacers, but the primary function of these spacers is to keep the contact surfaces apart, not to promote heat and mass transfer between the air and the desiccant. Surface enhancements such as fins, spines, and other extended surfaces are commonly used in heat exchangers to reduce their size. Although the desiccant films that flow on the contact surfaces complicate the design of the regenerator and conditioner, approaches to increasing heat and mass transfer coefficients should be explored as a way to reduce the size, pressure drop, and cost of these critical components.

Application of Advanced Evaporative Cooling to LDACs

The cooling capacity of a LDAC that uses an internally cooled conditioner increases as the temperature of the desiccant/air contact surfaces decreases. In many applications the conditioner rejects heat either directly or indirectly by evaporative cooling. This limits the temperature of the contact surfaces to a value above the wet-bulb temperature of the air that drives the evaporative cooling. Advanced indirect evaporative coolers have been demonstrated that can cool air to below the wet-bulb temperature of air that acts as the heat sink (Maisotsenko et al. 2004). The integration of these advanced evaporative coolers with a LDAC has the potential to lead to a more commercially competitive HVAC product.

Active Management of Desiccant Quality and Chemistry

Liquid-desiccant dehumidifiers in industrial settings have encountered conditions which can acidify the desiccant, produce foaming, or precipitate solid salts (Griffiths 2007). Although commercial and residential air conditioners operate in a much more controlled environment than industrial units, chemical interactions between the desiccant and gaseous species in the air are possible. Once again, longer term operating experience with LDACs is needed to identify possible problems, and if problems are encountered, to address them.

CONCLUSIONS

Although now limited primarily to industrial applications, LDACs could help solve the most pressing problems now facing the HVAC industry:

- peak electric demand created by compressor-based air conditioners
- poor indoor air quality and high indoor humidity that can be difficult to correct with conventional air conditioners
- carbon emissions from the power plants that support electric air conditioners

In HVAC applications, the desiccant must be nonvolatile. Halide salt solutions are the most commonly used liquid desiccant that meets this requirement. The corrosiveness of halide salt solutions can be managed by working with very low desiccant flow rates in both the regenerator and conditioner (i.e., desiccant-to-air mass flow ratios (L/G) less than 0.1). At these low flow rates, the desiccant must be either continually cooled in the conditioner or continually heated in the regenerator to prevent large changes in its temperature. Several researchers have successfully implemented this internal heat exchange by configuring both the conditioner and regenerator as plastic heat exchangers and using the external surfaces of the heat exchangers as the contact media between the desiccant and airflows. The low surface-energy walls of the plastic heat exchangers cannot be easily wetted with desiccant. Thin wicks applied to the walls of the heat exchangers are used to create uniform films of desiccant. Low-flow conditioners and regenerators that deliver the desiccant directly to the contact surfaces, avoiding sprays and drip pans, have operated with no entrainment of desiccant droplets in the exiting airflows.

The most promising early markets for an LDAC will be those where its exceptional latent cooling and low electrical demand give it a competitive advantage. The demand for sustainable air conditioning is one such market. Solar energy can be effectively applied to air conditioning by using relatively low-cost solar thermal collectors to supply hot water to run an LDAC. By storing "cooling" as concentrated desiccant, a solar LDAC can operate during the evening and night. This capacity for storage gives LDAC systems an important advantage over a competing solar air-conditioning technology, compressor-based air conditioners powered by solar photovoltaic panels. The compressor-based systems are difficult to implement as solar cooling systems that serve 24-hour loads because of the high cost and inefficiency of storing electric or thermal energy for evening and night hours.[1]

Combined heat, power, and cooling (CHPC) applications are a second promising early market for LDACs. In this market, the LDAC would compete with absorption chillers, a mature technology that can run on the low-grade heat recovered from thermally driven power sources. In applications where humidity control is important, the LDAC would have a competitive advantage. In the U.S. market, absorption chillers tend to be used on larger buildings (e.g., more than 100 tons or 350 kW), whereas the LDACs now under development are in the range of 5 to 25 tons (18 to 88 kW).

The LDAC may also be preferred in CHPC systems in which heat is available at a lower temperature. The performance of absorption chiller degrades severely when the heat source is below 180°F (82°C). A small, single-effect 10 ton absorption chiller may only supply 3 tons of cooling, or 30% of its nominal cooling rate, when the temperature of the hot water decreases from 190°F (88°C) to 160°F (71°C) (Yazaki, 2004). As shown in Figure 9, an LDAC's regenerator might decrease to only 55% of its nominal capacity over the same temperature range.

Scavenging-air regenerators and regenerators configured as simple boilers will typically have COPs between 0.7 and 0.8. If these regenerators run on hot water provided by a gas-fired water heater, the LDAC will have much higher operating costs than a conventional electric air conditioner. However, advanced regenerators that employ either multiple-effect boilers or

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[1] Thermal energy storage with chilled water or ice can be very effective at shifting peak cooling loads to off-peak, evening hours. It is far less attractive for extending the operation of a solar electric cooling system. For solar applications, thermal energy would be stored during hours when ambient temperatures are highest and when the cooling loads are greatest—conditions that degrade the efficiency of the compressor-based cooling system while increasing the required capacity.

vapor-compression distillation could have significantly higher COPs, perhaps as high as 2.0. These advanced regenerators would allow the LDAC to compete with compressor-based air conditioners in the broader HVAC market.

Liquid-desiccant technology is now at a critical juncture where promising systems have been demonstrated in the lab and, to a limited extent, in the field. However, much more field experience is needed before the engineers that design and specify cooling systems will be comfortable replacing a conventional air conditioner with an LDAC. The unique issues now facing the HVAC industry may provide the final push needed for LDACs to cross this last hurdle.

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