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# A High Efficiency Air Conditioner for Humidity Control in Residences

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## 1.0 Summary

A novel air conditioner that achieves a very high latent cooling fraction while surpassing the efficiency of the best technology now available has been reduced to practice. Both the improved latent performance and the higher efficiency are realized by wetting the external surfaces of both the evaporator and the condenser of a vapor-compression air conditioner with a liquid desiccant. The desiccant, which has a strong affinity for water vapor, significantly increases the amount of dehumidification performed by the evaporator. The desiccant also allows the evaporator to meet its design total cooling rate while operating at a temperature that is 10 F to 15 F higher than would be required for a conventional evaporator. This higher evaporator temperature increases the efficiency of the vapor-compression cycle by reducing the temperature "lift" required to reject the cooling load to ambient.

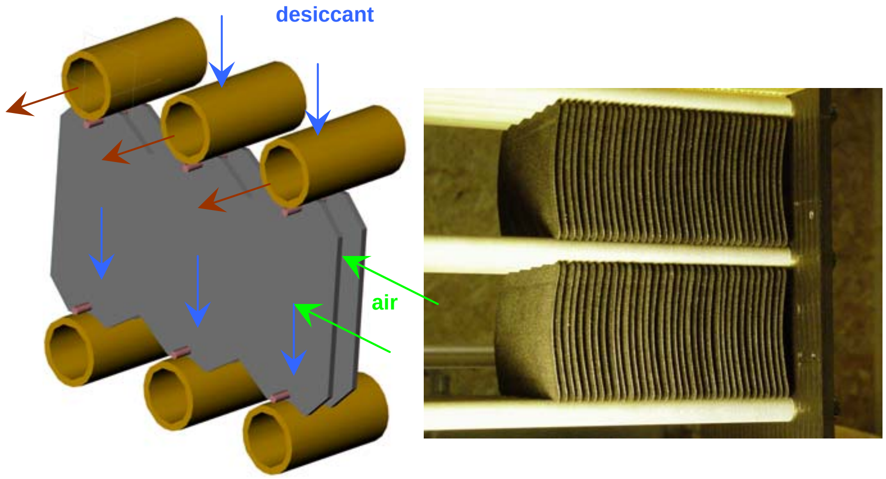


Figure S. 1 – Liquid Desiccant Finned-Tube Heat and Mass Exchanger

As described in U.S. Patent No. 7,269,966 and shown in Figure S.1, a liquid-desiccant direct-expansion (LDDX) air conditioner uses a condenser and evaporator that are finned-tube heat exchangers with the refrigerant flowing within the tubes and films of desiccant flowing down the fins and over the outsides of the tubes. The desiccant film on the evaporator will absorb water from the process air even if the evaporator's temperature is above the air's dewpoint. Heat is released as the desiccant absorbs the water vapor and the desiccant's temperature will increase as it flows down the fin. However, before the desiccant gets too warm to effectively cool and dry the process air, it flows off of the fin and onto a cooled tube. After being cooled on the tube, the desiccant flows onto the next lower set of fins.

The condenser functions identically to the evaporator except now the desiccant is heated as it flows onto the tubes of the condenser. The warm desiccant releases water that is carried to ambient by the air that flows through condenser. Weak and strong desiccant are exchanged between the condenser and the evaporator, and in steady operation, the desiccant concentration adjusts to a value that balances the water absorption on the evaporator with the water desorption on the condenser.

A two-ton, R410A, breadboard model of the LDDX was built and tested. The model was tested at conditions typical of a Dedicated Outdoor Air System (DOAS)—an application that requires a high fraction of latent cooling. In a typical test, air at 87 F and 0.01693 lb/lb was drawn over both the evaporator and the condenser of the model. The evaporator flow was 577 cfm and the condenser air flow was 870 cfm. The desiccant flow between the evaporator and the condenser was 0.85 gpm. At these operating conditions, the evaporator and condenser refrigerant saturation temperatures were 68 F and 110 F. The total cooling supplied by the evaporator was 22,750 Btu/h, 79% of which was latent cooling. The EER was between 16 and 17 (based only on compressor power). Although cumulative operating hours have been short (i.e., about 40), no potential O&M problems have been identified.

## 2.0 Introduction

Both ventilation and the control of indoor humidity are essential to healthy and comfortable conditions within homes.  Unfortunately, the two can be at odds.  When ventilation rates are increased to improve indoor air quality, humidity can become too high, reaching levels that are not only uncomfortable, but unhealthy.

As noted in the Phase I solicitation, “recent research indicates that 30% improvements in space cooling efficiency…could be achieved by separating the functions of dehumidification and cooling in HVAC systems”.  Perhaps equally important for the consumer, an HVAC system that could independently control humidity and temperature would greatly improve comfort and health.

Essentially all residential HVAC systems are controlled so that they keep temperature within an acceptable range.  No attempt is made to control humidity.

Those of us who live in the eastern half of the country are familiar with the problem that simple temperature control can cause.  A rainy summer night with temperatures in the high 60s or low 70s can have an outdoor humidity ratio above 0.015 lb/lb (dewpoint above 68$^o$F).  Since the sun is down and the air temperature is moderate, the cooling loads on the house will be almost zero.  If the air conditioner does not run, the absolute humidity within the house will equal or exceed that of the outdoors.  For a 75$^o$F indoor temperature, the relative humidity will be at least 80%—a level that is not only uncomfortable, but exceeds the 70% threshold at which mold and mildew proliferate.

There is little that conventional HVAC equipment can do to restore comfort.  All conventional systems dehumidify by cooling air below its dewpoint.  While it is possible to first cool the air to condense water vapor and then reheat the air—as occurs in a conventional vapor-compression dehumidifier—this approach is inefficient

Desiccants are materials that have a high affinity for water vapor.  This property enables a desiccant air conditioner to dry air without first cooling the air below its dewpoint.

There have been past attempts to develop a vapor-compression air conditioner that directly coupled a liquid desiccant to both the evaporator and condenser of the air conditioner.  The earliest work was done by John Howell and John Peterson at the University of Texas[1].  Although Howell and Peterson modeled the performance of a liquid-desiccant direct-expansion (LDDX) air conditioner that used lithium chloride, the prototype that they built and tested used ethylene glycol.

Unfortunately, this switch to glycol leads to an impractical air conditioner.  All glycols have a finite vapor pressure.  In both the evaporator and the condenser, glycol will evaporate into the air streams, leading to an unacceptable requirement to regularly recharge the system.

More recently, the Drykor Corporation manufactured and sold several models of liquid-desiccant vapor-compression air conditioners.  The Drykor technology used lithium chloride as the liquid desiccant.  This is a significant improvement over University of Texas’s work since solutions of all ionic salts (including lithium chloride) do not “evaporate” the salt, i.e., the vapor pressure of an ionic salt is essentially zero.

However, the Drykor technology had several important limitations.  First, both the cooling and drying of the process air and the rejection of heat and moisture to the ambient air were <u>indirectly</u> coupled to the evaporator and the condenser.  In the Drykor system, the liquid desiccant was first cooled in the evaporator and then the cool desiccant was delivered to a porous bed of contact media where the process air was dried and cooled.  Similarly, the desiccant was regenerated by first heating it in the condenser and

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[1] Howell & Peterson, “Preliminary Performance Evaluation of a Hybrid Vapor Compression/Liquid Desiccant Air Conditioner,” ASME Paper No. 86-WA/Sol-9, 1986.

then flowing the warm desiccant over a porous bed of contact media that also had a stream of ambient air flowing through it. This indirect approach introduces temperature drops that reduce the efficiency of the air conditioner. Furthermore, the contact media needs high flows of desiccant if it is to stay uniformly wetted. These high flow rates are more likely to lead to carryover of desiccant droplets by the process air.

A final limitation in the Drykor technology was its failure to exchange heat between the warm, concentrated desiccant that leaves the condenser and the dilute, cool desiccant that leaves the evaporator. Continuous operation requires that concentrated and dilute desiccant be exchanged between the evaporator and condenser so that the water absorbed from the process air can be rejected to ambient. However, the warm, concentrated desiccant flowing to the evaporator, if not pre-cooled by heat exchange with the weak desiccant that flows from the evaporator, will dump heat back onto the evaporator. The refrigeration circuit must pump this heat back to the condenser, which increases the compressor work without increasing the net cooling supplied to the process air. Although it is possible to greatly decrease this heat "dump back" by operating the condenser and evaporator liquid-desiccant flows at a large difference in concentration (so that less desiccant has to be exchanged), the higher desiccant concentration on the condenser increases its temperature and the lower concentration on the evaporator decreases latent cooling. Both effects compromise the performance of the liquid-desiccant air conditioner.

At the time this report was prepared, Drykor was no longer operating in the U.S. However, a new company with a very similar line of liquid-desiccant air conditioners, DuCool Ltd, had replaced them in the market.

## 2.0 The Technical Approach

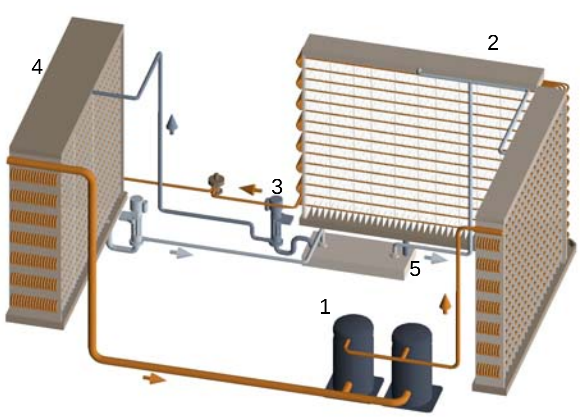


**Figure 1 – A Functional Schematic of a LDDX**

The liquid-desiccant vapor-compression air conditioner that was developed in this project functions similarly to a conventional direct-expansion (DX) air conditioner. As shown in Figure 1, a compressor (1) delivers high pressure refrigerant vapor to a condenser (2). Heat is rejected from the refrigerant to an ambient air stream, converting the refrigerant vapor to a liquid. The liquid refrigerant is metered through a control valve (3) or capillary tube to an evaporator (4). The pressure within the evaporator is kept low by the compressor. At this low pressure the refrigerant boils within the evaporator, absorbing heat from the process air stream.

The liquid-desiccant direct-expansion (LDDX) system shown in Figure 1 modifies the conventional condenser and evaporator by configuring them as finned-tube heat exchangers that have the refrigerant flowing within the tubes and films of desiccant flowing down fins and over the outsides of the tubes. As described in U.S. Patent No. 7,269,966[2] and shown in Figure 2, the LDDX air conditioner uses a condenser and evaporator that are finned-tube heat exchangers with the refrigerant flowing within the tubes and films of desiccant flowing down the fins and over the outsides of the tubes. The desiccant film on the evaporator will absorb water from the process air even if the evaporator's temperature is above the air's dewpoint. Heat is released as the des-

[2] Lowenstein, et al., "Heat and Mass Exchanger", U.S. Patent No. 7,269,966, September 2007.

iccant absorbs the water vapor and the desiccant's temperature will increase as it flows down the fin. However, before the desiccant gets too warm to effectively cool and dry the process air, it flows off of the fin and onto the cooled tube. After being cooled on the tube, the desiccant flows onto the next lower set of fins.

The condenser functions identically to the evaporator except now the desiccant is heated as it flows onto the tubes of the condenser. The warm desiccant releases water that is carried to ambient by the air that flows through condenser. Weak and strong desiccant are exchanged between the condenser and the evaporator, and in steady operation, the desiccant concentration adjusts to a value that balances the water absorption on the evaporator with the water desorption on the condenser.

The cool, weak desiccant that leaves the evaporator exchanges heat with the warm, strong desiccant that leaves the condenser in the interchange heat exchanger (5 in Figure 1). This heat exchange improves the efficiency of the LDDX by reducing the parasitic cooling load that the strong desiccant imposes on the evaporator.

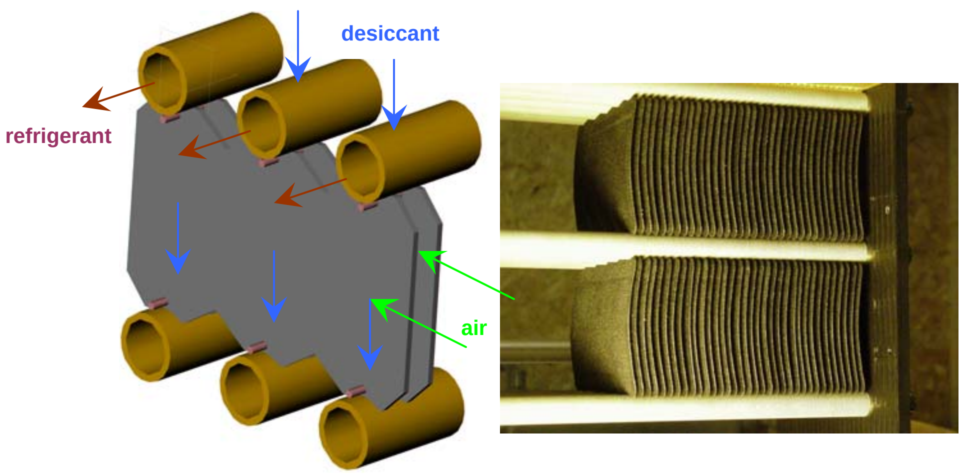


**Figure 2 – Finned-Tube Liquid-Desiccant Heat and Mass Exchanger**

The configuration of the fins and tubes in both the evaporator and condenser are critical to the LDDX achieving good performance. The fins must uniformly spread the desiccant over their surfaces and deliver the desiccant to the tubes. Once on the tubes, the desiccant must again spread out uniformly over the surface so that good heat transfer occurs between the desiccant and the tube. Furthermore, both the fins and tubes must be compatible with a concentrated solution of lithium chloride (or similar ionic salt), which is the desiccant for the LDDX.

## 3.0 Experimental Performance of the LDDX

A significant fraction of the project was devoted to developing an effective fin and tube design. The final configuration is similar to the one shown in Figure 2 in which each fin fits between the rows of tubes and contacts several tubes in one row. The tubes were a copper-nickel alloy with 0.5" outer diameter. The fin height was approximately 2.5" with seven fins per inch. The fins were stamped from thin plastic film that was flocked on both sides. Figure 3 shows the completed evaporator, and Figure 4 shows the tubing array for the condenser before the fins were inserted. Figure 5 shows the completed two-ton model of the LDDX. The model uses R410A as the refrigerant.

The model LDDX was performance tested under conditions typical of a Dedicated Outdoor Air System (DOAS) operating on a hot, humid summer day. It was not within the scope of the project to set up accurate mass flow measurement on either the air side or refrigerant side of the LDDX. In place of these direct mass flow measurements, the performance of the LDDX was estimated by measuring the high and low side pressures in the refrigerant circuit and then using the performance map for the LDDX's compressor to calculate refrigerant mass flow and isentropic efficiency. Thermocouples on the surface of the refrigerant tubing and covered by insulation measured the refrigerant temperature at several locations in the refrigerant circuit. These temperature measurements along with the refrigerant pressures were used to calculate both the subcooling and superheating of the refrigerant leaving the condenser and evaporator, respectively.

A thermodynamic model of a vapor-compression cycle was set up in EES (Engineering Equation Solver, available from University of Wisconsin). With the refrigerant high and low pressures, refrigerant flow, compressor isentropic efficiency, and the tube temperature measurement for the refrigerant at the outlet from the evaporator (which could be used to calculate the amount of superheat in the refrigerant vapor), the thermodynamic model calculated the thermodynamic state of the refrigerant at the outlet from the condenser and at the inlet to the evaporator. With the refrigerant state know throughout the circuit, the cooling capacity of the evaporator was calculated. A second calculation of the cooling capacity that used the refrigerant subcooling calculated from the measurement of the refrigerant tube temperature at the condenser outlet typically agreed with the first calculation to within 5%.

Air-side measurements of the dry-bulb and wet-bulb temperature of the air entering and leaving the evaporator were made during the test of the LDDX. These measurements were used to calculate an enthalpy change for the air across the evaporator. Since the heat transferred by the strong desiccant that enters the evaporator is small, the enthalpy change of the air and the calculated cooling rate for the evaporator were used to calculate the volumetric flow of air across the evaporator. Since the air-side measurements also yield the absolute humidity of the air entering and leaving the evaporator, the volumetric flow of air was used to calculate the water absorption by the evaporator.

The strong and weak desiccant concentrations were measured during a run as was the exchange flow rate of desiccant between the condenser and evaporator. Using these measurements, the water absorption rate in the evaporator was calculated independently of the air-side value.

Table 1 summarizes the performance of the LDDX during seven runs. The temperature and humidity of the evaporator/condenser air varied with the natural changes in ambient weather, but all runs were during warm, relatively humid conditions, i.e., dry bulb temperatures varied between 84 F and 87 F, and humidities, between 109 and 124 grains per pound of dry air. In addition to the uncontrolled variations in air temperature and humidity, the condenser air flow and the desiccant flow were varied in the tests.

The performance in Table 1 demonstrates both the very high latent cooling capacity and the high efficiency of the LDDX. For the seven runs, the fraction of cooling that was latent ranged from a low of 0.68 to a high of 0.82. When calculated solely from the manufacturer’s compressor tables, the compressor-based EER for the LDDX ranged from 16.9 to 20.7. When the compressor tables were used to calculate a refrigerant mass flow, but compressor power was directly measured, the calculated EER was between 8% and 14% lower.

The varying air conditions made it difficult to identify performance trends as the condenser flow and desiccant flows varied. However, it is noted that a significant decrease in condenser air flow (from 1,088 cfm to 584 cfm in runs 5,6 and 7) had a relatively small effect on performance: total cooling stayed constant at about 22,800 Btu/h; SHR decreased slightly from 0.21 to 0.18; and compressor-based EER decreased from 18.0 to 16.9.

Comparing runs 2 and 4 shows that a decrease in desiccant flow rate from 1.01 gpm to 0.74 gpm, lowered the total cooling by 6% (from 23,945 Btu/h to 22,587 Btu/h); increased the SHR from 0.19 to 0.23; and decreased the compressor-based EER from 19.2 to 17.9.

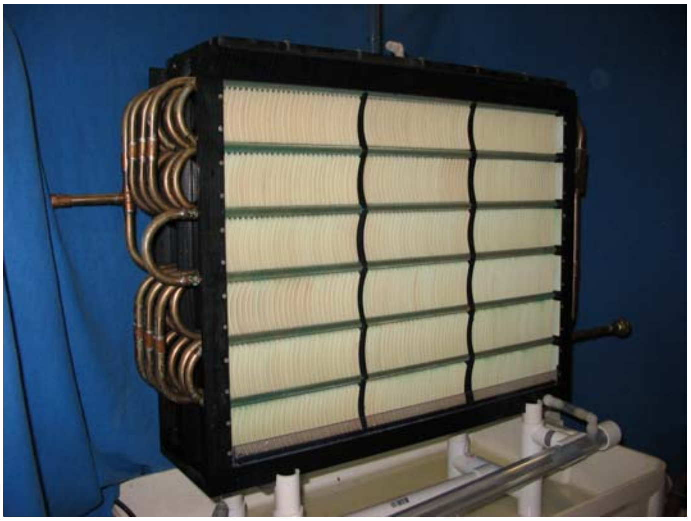
Figure 3 – Completed Finned-Tube Evaporator

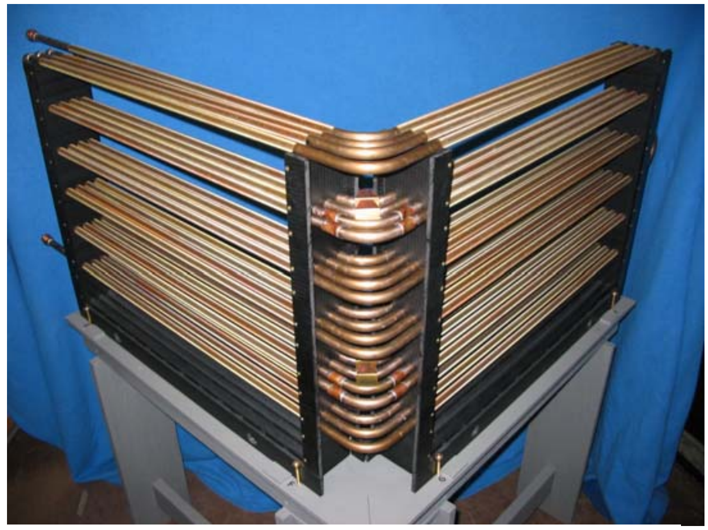
Figure 4 – Condenser Under Construction


Figure 5 – Completed Two-Ton Model of the LDDX

Table 1 - Performance of the LDDX

| Run | OA T F | OA grains | SA T F | SA grains | Evap cfm | Evap sat T F | Cond cfm | Cond sat T F | des gpm | TC Btu/h | WR air-based lb/h | WR des-based lb/h | SHR | measured compressor EER | map-based compressor EER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 86.0 | 113.7 | 74.8 | 77.4 | 599 | 62.8 | 1,333 | 99.0 | 1.04 | 22,714 | 14.6 | 25.7 | 0.32 | | 20.7 |
| 2 | 83.8 | 116.0 | 76.9 | 72.6 | 626 | 65.8 | 1,415 | 104.5 | 1.01 | 23,945 | 18.2 | 19.4 | 0.19 | 16.4 | 19.2 |
| 3 | 84.9 | 109.4 | 75.5 | 66.2 | 554 | 63.8 | 1,208 | 103.6 | 0.97 | 22,597 | 16.0 | 18.5 | 0.25 | 16.8 | 19.2 |
| 4 | 86.2 | 114.6 | 78.0 | 71.8 | 575 | 66.1 | 1,295 | 108.2 | 0.75 | 22,587 | 16.5 | 19.2 | 0.23 | 15.9 | 17.9 |
| 5 | 86.6 | 115.8 | 78.8 | 72.5 | 583 | 67.1 | 1,088 | 108.2 | 0.85 | 22,846 | 16.9 | 21.6 | 0.21 | 16.3 | 18.0 |
| 6 | 87.2 | 118.5 | 79.7 | 74.5 | 577 | 67.7 | 820 | 110.1 | 0.85 | 22,749 | 17.1 | 16.1 | 0.21 | 15.9 | 17.3 |
| 7 | 87.1 | 123.8 | 80.5 | 78.3 | 580 | 68.9 | 584 | 111.7 | 0.88 | 22,896 | 17.7 | 16.9 | 0.18 | 15.6 | 16.9 |

## 4.0 Design of a Manufacturable LDDX

The commercial value of the LDDX depends strongly on its competitiveness against other high-latent air conditioners. Although there is a growing need for better humidity control both in residential and commercial applications, this assessment is most meaningfully done in the commercial sector where sales of high latent DOASs are expanding.

For the purposes of this assessment, high latent air conditioners (or DOASs) can be divided into the following four classes:

- Units that use condenser or hot-gas reheat
- Units that use air-to-air heat exchangers to pre-cool and reheat the process air
- Units that use solid desiccant rotors, and
- Units that use liquid desiccants.

All units except those that use liquid desiccants remove some or all of the moisture from the air by cooling the air below its dewpoint in an evaporator. They differ, however, in the way that the saturated air that leaves the evaporator is reheated or further dried.

The use of thermal energy from the condenser to reheat the process air is the least expensive and least efficient approach to increasing an air conditioner's latent cooling. As reported by Kosar[3], a vapor-compression air conditioner that uses condenser reheat to decrease its SHR from 0.76 to 0.50, will typically see it efficiency reduced in half.

Despite this their lower efficiency, condenser-reheat air conditioners are now the most common type of DOAS. Their popularity is undoubtedly tied to their low cost.

As reported in Reference 3, the second and third classes of DOASs in the preceding list can both increase an air conditioner's latent cooling with only minimal loss in efficiency. DOASs now on the market that fall into either of these classes have about the same first cost.

The Munters Humidity Control Unit (HCU) falls into the third class of DOASs: a unit that uses a solid-desiccant rotor to increase its latent cooling. The saturated air that leaves the evaporator is dried as it passes through one side of a solid-desiccant rotor. The desiccant is regenerated by air that is first warmed as it passes over the unit's condenser. The HCU appears to be one of the stronger competitors for high efficiency DOAS, and its performance will next be compared to that of an LDDX that serves the same function.

[3] Kosar, "Dehumidification System Enhancements," ASHRAE J., vol. 48, Feb 2006.

Figure 6 shows a 6,000-cfm LDDX that would compete with a 6,000-cfm HCU. This LDDX uses a finned tube evaporator and condenser that are scaled-up versions of the ones used in the two-ton model (Figure 5). The depths of both the condenser and evaporator have been doubled compared to that of the two-ton model to increase their effectiveness.

As shown in Figure 7, both units deliver nearly identical latent and sensible cooling when processing outdoor air at 95°F dry-bulb and 78°F wet-bulb. However, the LDDX uses almost one-third less electricity than the HCU.

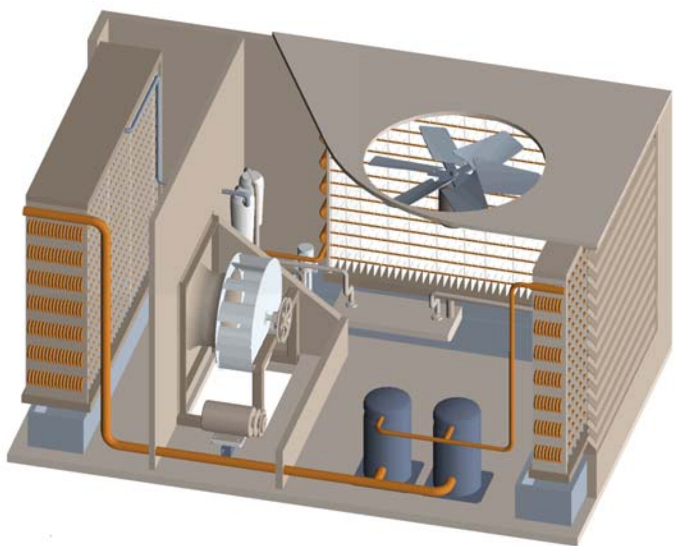

**Figure 6 – A 6,000-cfm LDDX DOAS**

The two primary reasons for the LDDX's lower power requirements are (1) it has a high evaporator temperature and relatively low condenser temperature, and (2) it has low air-side pressure drops. At the operating conditions shown in Figure 7, the LDDX's evaporator and condenser temperatures are 67°F and 130°F. Although Munters does not publish the evaporator and condenser temperatures in its technical bulletin, the higher compressor power for the HCU—28 kW for the HCU versus 24 kW for the LDDX—would mostly be due to a higher temperature lift from the evaporator to the condenser.

More important then the higher temperature lift, however, is the large pressure drop across the solid desiccant rotor. Although this parameter is not reported in the Munters technical bulletin, the HCU requires a 7.5 HP blower for the supply air (assuming a 1" w.c. pressure drop across the external ductwork), and a 7.5 HP blower for the air that regenerates the solid desiccant. The total horsepower for the fans in the 6,000-cfm HCU is 16.5 HP, compared to 4.4 HP for the LDDX. Including fan/pump power and compressor power, the EER for the LDDX and HCU at the operating conditions shown in Figure 7 are 8.6 and 14.0, repectively (i.e., the LDDX uses 39% less power than the HCU).

The LDDX will have a significantly smaller foot print and enclosed volume than the HCU. The LDDX shown in Figure 6 is 123" (L) x 76" (W) x 65" (H). The HCU with the same cooling capacity is 157" (L) x 80" (W) x 70" (H).

As noted in the introduction, high latent air conditioners that integrate liquid desiccants into the vapor-compression cycle have been manufactured and sold. The most serious effort was the product line offered by the Drykor Corporation. Drykor had sold over 3,000 liquid-desiccant air conditioners before they declared bankruptcy in 2006.

Although Drykor is no longer in business, several principals of Drykor have started DuCool, a company that manufacturers and sells a liquid-desiccant air conditioner with strong similarities to the Drykor technology. Figure 8 compares the performance of a DuCool DT-3400 air conditioner with a finned-tube LDDX processing the same 3,400 cfm of air. The LDDX delivers 45% more latent cooling and 60% more total cooling. The EER for the DuCool units is 8.8 compared to 13.8 for the LDDX.

The causes of the DuCool's poorer performance are three-fold:

- high desiccant flooding rates (estimated to be at least five times the flooding rate for the LDDX), which leads to high pump power and high air-side pressure drops,

- the use of separate desiccant-to-refrigerant heat exchangers and desiccant-to-air heat/mass exchangers (as opposed to integrating these two functions into a single component as is done in the LDDX), and
- the direct exchange of cold, weak desiccant and hot, strong desiccant without recovering heat in an interchange heat exchanger (as is done in the LDDX).

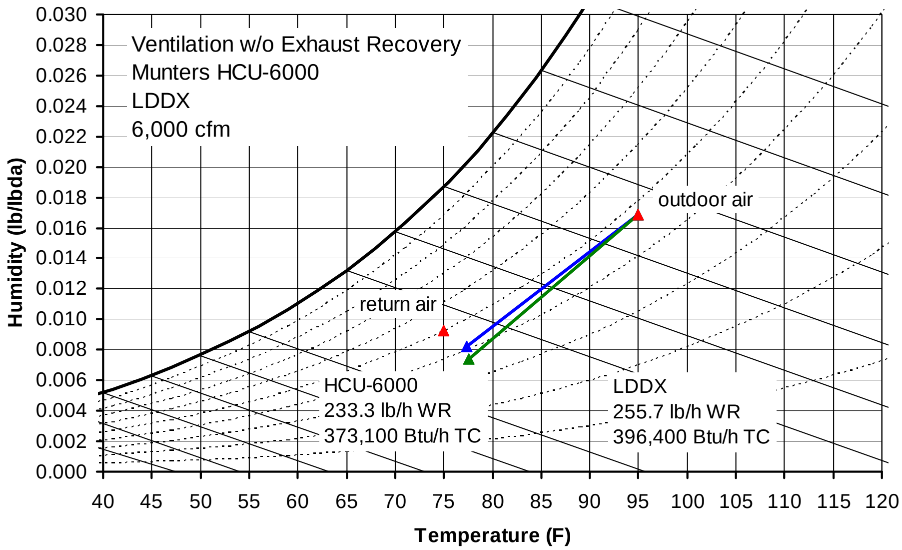


**Figure 7 – Comparative Performance of the HCU-6000 and an LDDX of Equal Capacity**

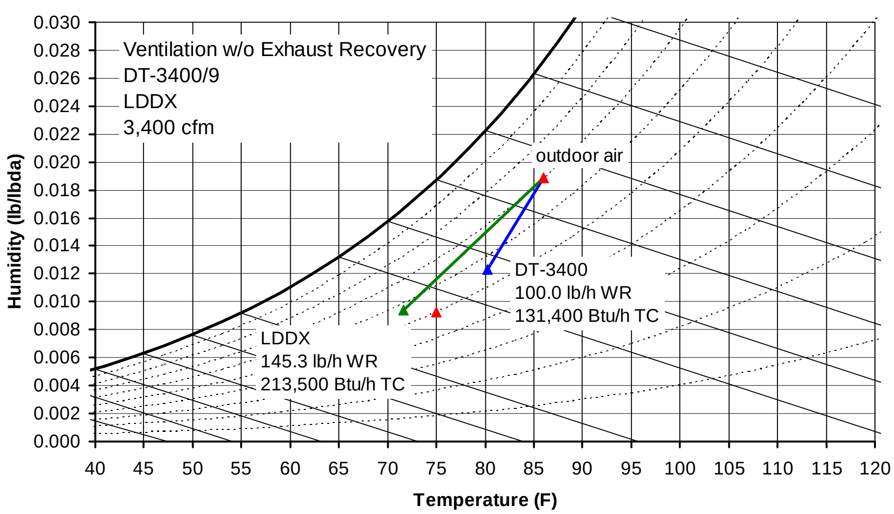


**Figure 8 – Comparative Performance of the DuCool DT-3400 and an LDDX with the same Air Flow Rating**

## 5.0 Conclusion

The demand for air conditioners that can meet very high latent loads is growing, spurred on by factors that include the need to increase building ventilation and the need to better control indoor humidity. Several technologies have been integrated into the standard vapor-compression cycle to produce high latent air conditioners, but in all cases this integration has produced a less efficient air conditioner that has a higher selling price (in some cases much higher).

In the project reported on here, a novel air conditioner that achieves a very high latent cooling fraction while surpassing the efficiency of the best technology now available has been reduced to practice. Both the improved latent performance and the higher efficiency are realized by wetting the external surfaces of both the evaporator and the condenser of a vapor-compression air conditioner with a liquid desiccant. The desiccant, which has a strong affinity for water vapor, significantly increases the amount of dehumidification performed by the evaporator. The desiccant also allows the evaporator to meet its design total cooling rate while operating at a temperature that is 10 F to 15 F higher than would be required for a conventional evaporator. This higher evaporator temperature increases the efficiency of the vapor-compression cycle by reducing the temperature “lift” required to reject the cooling load to ambient.

Several important hurdles must still be overcome before the liquid-desiccant/direct-expansion (LDDX) air conditioner is accepted by users. Industrial liquid-desiccant systems that use the same halide salts (e.g., lithium chloride or calcium chloride) that would be used in the LDDX typically require much more maintenance than would be standard for an HVAC product. However, these industrial systems work at desiccant flooding rates that are five to ten times higher than that used in the LDDX. At these high flooding rates desiccant droplets are created that then get entrained in the air streams. The laboratory operation of the LDDX shows that a properly designed unit can operate with very low flows of desiccant that does not create desiccant droplets and, thereby, dramatically reduces the unit’s maintenance requirement. Much more field operation will be needed to prove that the O&M requirements for the LDDX are reasonable by the standards of the HVAC industry.

A realistic estimate of the LDDX’s manufacturing cost, and ultimately its selling price to the user, cannot be complete until a manufacturable and maintainable prototype has designed and proven in the field. At this stage of development, there does not appear to be any aspect of the LDDX that will lead to an unacceptably high manufacturing cost. The tubing of the evaporator and condenser does have to be made from a corrosion-resistant alloy such as cupronickel, which will add cost, but the plastic, wicking fins for these heat exchangers should be much less expensive than the aluminum fins of conventional units. Considering its superior efficiency and the current trends towards higher energy prices, the LDDX should command a premium price compared to the competing high-latent air conditioners.