POTENTIAL FOR HEAT STRESS RELIEF USING DESICCANT SYSTEMS IN SWINE BREEDING FACILITIES

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ABSTRACT

Heat stress associated with extreme temperatures and relative humidity has been shown to reduce the productivity from swine facilities, especially breeding facilities. Traditional cooling methods used in these settings include evaporative pad cooling or misting with water. These methods are unable to lower relative humidity. Direct-expansion air-conditioning (DX-AC) has been shown to be effective, but generally not economically feasible at current energy costs. This paper presents an analysis of a desiccant technology for dehumidification configured with different ventilation systems, to enhance different cooling methods including evaporative pads. Results from this study suggest that cost-effective hybrid desiccant systems may be designed to effectively eliminate stress conditions in a high-value swine breeding operations.

INTRODUCTION

This report offers an initial evaluation of a novel application of desiccant systems to enhance the environment in swine breeding and genetic improvement facilities, to be retrofitted to existing systems or included in new facilities. Basic concepts of desiccant systems and design modifications to adapt the technology from human comfort applications to swine environmental control applications are presented. A computer simulation predicts the performance and economic analysis of a conceptual swine facility located in Charlotte, NC. The results suggest a system that could improve the thermal comfort of breeding swine, especially for climatic conditions associated with heat stress, and should enhance animal productivity and welfare.

THERMAL ENVIRONMENT STRESS

There were 6.957M and 6.672M breeding swine in the U.S.A. on Dec 1, 1997 and 1998, respectively (USDA, 1998). Of these, 2.715M (1997) and 2.635M (1998) were in hot and humid regions. For farrowing sows, the total respective numbers for 1997 and 1998 were 11.5M and 12.1M total respectively, with 4.7M and 5.1M in hot/humid regions. Heat stress has a profound negative impact on feed intake and growth for pigs reared in hot, humid locales (NRC, 1981; Close, 1978). Swine exhibit a strong thermostatic regulatory mechanism (Nienaber et al, 1994), with feed intake reduction as a control variable and body temperature as a feedback. At the biological engineering unit of the USDA-ARS Meat Animal Research Center (MARC), research has shown that relatively large increases in body temperature and heat production are associated with eating events. Under heat stress conditions, the decline in the rate of heat production is much more rapid than the decline in body temperature. Thus, heat storage within the body (elevated body temperature) appears to be a feedback mechanism to effectively delay additional eating activity (Eigenberg et al, 1995).

Several researchers have shown that high temperature adversely affects swine growth and feed intake. In a 21-day study of the effects of warm diurnal temperatures, Lopez et al. (1991) found that pigs raised in a hot environment [22.5 to 35 ^{o}C] gained weight at a 16.3 % lower rate and feed intake was 10.9% less compared to pigs raised under a constant temperature of 20 ^{o}C. Morrison et al. (1975) observed reduced growth rate for finishing pigs under a high temperature of 27.5 ^{o}C compared to those at a thermoneutral temperature. Daily feed consumption, average daily gain, and reproductive performance is significantly reduced as dry bulb and dew point temperature increase (Roller et al., 1967; Roller and Goldman, 1969). Thus, some form of cooling the interior environment of swine housing is beneficial for reducing animal heat stress under warm climates, and for sows, could improve the rate of milk production and piglet survival.

The literature also indicates that humidity negatively impacts controlled environment pig production. This impact can be correlated with a temperature-humidity index (THI). The reader is referred to Table 1 in Gates et al (1991a,b) for a listing of different THI values used by livestock researchers. Thus, while temperature reduction within facilities is important, dehumidification can facilitate alleviation of heat stress by increasing the opportunity for latent heat loss (panting, sweating) as temperatures increase. In fact, in more humid climates latent energy (humidity) loads are often greater than sensible loads, and can result in significantly over-sized cooling equipment to handle dehumidification needs (Colliver et al., 2000; Harriman et al, 2000).

DESICCANT SYSTEM TECHNOLOGY

Desiccant systems can control humidity of a process air stream (Kosar, 1998). However, until recently, their costs were considered prohibitive for many applications (Kosar, 1999). Desiccant technology in conjunction with a cooling system has been shown in non-agricultural applications to effectively control both humidity and temperature of an indoor environment at lower total energy cost, compared with a cooling system alone. This occurs because for most applications that use a direct-expansion (DX) cooling system, the sensible cooling capacity is oversized to provide dehumidification. Desiccant applications include corrosion prevention, condensation prevention, mold/mildew prevention, moisture regain prevention and product drying. Industries using desiccant technology include supermarkets, ice arenas, cold warehouses, hospitals, hotels, theaters, schools, restaurants, other retail stores and nursing homes.

A desiccant system dries an incoming air stream as it passes through a section of a desiccant wheel, as shown in Fig. 1. The desiccant wheel consists of a matrix material that is either coated or impregnated with a desiccant, which removes moisture from the air stream via adsorption. The wheel rotates during operation, and to prevent the wheel from becoming saturated with water a counter-flow (to the direction of the process air stream) "reactivation" air stream regenerates the wetted section of the wheel. The reactivation stream is typically heated prior to entry into the desiccant wheel. The hot reactivation air stream absorbs water from the wheel matrix, and regenerates the matrix for another cycle of processing incoming air.

A significant challenge in applying desiccant technology to agricultural ventilation systems is the typically higher fresh air make-up requirements. However, these have arisen because ventilation has been the primary means of temperature control, and may be reduced significantly if DX cooling can be used.

DESICCANT SYSTEM DESIGNS

The purpose of a desiccant system is to control humidity of the process air stream. A cooling system then removes sensible heat from this drier air. Coupling a desiccant wheel with some form of a sensible cooling system, a so-called "desiccant hybrid system", has been shown in different applications to effectively and economically control both humidity and temperature of an indoor environment. One of the benefits of controlling the amount of moisture in the air is to enhance utility of evaporative cooling, which can be beneficial both for directly evaporating moisture from skin, and to increase the effectiveness of evaporative cooling pads. The utility of evaporative pad cooling is dramatically reduced in moderate temperature, high humidity climates.

Cooling loads may be divided into latent loads associated with the control of humidity, and sensible loads associated with the control of the dry bulb temperatures. A hybrid desiccant wheel configuration with direct-expansion air conditioning (AC) can result in significant operating cost savings compared to a traditional AC-only system, because the removal of the moisture from the air eliminates the latent load and thus significantly lowers the load on the AC system. Desiccant systems often have a smaller operating cost because they operate using natural gas, propane or waste heat as compared to an electric AC. Generally, the energy cost of gas is significantly less than for electricity.

Current commercially available options for cooling swine include evaporative pad cooling, direct sprinkling, and misting systems. Bridges et al. (1992a) indicate that for Kentucky and much of the Southeastern U.S.A, most cooling for finishing swine is done using direct sprinkling systems. Desiccant based systems work best in conditions where removal of moisture from the air is as important as lowering the air temperature. Moisture removal can be helpful in two ways for high-value breeding swine: as a tool to enhance evaporative cooling, or as a means to remove building latent load to improve economics of AC application. This can be seen by examining the process by which warm, humid air is processed as it enters a building.

As depicted on the psychrometric process chart of Figure 2, outside air passes through a desiccant wheel (process line A-B) and follows a path that diverges slightly upward from a constant enthalpy line. The cost of removing moisture to the conditions at point B is an increase in temperature. Some of this temperature can be recovered using a heat exchange wheel in the desiccant system, thus sensibly cooling the air at point B toward point C. Additional sensible cooling, including AC cooling, drives the air to state point C. Now if the air at point C is passed through an evaporative pad, rather than the air at point A, the resulting air temperature is at point D. Without the desiccant system, the air after the evaporative pad would go from point A to point E. The difference in the absolute humidity of the air at points C or D, compared with point E, is significant. The air is both cooler (at point D), and substantially drier (at both points), thus lowering or eliminating thermal stress on the animals. A concern with this method is whether the reduced heat stress levels, which lead to increased animal health, well-being and productivity, can offset the higher investment and operational costs of a desiccant system.

The basic concept of the system along with points A through D from Figure 2 is shown in Figure 3. Here, we have assumed an "inlet air cooler" that is responsible for removing the sensible heat along the process line B-C in Figure 2. In the simulations reported here, this is an AC system. Success of the hybrid desiccant system depends on the costs involved in the heat recovery along path B to C in Figure 2. These costs must be compared with, for example, sensible cooling of outside air to the saturation curve, dehumidification to the dew-point of air at state D, and then injection into the building as would be accomplished with direct expansion (DX) air conditioning.

DESICALC® SIMULATIONS

The potential overall savings benefit of using a desiccant system was evaluated using a software package entitled DesiCalc®. DesiCalc® models the environment within a building using desiccant technology to supplement a traditional AC system. The DesiCalc® software includes templates for 11 commercial building types, weather conditions for 236 cities in the USA and can be modified for specific cases. DesiCalc® calculates the energy loads and costs using the US Department of Energy (US-DOE) 2.1E computational engine, and thus can be considered thoroughly validated for energy calculations.

The versatility of the software facilitates fine-tuning a system design to utilize waste heat from the regeneration system. The DesiCalc® software can be used to determine the feasibility of using the extra thermal energy for the purpose of dehumidification in a light commercial building. The results using DesiCalc® allow comparison of the operational costs of a generator-cogeneration system with traditional AC methods, including the reduction in costs of thermal building loads.

The proposed design uses a desiccant unit for dehumidification, coupled with an AC system to provide sensible cooling. The use of electric AC with a desiccant system has the potential to eliminate some of the disadvantages that AC-alone has experienced in agricultural applications, including equipment size, capital and operating costs, and reliability. Alternate methods of sensible heat recovery include evaporative pads to further reduce electric costs (e.g. Figure 3), or indirect evaporative cooling to reduce the latent regain.

Because DesiCalc® is designed for human application to commercial buildings, modifications to the inputs were required to simulate a swine facility. This simulation focused on a boar stud facility. The annual climatic and energy rate data for Charlotte, NC (U.S.A.) were used. The space area was set to 200 m^2. A barn this size holds 36 boars, with heat and moisture production assumed to be 144 W (490 Btu hr^{-1}) and 145 g H_2O h^{-1}, respectively (ASHRAE, 1997). This is approximately equivalent to 72 human occupants.

The simulation results are based on the desiccant system maintaining a desired temperature and relative humidity within the barn (20 ^{O}C and 60 % relative humidity) for boar productivity. At these conditions, the recommended minimum required ventilation rate is 34 m^3 h^{-1} pig^{-1}, or 1,223 m^3 h^{-1} (20 ft^3 min^{-1} pig^{-1}, 720 ft^3 min^{-1}) to satisfy the building's latent load and design outside minimum temperature. However, because the minimum rate was developed for cold weather conditions where moisture control (not odor and thermal comfort) was the primary reason for fresh air make-up, a ventilation rate of 2,550 m^3 h^{-1} (1,500 cfm) was used.

For this analysis, the energy rate schedule used was for Charlotte, NC, USA (1999 data). This schedule includes:

- Miscellaneous Charges
  - $12 Monthly Charge
  - 3% Taxes & Surcharges
- Electricity
  - Stepped Charge: 4.7¢ per kWh
  - Demand Charge: $4.89 per kW
- Gas (1 therm =100,000 BTUs = 29.31 kW)
  - 48.2¢ per therm summer
  - 51.4¢ per therm winter
  - 39.1¢ per therm cooling

Analysis using DesiCalc® was performed for three types of systems compared to a desiccant hybrid system. The three alternate systems were:

- a single AC system,
- two AC system, and
- AC system with no planned humidity control.

The desiccant hybrid system depicted in Figure 3, without an evaporative cooler, was assumed. The single AC system used standard AC for controlling both air temperature and humidity. The two AC system used one AC system for dehumidification, and another smaller AC system to lower the air temperature. The AC system without planned humidity control used an AC system to lower the air temperature to a set value without concern for the air humidity levels. Each system has advantages and disadvantages, as discussed in the results. The relative sizes of installed components, for the building system described, are given in Table 1.

RESULTS

Three calculated values: Design Cooling Capacity (tons of refrigeration, where 1 ton is equivalent to 3.517 kW or 12,000 BTU h^{-1}), Annual Energy Costs and Occupied Hours above 60% relative humidity, were used to compare the systems' performance. Results are provided in Table 1 and Figure 4.

The desiccant hybrid system requires cooling capacity that is only 41% of the one AC system (with temperature and relative humidity control). This significant size reduction occurs because the desiccant system removes the latent load from the air. The difference in annual energy costs ($2,431/year) between the two systems is due to the difference in the cost of electricity and natural gas in the Charlotte area. The one AC system is using electric energy to control air humidity while the desiccant system using natural gas energy. The required cooling capacity for the desiccant hybrid system is also less than the other two AC systems.

Predicted annual energy costs were about 7% less for the two AC system ($206) than the desiccant system, although the required cooling capacity is 220% greater. For the single AC system without humidity control, the annual energy expense is $486, or about 17% less than the desiccant hybrid system. However, this savings was offset by inferior humidity control. Each AC-only systems resulted in significant time periods when relative humidity exceeded 60%: greater than 86, 232 and 248 days per year for the one AC, two AC and one AC without humidity control systems, respectively. The desiccant system never allowed room humidity to rise above 60%.

These results demonstrate a serious failure when using electric AC only for swine barn cooling, a technique that has been tried repeatedly in the past. Because of the animal heat and moisture production, an AC system capacity must be greater for a similar sized building, to keep the interior barn temperatures below stress levels. The AC systems, however, are still unable to maintain relative humidity below 60% during periods of high latent loads.

An overall economic analysis, in which system capacity differences, equipment costs, and building life cycles are taken into consideration, is needed to determine which systems are most feasible to provide optimal interior environments for breeding and genetic improvement. Also of importance, regardless of cooing/dehumidification method, is a re-evaluation of fresh air ventilation rates appropriate for such facilities. Current ventilation rate guidelines have been developed based upon 100% fresh air to limit temperature rise within the building, and result in large building latent and sensible loads from outside air that must then be conditioned.

Based on energy considerations alone, the desiccant hybrid system was optimal in that it was the least expensive of those evaluated, which also satisfied constraints on maximum interior humidity levels.

SUMMARY

This analysis compared alternate technologies for providing temperature and humidity control in a swine breeding facility. The technologies all utilized direct-expansion AC systems. The desiccant hybrid system provided dehumidification of the incoming air stream by a desiccant wheel, and sensible cooling with a conventional AC system. The other three systems utilized only AC in different configurations.

Simulation results showed that a hybrid desiccant wheel coupled to direct-expansion air conditioning AC could completely eliminate thermal stress conditions (both temperature and humidity) at similar annual costs.

An AC-only system is capable of controlling thermal stress related to temperature, but can eliminate thermal stress related to humidity only by over-sizing the evaporator section for dehumidification and then providing some sensible re-heat, unlike a desiccant hybrid system. The simulations reported in this paper also suggest that a desiccant system represents potential annual energy savings over an AC-only system because of the cost difference between electricity and natural gas. Thus, in terms of application to swine breeding facilities, in which the increased productivity of heat stress relief is clearly greater than the added energy and capital costs, a hybrid desiccant-AC cooling system appears to have great potential. By contrast, AC-only systems can achieve similar temperature control performance at lesser or greater energy costs, but cannot provide adequate humidity control. Conventional evaporative pad cooling, or spray misting, as commonly used in swine breeding facilities, cannot be expected to eliminate heat stress. Further investigation and field trials with desiccant hybrid systems for swine breeding and genetic improvement facilities with high-value animals thus appears warranted.

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Table 1. Simulation Results for Charlotte, North Carolina, U.S.A.

System Configuration for Temperature and Humidity Control	Design Cooling Capacity (tons refrig.)	Design Cooling Capacity (kW)	Annual Energy Cost ($)	Annual Frequency Exceeding 60 % Relative Humidity (days/year)
One Larger AC System	11.22	39.5	$5,315	86.0
Two AC System	10.3	36.2	$2,679	131.9
AC System without Humidity Control	5.7	20.0	$2,398	148.0
Desiccant Hybrid System	4.6	16.2	$2,884	0.00

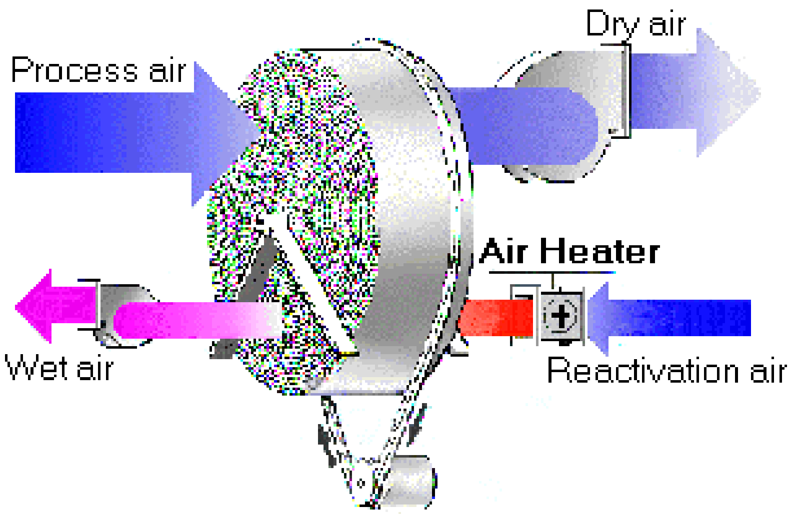

Figure 1. Schematic of desiccant wheel operation including process and reactivation air streams.

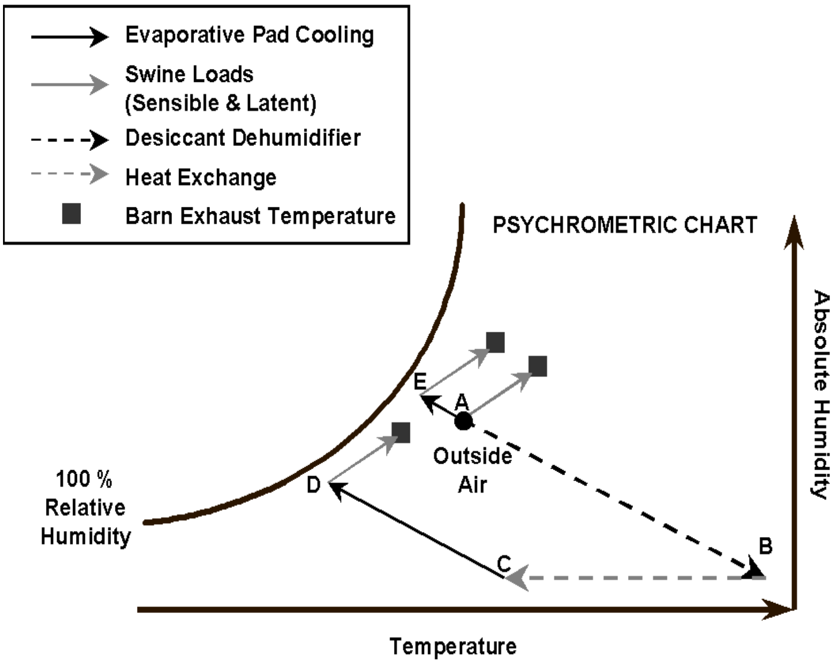

Figure 2. Psychrometric chart plotting the operational conditions for a desiccant-based system using an evaporative pad. Each path between points in the chart is as follows:

Path A-B: outside air passes through the desiccant wheel
Path B-C: sensible heat recovery from air conditioner
Path C-D: evaporative pad cooling

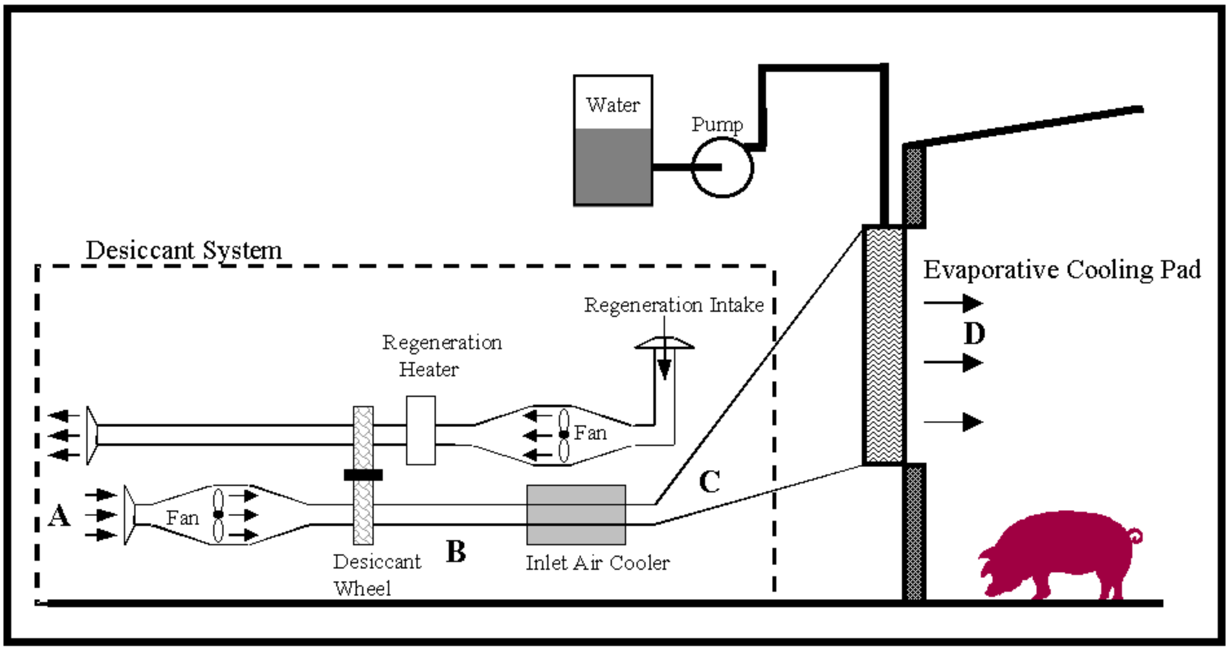

Figure 3. Design concept for swine facility desiccant hybrid system incorporating sensible cooling downstream of the desiccant wheel, followed by further cooling (and humidification) with evaporative cooling.

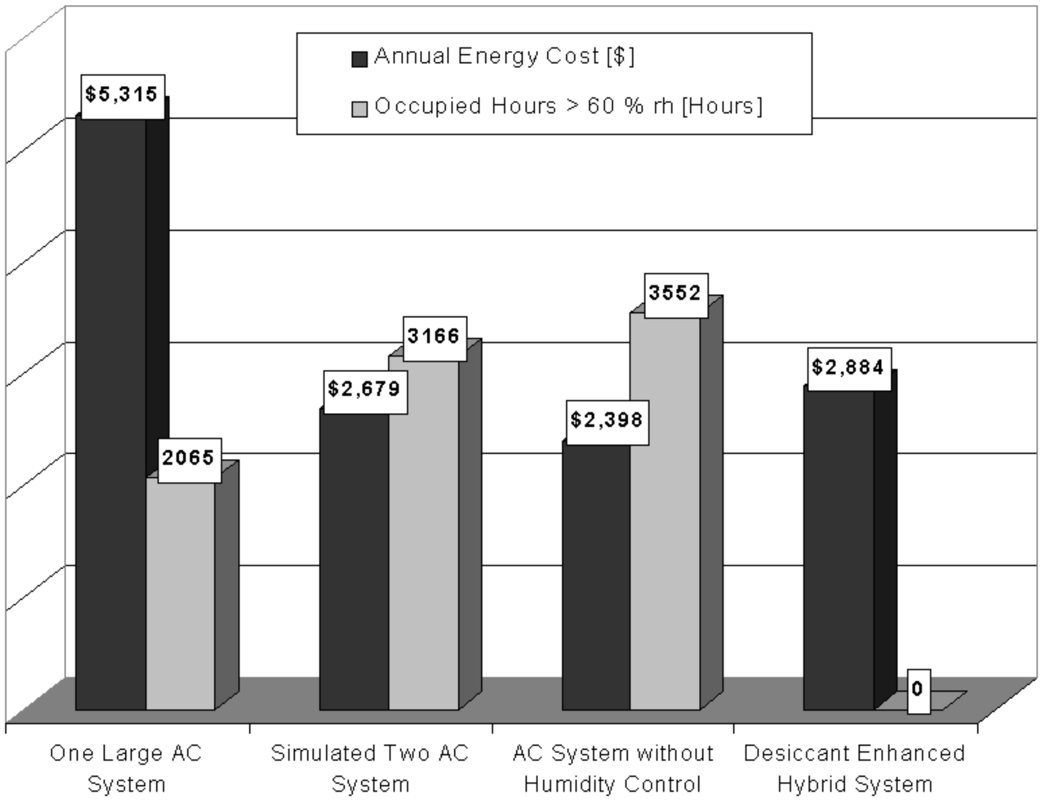

Figure 4. Simulation performance results for AC cooling systems compared to desiccant system.