Design and Testing of a Liquid Desiccant Dehumidifier

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ABSTRACT

A dehumidification system employing liquid desiccant was designed, constructed, and tested to determine the effect desiccant and air temperatures have on water vapor absorption rate. Calcium chloride desiccant was used for experimentation. A linear mathematical equation expressing concentration and concentration ratio as a function of time described the sorption process. The slope of this line, termed the sorption constant, increased with increasing air temperature and/or decreasing desiccant temperature. Air temperature had a more significant effect on the sorption constant than did desiccant temperature. The sorption constant can be adequately described as a logarithmic function of initial vapor pressure difference between the air and desiccant solution.

INTRODUCTION

In confined livestock environments, ventilation air is required for one or more of the following purposes: (a) to provide oxygen to the animals, (b) to remove moisture and odors, (c) to prevent heat build up, and (d) to control airborne disease organisms. Most researchers agree that the primary requirements for ventilation design are summer cooling and winter dehumidification. It has been estimated that a 20 kg pig subjected to a room temperature of 32.2 °C on a fully slotted floor, can produce as much as 0.09 kg of water vapor per hour (Huhnke et al., 1980). The suggested winter ventilation rate required to remove this quantity of water vapor can be as high as 0.2 m^3/min (Jones and Friday, 1980).

Conventional ventilation for winter dehumidification results in a high energy demand. Cold ventilation air entering a building is warmed by water vapor adsorption and sensible heating before being expelled, resulting in considerable energy loss. The quantity of air required for dehumidification in this manner is far in excess of the oxygen requirements of the animals. If other means were used to control humidity so that ventilation could be limited to oxygen requirements, possibly 50% or more savings could be realized in the ventilation heat load (Jones and Friday, 1980). The use of desiccants for moisture removal has potential application to solve this problem.

A large portion of work with desiccants has involved the drying of industrial gases and control of human environments. Desiccants recently received some attention in agriculture and food industries. Odighob (1976) used calcium chloride for preservation of food grains under humid tropical conditions. Fletcher (1980) constructed and tested a grain drying system using liquid calcium chloride with annual solar regeneration of the desiccant. Farmer et al. (1980) studied direct solar paunch drying, supplemented by solar regenerated desiccant. The prospect of using desiccants for dehumidification is further enhanced by recent developments in solar technology for desiccant regeneration.

The specific objectives of this research were to: (a) design and construct a lquid dehumidification system suitable for use in housed animal environments, and (b) test the dehumidification effectiveness of the system using calcium chloride solution at various desiccant and air temperatures.

LITERATURE REVIEW

Hougen and Dodge (1947) refer to calcium chloride as one of the oldest and well known desiccants amongst chemists and the gas industry. It is deliquescent because, in the presence of water vapor, it will dissolve or dilute completely in its own absorbed moisture and continue to do so until the vapor pressure of the solution and surrounding medium are equal. Therefore vapor pressure difference is a good indicator of the moisture exchange potential between solution and air. Considerable amounts of latent and sensible heat are transferred to the desiccant during absorption. Allied Chemical (1956) graphically describes the vapor pressure of calcium chloride solutions as a function of concentration and temperature.

Several types of liquid desiccant dehumidifiers using calcium chloride ($CaCl_2$) and other desiccants have been studied. C. R. Downs and the Colorider Corporation (Hougen and Dodge, 1947) constructed a system where air is passed through a $CaCl_2$ spray chamber and then through a compartment filled with solid, cubed CaCl. The liquid portion of the cubed $CaCl_2$ is used in the spray chamber. With this system it is possible to dry air at 36.5 °C and 85% relative humidity to 27% relative humidity. Heath (1932) tested equipment consisting of several circular discs rotating, partially submerged, in a solution of 78.5% $CaCl_2$. Air passed through the unsubmerged part of the discs allowing moisture exchange. The system removed a 75% sensible and 25% latent heat load at less cost than conventional systems. Fletcher (1980) proposed a system for grain drying that included solar regeneration of the desiccant. The system operated on an annual cycle where grain was dried during or directly after harvest and regeneration occurred throughout the rest of the year. Fossil fuel savings have been estimated

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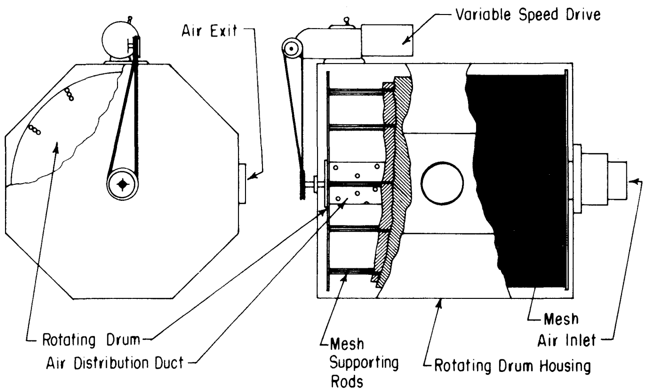

Fig. 1—Schematic diagram of air dehumidification equipment.

to be 87 to 90% for dehumidification systems using packed beds and solar regeneration during a process of simultaneous absorption and regeneration (Ko and McCormick, 1977).

EQUIPMENT AND METHODS

The design of a dehumidification system is dictated by a number of compromising requirements. To achieve simplicity and compactness, the system should perform both dehumidification and regeneration using a minimal amount of additional equipment. The system should have a small amount of liquid desiccant in circulation to minimize the power required and reduce the possibility of desiccant solidification in pipes and pumps. To reduce the energy input for regeneration, the system should be adaptable to simple solar energy collection systems. The mechanical design should be simple and relatively maintenance free.

Using the above criteria for a design concept, a system was developed consisting of a mesh covered cylindrical frame which rotates about a horizontal axis, Fig. 1. The cylindrical frame is partially submerged in desiccant solution while air is passed through the unsubmerged mesh. Regeneration or dehumidification can be achieved by adjusting the temperatures of solution and air, which govern the vapor pressure differential.

The rotating drum consists of a tubular air duct which is the axis of rotation for the mesh. Two circular plates are attached at the end of the tubular duct through which aluminum rods are bolted to support the mesh. The drum acts as a low head pump to keep the solution mixed. Two layers of polypropylene mesh are used with an opening size of 0.985 mm, 0.72 openings per mm and 50% open area. The mesh opening size selection was based on providing a large wetted surface area and low air pressure drop. The rotating drum is located inside an aluminum housing. The housing formed the reservoir for the desiccant and has a capacity of 110 L when the desiccant submerges approximately 1/3 of the circumference of the mesh. Submerging this portion of the mesh allows ample time for reconcentration of desiccant on the revolving mesh. A heat exchanger located in the bottom of the drum housing is used for desiccant temperature control. The length of the housing is 660 mm and the drum length is 600 mm with a radius of 280 mm.

Dehumidification experiments were planned using air temperatures of 25.0 and 20.9 °C at 80% relative humidity. These temperatures are representative of temperatures found in young animal environments. A relative humidity of 80% has been suggested as the upper limit for control of airborne bacteria, respiratory problems and building deterioration. Desiccant temperatures of 18.8, 22.2 and 23.5 °C were tested for each air temperature. At these temperatures the solution can be safely stored at a concentration of 45% without encountering solidification problems.

Calcium chloride was chosen based on cost and availability. Commercially available anhydrous calcium chloride in granular form, with a 94 to 97% content of $CaCl_2$, was used to mix solutions. To enhance air flow through the mesh, 75 mL of wetting agent was added to the solution.

Desiccant concentration was determined as a function of time for each test. At the beginning of each test, concentration was determined by measuring the specific gravity. The total mass of desiccant was recorded throughout the experiment and concentration calculated.

An AMINCO-AIRE unit was used to supply constant temperature/humidity air. An environment chamber was constructed and connected to the AMINCO unit from which the desired amount of air could be withdrawn. Cooling water, conditioned in a Hotpack environment chamber, was circulated through the housing heat exchanger to control desiccant temperatures. Inlet and outlet air conditions from the dehumidifier were measured using a dew point probe, hygrothermograph, wet and dry bulb type T thermocouples. Desiccant and cooling water temperatures were measured (±0.2 °C) with thermocouples. Thermocouples and dewpoint probes were connected to a Doric Digitrend 220 data logger.

A drum speed of approximately 3 r/min was observed as the maximum speed before desiccant was thrown from the mesh. Air flow for all tests was 4.4 m^3/min (±2%).

MATHEMATICAL MODEL

A simple mathematical model suggested by Henderson and Perry (1976) and often used to describe the drying of porous solid materials was considered to describe the absorption process. The equation is based on the empirical observation that the moisture content of hygroscopic material asymptotically approaches an equilibrium value in a steady state environment. This observation similarly applies to desiccant solutions. It is assumed that the rate of moisture transfer is directly proportional to the difference between the equilibrium and instantaneous moisture content.

Mathematically,

$$dM/d\theta = k(M - M_E).^* \quad [1]$$

Separating the variables and integrating yields

$$\frac{M - M_E}{M_o - M_E} = \exp(-k\theta) \quad [2]$$

Defining the left hand set of variables as a dimensionless moisture ratio (MR) yields

$$MR = \exp(-k\theta) \quad [3]$$

*See list of symbols for definition of variables.

TABLE 1. NON-LINEAR REGRESSION ANALYSIS FOR CONCENTRATION OF CALCIUM CHLORIDE

Rep. no	Air temp, °C	$CaCl_2$ temp, °C	Initial $CaCl_2$ conc, %	Predicted equilibrium, C_e* %	Predicted sorption constant, k
1	25.0	18.8	122.0	300.3	0.0106
2	25.0	18.8	122.2	311.7	0.0121
3	25.0	18.8	122.2	294.0	0.0116
1	25.0	22.0	122.2	280.0	0.0094
2	25.0	22.0	122.2	264.1	0.0088
1	25.0	23.5	122.2	239.4	0.0079
2	25.0	23.5	122.2	245.5	0.0068
3	25.0	23.5	122.2	250.3	0.0078
1	20.9	18.8	121.7	300.0	0.0060
2	20.9	18.8	121.7	288.1	0.0064
3	20.9	18.8	121.7	266.7	0.0076
1	20.9	22.0	121.7	274.4	0.0048
2	20.9	22.0	121.7	313.2	0.0060
3	20.9	22.0	121.7	296.2	0.0052
1	20.9	23.5	121.7	310.0	0.0036
2	20.9	23.5	121.7	290.4	0.0043
3	20.9	23.5	121.7	278.1	0.0054

* Data fitted to equation $C = C_e^* + (C_o - C_e^*)e^{-k\theta}$

TABLE 2. LINEAR REGRESSION ANALYSIS FOR CONCENTRATION RATIO USING A PSEUDO-EQUILIBRIUM CONCENTRATION

Rep. no	Air temp, °C	$CaCl_2$ temp, °C	Predicted sorption constant, k	R^2	Average sorption constant, k
1	25.0	18.8	0.0103	0.998	0.0114
2	25.0	18.8	0.0124	0.999	
3	25.0	18.8	0.0115	0.997	
1	25.0	22.0	0.0096	0.996	0.0091
2	25.0	22.0	0.0086	0.998	
1	25.0	23.5	0.0076	0.997	0.0074
2	25.0	23.5	0.0067	0.996	
3	25.0	23.5	0.0078	0.997	
1	20.9	18.8	0.0062	0.998	0.0067
2	20.9	18.8	0.0063	0.999	
3	20.9	18.8	0.0075	0.996	
1	20.9	22.0	0.0049	0.997	0.0054
2	20.9	22.0	0.0058	0.998	
3	20.9	22.0	0.0054	0.998	
1	20.9	23.5	0.0039	0.995	0.0045
2	20.9	23.5	0.0041	0.998	
3	20.9	23.5	0.0055	0.997	

* Data fitted to equation $Ln(CR) = -k\theta$.

If moisture content of calcium chloride is expressed as a concentration and the equation linearized using the natural logarithm the equation becomes

$$Ln(CR) = -k\theta \quad [4]$$

This model, by using the non-dimensional concentration ratio CR, allows comparisons despite different initial and equilibrium concentrations, C_o and C_e. The dependent variable, CR, can be directly expressed as a function of time using the sorption constant, k.

This approach does have a problem because equilibrium concentration values do not exist for the experimental desiccant and air temperatures. At 0% concentration there still exists a vapor pressure difference. To utilize this model, a pseudo equilibrium value, C_e* was estimated using non-linear regression and a rearranged form of equation [4].

$$C = C_e^* + (C_o - C_e^*)\, e^{-k\theta} \quad [5]$$

RESULTS

The dehumidifier operated during 1500 h of data collection with few mechanical problems. The following observations were made with respect to future design. (a) Steel is considered an adequate construction materail for all parts of the dehumidifier except for the desiccant air contactor. (b) The tubular duct may be constructed with fewer but larger holes and still maintain an even flow through the mesh. (c) A separating device to trap desiccant entrained air could be fitted to the air exhaust. For further details see Armstrong (1982).

The system was able to absorb 15 kg of water vapor in 50 h at the greatest absorption rate. This represents an average absorption rate of 0.30 kg/h which is equivalent to the total moisture production rate of three 20 kg pigs on a fully slotted floor in an environment at 25 °C.

Results of the tests (Table 1) gave the regression values of C_e* and k for equation [5]. Linear regression was applied to the log transformed equation [4] to obtain the best fit slope of concentration ratio as a function of time when forced through zero. The values of k and resulting R^2 values are shown in Table 2. Note how the k values derived by the two procedures differ by an average of 1%. Fig. 2 is representative of typical data and regression lines obtained for concentration and concentration ratio as a function of time.

Figs. 3 and 4 show the average sorption constant values obtained at different desiccant temperatures for the two air temperatures. In both cases, k values increased with greater temperature differences between air and desiccant. This is expected because larger temperature differences produce larger vapor pressure

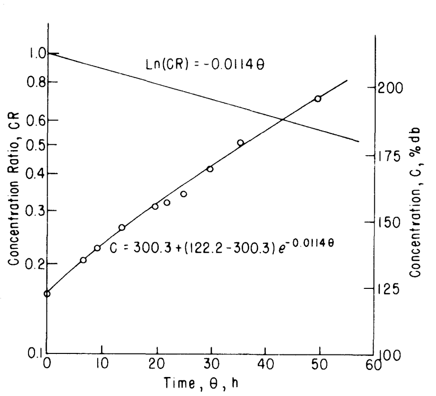

Fig. 2—Regression equations for concentration and concentration ratio as a function of time for 25.0 °C air temperature, 18.8 °C desiccant temperature, and 80% humidity.

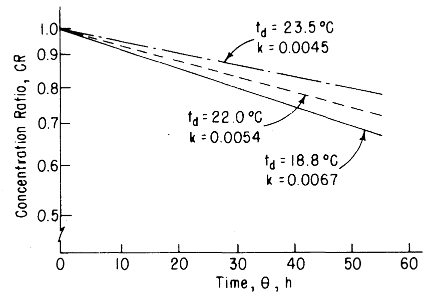

Fig. 3—Regression lines for concentration ratio as a function of time at three different desiccant temperatures at 25 °C air temperature and 80% relative humidity.

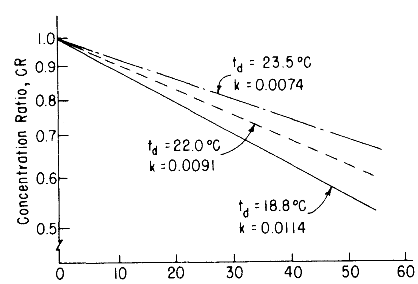

Fig. 4—Regression lines for concentration ratio as a function of time at three different desiccant temperatures at 20.9 °C air temperature and 80% relative humidity.

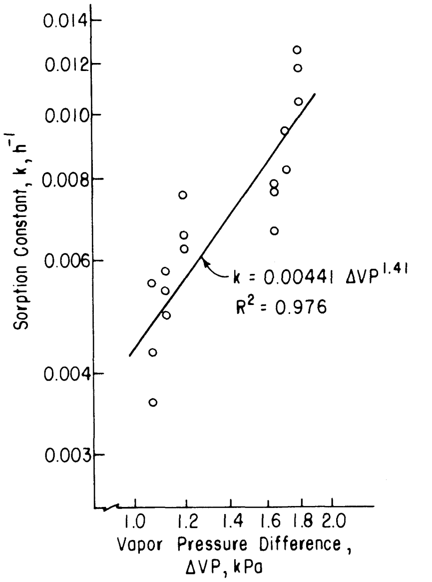

Fig. 5—Regression line and data for sorption constant as a function of initial vapor pressure difference.

differences at the same relative humidity.

To predict the moisture adsorption behavior of the system for different air and desiccant temperatures, k was assumed to be a function of the vapor pressure difference between the air and desiccant. In all tests the desiccant solution was initially saturated. Therefore vapor pressure difference was determined as the vapor pressure of inlet air minus vapor pressure of a saturated solution at the beginning of each test at the design temperatures tested. A non-linear relationship was expected since vapor pressure of a saturated solution increases non-linearly with temperatures. The data was fitted to a logarithmic regression equation (Fig. 5) forced through zero. This model can be expected to be highly reliable over an initial vapor pressure range of 1.08 to 1.80 kPa at an air inlet relative humdidity of 80% and an initial desiccant concentration of 45%. There is no reason to expect any less accuracy at different inlet air humidities or less than one kPa initial vapor pressure.

CONCLUSIONS

Conclusions drawn from this study were:

1. The system can effectively dehumidify air under the conditions tested.

2. The mathematical model, $Ln(CR) = -k\theta$, adequately describes the sorption process as demonstrated by high R^2 values.

3. Air temperature from 21 to 25 °C has a greater effect on the sorption rate than does desiccant temperature over the 19 to 24 °C range.

4. The sorption constant can be adequately described as a function of initial vapor pressure difference for saturated solutions ($R^2 = 0.976$) using a logarithmic model.

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LIST OF SYMBOLS

C	Instantaneous concentration, % db
C_e	Equilibrium concentration, % db
C_e*	Pseudo equilibrium concentration, % db
C_o	Initial concentration, % db
CR	Concentration ratio, dimensionless
k	Sorption constant, h^{-1}
M	Instantaneous moisture content, % db
M_e	Equilibrium moisture content, % db
M_o	Initial moisture content, % db
MR	Moisture ratio, dimensionless
R.H.	Relative humdity, %
td	Desiccant temperature, °C
tdbair	Dry bulb air temperature, °C
twbair	Wet bulb air temperature, °C
θ	Elapsed time, h
V.P.	Initial vapor pressure difference, kPa