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Facilities for Testing Desiccant Materials and Geometries of Dehumidifiers for Solar-Regenerated Desiccant Cooling Systems

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FACILITIES FOR TESTING DESICCANT MATERIALS AND GEOMETRIES OF DEHUMIDIFIERS FOR SOLAR-REGENERATED DESICCANT COOLING SYSTEMS

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ABSTRACT

Four experimental test facilities for characterizing the performance of solid desiccant materials and dehumidifier matrices which have the potential to be used in solar-regenerated desiccant cooling systems are reviewed. The water equilibrium capacity and sorption rates of desiccant materials, depending on their form, can be either measured with a quartz crystal microbalance or a desiccant sorption test facility. Pressure drop, heat- and mass- transfer rates and transient equilibrium dehumidification capacity of a dehumidifier matrices are measured in a desiccant heat and mass transfer test facility. The performance and steady state dehumidification capabilities of prototype dehumidifier components under realistic conditions are measured in a desiccant cyclic test facility. The description of the test apparatus, experimental procedure, measurement errors, and typical results for the four test facilities are presented here.

INTRODUCTION

There has been considerable interest and research in solid desiccant cooling and dehumidification systems as mechanically simple, thermally driven alternatives to electrically driven vapor compression machines for air conditioning of buildings with relatively high latent loads. Such systems have advantages over vapor compression systems of using various energy sources such as solar heat, waste heat, natural gas and off-peak electricity, meeting latent load more effectively, and cost-effective delivery of fresh air. In desiccant cooling systems, humid air is dried using a desiccant dehumidifier and then cooled by evaporative or sensible cooling. The desiccant in the dehumidifier is then regenerated (dried) using hot air—e.g., from solar collectors—to drive the water vapor adsorbed from the process air out of the desiccant. Other cost-effective energy sources such as natural gas, waste heat, or off-peak electricity can be used for desiccant regeneration. Many system configurations have been identified that use desiccant dehumidifiers for latent heat removal and space humidity control (e.g., Kettleborough et al. 1986). The dehumidifier is one of the major components of the desiccant system and should be efficient, compact, cost-effective, and reliable for economic viability of desiccant cooling systems. The performance of a dehumidifier depends on the type of desiccant used, the geometry of the dehumidifier matrix and the operating conditions such as regeneration temperature, air conditions during adsorption, and the regeneration-adsorption cycle time. Experiments are needed to evaluate the potential of new and innovative materials and geometries for desiccants.

DESICCANT COOLING TEST FACILITIES

The Solar Energy Research Institute (SERI), with funding from the U.S. Department of Energy, has developed experimental facilities (Figure 1) to evaluate new and promising desiccant materials and matrices, and to validate mathematical models. The facilities were designed to measure the important characteristics of the desiccant materials, dehumidifier matrices, and components under conditions expected in the operation of solar-fired desiccant cooling systems. The sorption properties of a new desiccant are measured in the quartz crystal microbalance (QCM) and/or the sorption test facility (STF) depending on its form and shape to be tested. The sorption properties of special interest are water vapor equilibrium isotherms, rates of moisture adsorption and desorption, cyclic stability, and diffusivity. An isotherm is "desiccant moisture capacity as a function of relative humidity at a constant temperature" and also contains information about maximum water capacity, and capacity change between any two relative humidities, as well as hysteresis between adsorption and desorption.

After initial evaluation that a desiccant material is promising (based on its sorption properties), it is made into a dehumidifier matrix material. If the desiccant is bonded to or embedded in a support material for structural integrity, its sorption properties are measured in the STF again. When it is assessed that the matrix material (desiccant plus support) is still a promising desiccant, a dehumidifier matrix is fabricated and its pressure drop and heat and mass transfer characteristics are measured in the desiccant heat and mass transfer test facility (HMTF). The characterization includes obtaining the friction-factor x Reynolds number, heat- and mass-transfer Nusselt numbers, and dehumidification capability at various flow conditions. The experimental data can also be used to validate fundamental momentum, heat and mass transfer models for the matrix.

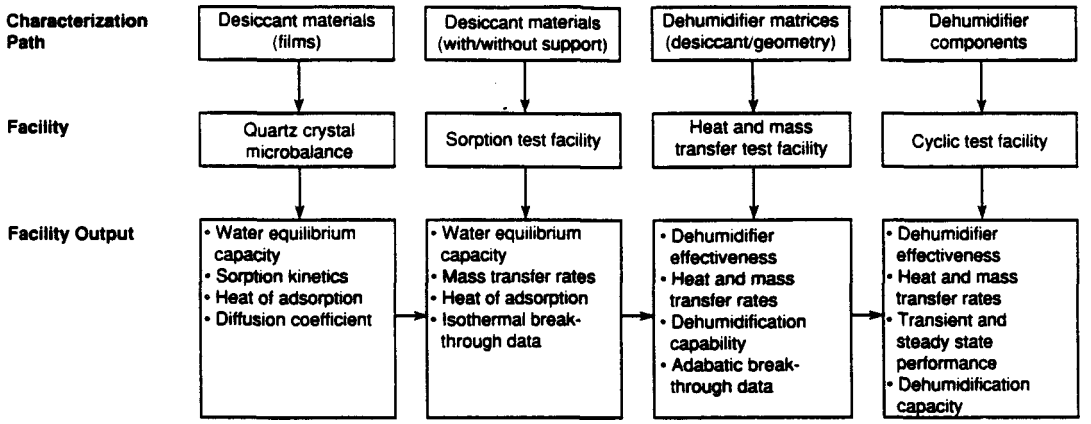

Fig. 1 SERI desiccant cooling test facilities.

When it is determined that the dehumidifier matrix is promising and feasible to build, a prototype rotating dehumidifier component is built and tested in the desiccant cyclic test facility (CTF). This process is to evaluate the cyclic performance of the dehumidifier under real operating conditions. The moisture removal effectiveness of the dehumidifier along with its pressure drop are measured at various regeneration and adsorption stream flow conditions. The experimental data can be used to validate cyclic dehumidifier models.

There is a progression in the mass and the size of the items tested in the above test facilities. The QCM uses samples with masses that are usually less than 1 mg with thicknesses of less than 1 μm. The STF uses desiccant and matrix samples with masses between 0.5 and 10 g and sizes between 0.5 and 10 cm^3. Dehumidifier matrices that contain between 100 and 1000 g of desiccant and have volumes between 2 and 8 liters can be tested in the HMTF. The CTF can test dehumidifiers that contain 2 to 20 kg and have sizes of 20 to 100 liters. The approach of starting with small samples and, after screening and evaluating, progressing to larger samples prevents undue expenses of fabricating costly experimental dehumidifier matrices and prototype dehumidifiers and performing unnecessary experiments. Dehumidifiers are fabricated and tested using only materials and matrices that have shown sufficient potential.

Quartz Crystal Microbalance

The QCM is one of the best commercially available units (Czanderna and Thomas 1986) suitable for measuring water-vapor-sorption performance properties of thin film materials, especially polymeric desiccants. In the QCM, a desiccant material is coated onto a quartz crystal oscillator. Changes in the mass of the coating due to water vapor adsorption or desorption cause changes in the crystal vibrational frequency that can be measured by a frequency counter. The measured frequency can then be correlated to a mass gain or loss. At SERI, Czanderna and Thomas (1986, 1987) have developed a QCM to detect frequency changes that correspond to a mass change of about 10^{-9} g. They have demonstrated detectability of 10 ppm in a sample weighing 0.1 mg.

The QCM apparatus (Figure 2) consists of vacuum system; a residual gas analyzer; a QCM controller; a temperature bath for quartz crystal sensors; instrumentation to measure pressure, temperature, frequency; and a data acquisition system. The vapor pressure can be measured to a precision of 10^{-4} of total pressure and the temperature is maintained to a precision of less than 0.08°C. The apparatus has five crystal holders, so one can measure the sorption capacity and kinetics for several desiccant materials at the same time.

The experimental procedure consists of several steps (Czanderna and Thomas 1987). A quartz crystal is first cleaned ultrasonically. The crystal is weighed on an analytical balance. Then a polymeric desiccant is dissolved in a solvent that is subsequently pipetted onto the crystal surface, and the solvent is allowed to evaporate. After re-weighing to find the mass of the polymer film, the crystal is attached to the oscillator and is assembled in the vacuum system. The sample chamber is pumped to the 10^{-8} torr range and the oscillator mass is zeroed after the mass loss or gain has equilibrated. The system is allowed to equilibrate with the desired temperature. Then, water vapor is introduced into the chamber to increase the water vapor pressure incrementally as desired, which is typically in 1 to 2 torr steps. The pressure and mass measurements are taken at the intervals of 2 seconds during the adsorption. After reaching the desired maximum vapor pressure, the process is reversed by decreasing the water vapor pressure in the desired decrements followed by equilibration intervals, and thus obtaining the desorption data.

The water capacity is obtained by dividing the mass of water gained or lost by the mass of polymer. The relative humidity is the ratio of water vapor pressure to the saturation water vapor pressure at the crystal temperature. Figure 3 shows a typical result of sorption capacity measurement of polystyrene sulfonic acid sodium salts in the QCM apparatus. Of more than 30 commercial and lab synthesized desiccant polymers characterized (Czanderna 1988) with this QCM, 9 of them have shown potential for desiccant cooling applications when compared with a hypothetical desiccant with "ideal" isotherm identified by Collier et al. (1986).

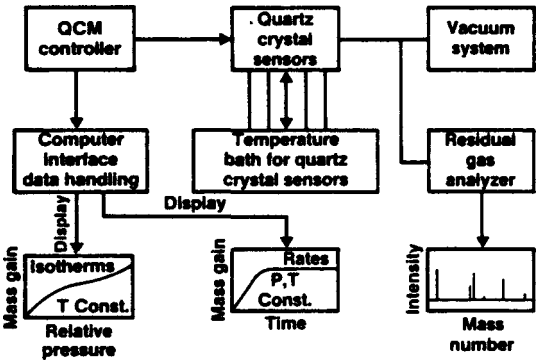

Fig. 2 Block diagram showing the principal components of a quartz crystal microbalance apparatus (Czanderna and Thomas 1987).

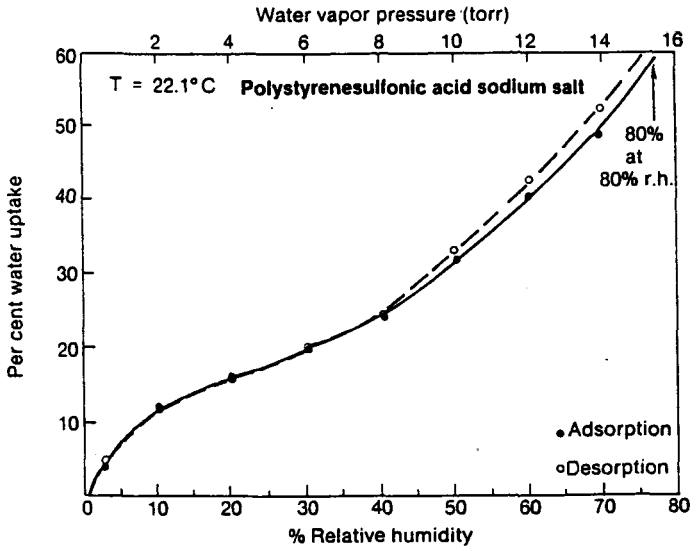

Fig. 3 Typical results of the quartz crystal microbalance apparatus, adsorption/desorption for polystyrene sulfonic acid sodium salt at 22.1°C (Czanderna and Thomas 1988).

Three of the most promising ones are polystyrene sulfonic acid sodium salt, sodium polystyrene sulfonate, and polyacrylic acid ammonium salt.

Sorption Test Facility

The STF is used to measure the water-vapor sorption capacity of desiccant materials, as well as their moisture transfer rates, under isothermal conditions (Zangrando et al. 1986). The sorption capacity,—i.e. the amount of moisture the desiccant can hold at various humidities—is obtained by a gravimetric technique.

The sorption test facility (Figure 4) consists of a dry air source, a humidifier, a sample test section, a constant temperature bath, and instrumentation for measurements and data collection. Bone-dry air from a compressed air cylinder enters a mass flow controller that measures and controls the air mass flow rate. Then, the air flows through a humidifier to obtain the desired level of water vapor concentration. In the humidifier the air becomes saturated by bubbling through deionized water kept at a desired temperature. The dew-point temperature and absolute pressure of the air before entering a test cell are measured by a chilled-mirror hygrometer and a capacitance-type pressure transducer, respectively. The test cell contains a desiccant and is immersed in the constant temperature bath which is measured with a thermocouple. Two types of test cells have been used: packed bed and parallel passage. The test cell is connected to a bypass line and three-way switching valves. The dew-point temperature and absolute pressure of the air leaving the test cell are measured with another hygrometer and pressure transducer, respectively. The air pressure in the test cell is controlled with a set of valves before the air is exhausted to the atmosphere.

We have developed a careful experimental procedure. A precision balance with repeatability of 0.1 mg is used to measure the dry mass of the test cell. Then, the test cell is loaded with desiccant and dried by passing bone-dry air through it at 100° - 120°C and near ambient pressures for at least 24 hrs. After being air cooled, the sample is weighed to determine the dry mass of the desiccant. The test cell is inserted in the housing and installed in the apparatus and then immersed in the constant-temperature bath. The process air, which is bypassing the air at this point, is conditioned to the desired humidity, temperature, pressure and flow rate. Once the process air conditions reach steady-state values, the air is switched to the test cell. The outlet dew-point temperature and pressure is recorded as function of time to provide kinetic data. When the air and the desiccant reach equilibrium with each other, the test cell is removed, capped, and weighed to determine any mass change in the desiccant resulting from moisture adsorption or desorption. The test cell is then re-installed in the apparatus and exposed to the

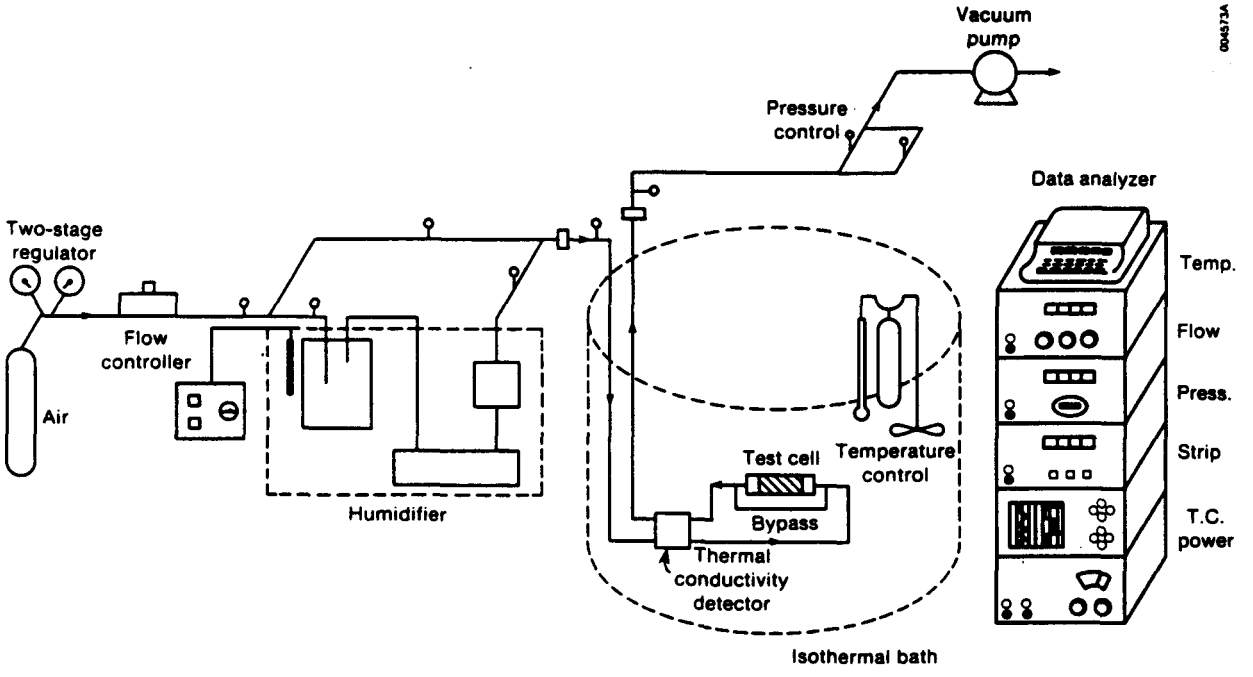

Fig. 4 Schematic of the desiccant sorption test facility.

same air conditions again. After 3-4 hours, the sample is removed for weighing again. This process is repeated until the difference between consecutive masses is not noticeable with the balance.

The equilibrium capacity is calculated by dividing the mass gain (or loss) by the dry mass of the desiccant. The relative humidity is calculated from the measurements of equilibrium pressure, dew-point temperature and bath temperature using a psychrometric relation. Generally the error in the sorption capacity is less than 2% and the error in the relative humidity is less than 5%. Several measurements at the same test cell temperature and various relative humidities enable us to construct the equilibrium isotherm of the desiccant, which can be used to evaluate its potential for desiccant cooling applications. Figure 5 shows the typical results of the STF, i.e., equilibrium water capacity of several desiccants at different relative humidities for 30°. Among more than 10 desiccants tested, microporous silica gels (e.g., grade 40, microbead silica gel grade 3A and Syloid 63) have been found to have the most suitable sorption properties for solar-regenerated solid desiccant cooling applications based on these results and system performance simulations.

Heat and Mass Transfer Test Facility

The heat and mass transfer test facility (HMTF) is used to test different dehumidifier matrices that contain a desiccant material, with or without a substrate, formed into a particular geometry. In the HMTF the pressure drop and heat- and mass- transfer rate data and dehumidification capacity of a promising dehumidifier matrix are obtained under adiabatic conditions. The HMTF (Figure 6) consists of an air heater, a steam injector, a variable speed fan, an orifice plate, a test section, and instrumentation to control and measure airflow rate, air temperatures, pressure drops, and dew-point temperatures (Pesaran 1986). The test section that contains a test matrix, temperature sensors, air samplers for humidity measurements, and pressure taps has a rectangular section with removable walls for inserting test matrices. Air temperatures are measured using copper-constantan thermocouple wires with uncertainty of less than 0.4°C. Air humidities are calculated from the dew-point

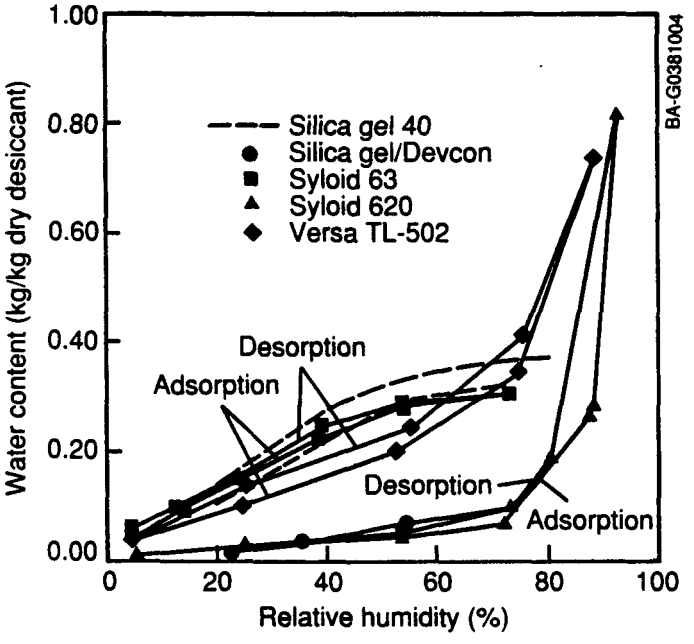

Fig. 5 Typical results of the sorption test facility, adsorption/desorption equilibrium capacity of several desiccants at 30°C.

temperatures measured using chilled-mirror dew-point hygrometers with an uncertainty of less than 3% in humidity ratios. The pressure drop across the orifice plate and a test matrix are measured using capacitance-type pressure transducers with an uncertainty of less than 1%. Air mass flow rates are determined by ASME standard orifice plates with an uncertainty of less than 3%.

In the experimental procedure each step transient test basically consists of three parts: matrix conditioning, process air preparation, and transient response. After the matrix is installed in the test section, it is insulated to simulate adiabatic conditions. The dehumidifier matrix is conditioned to a desired uniform state (temperature and desiccant water content) by passing conditioned air through the matrix. Then the air is bypassed and the matrix is sealed by closing butterfly valves on both sides. The process airstream is brought up to a new state (temperature and/or humidity) while passing through the bypass. Finally, when the process airstream reaches the desired humidity, temperature, and flow rate, it is abruptly introduced to the matrix and the transient response of the matrix is obtained by recording the outlet air temperature and dew-point temperature (humidity) as a function of time. Both adsorption (dehumidification) and desorption (regeneration) tests are performed. The pressure drop across the test matrix as a function of mass flow rate is measured when equilibrium is reached.

Figure 7 shows a typical adiabatic transient response of a dehumidifier test matrix. These typical adiabatic responses are a measure of how fast the heat and moisture are transferred from (or to) the matrix to (or from) airstreams and thus how effective the dehumidifier is in removing moisture from an airstream. The humidity curves can also be integrated to provide the dehumidification capability of the matrix. Using theoretical models (Pesaran 1986, Maclaine-cross and Pesaran 1986, and Van den Bulck 1987), the temperature and humidity response curves can be manipulated to obtain the heat and mass transfer coefficients of the matrix under tested conditions. Two silica-gel/ parallel-plate matrices, and a silica-gel/staggered-parallel-strip matrix have been tested. A lithium-chloride/sine-passage matrix and a silica-gel/sine-passage test matrix have been also tested and the results are being analyzed. Table 1 shows the results of analysis of the transient response and pressure drop characteristics of the first three matrices. Higher heat and moisture transfer rates and lower pressure drops are desired since these relate to higher moisture removal effectiveness and lower fan power, respectively. For these reasons, the microbead-silica-gel/staggered-parallel-strip matrix is expected to provide the highest dehumidifier efficiency of the three for a given size and pressure drop (Pesaran 1987).

Desiccant Cyclic Test Facility

The CTF is used to measure the performance of prototype desiccant dehumidifier components, such as rotary dehumidifier wheels. The facility simulates operating conditions expected in solar-regenerated desiccant cooling systems. The dehumidifier component, which consists of a desiccant in a dehumidifier matrix and necessary support and hardware, rotates between an adsorption airstream and a regeneration airstream. The dehumidifier adsorbs the moisture from the adsorption stream and releases it into the regeneration stream. The facility generates data on the amount of moisture and heat transferred as a function of air temperatures and humidities, airflow rates, and rotational speed of the dehumidifier wheel.

The cyclic test facility (Figure 8) consists of two duct heaters, a boiler with two steam injectors, two variable speed fans, flow nozzles, and the dehumidifier section (Schultz 1986, Bharathan et al. 1987). A full set of automated controls maintains steady state inlet conditions for the

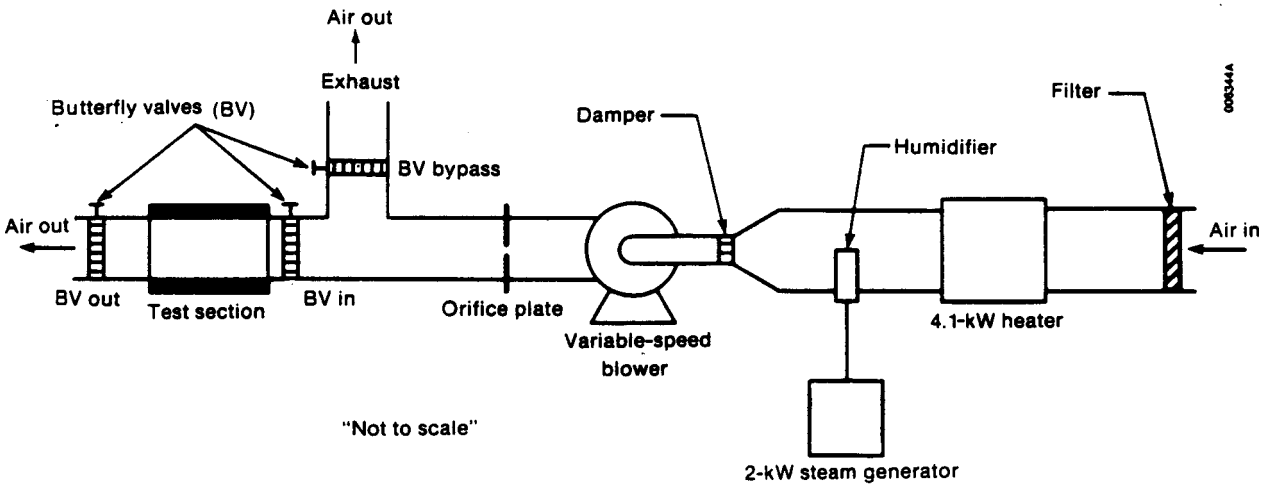

Fig. 6 Schematic of the desiccant heat and mass transfer test facility.

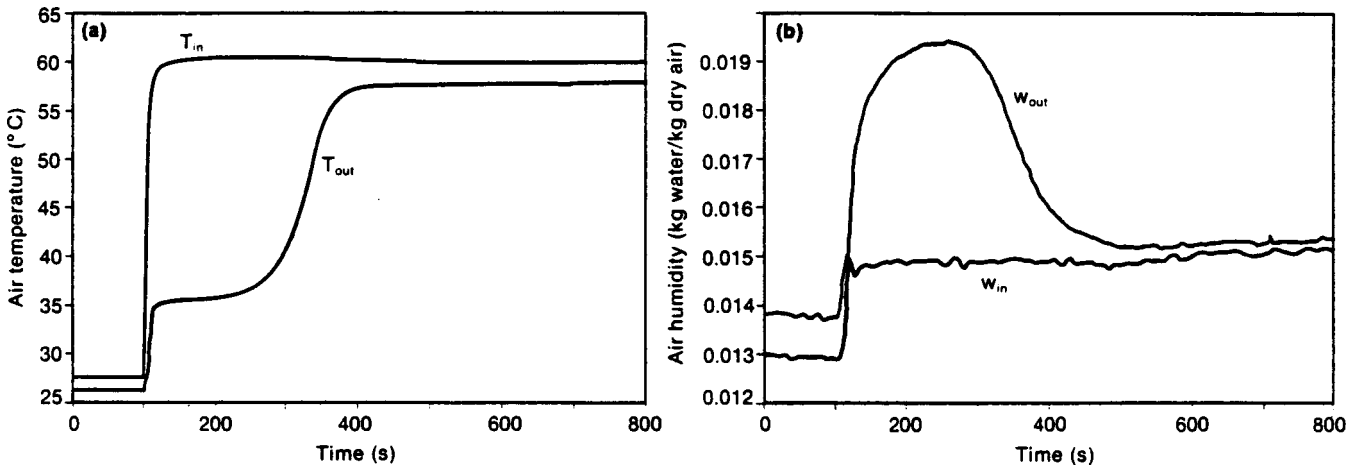

Fig. 7 Typical results of the heat and mass transfer test facility, transient response of the microbead silica-gel/parallel-plate test matrix (Pesaran 1987).

Table 1. Results of Analysis of Transient Response Curves for Three Matrices Tested in the Heat and Mass Transfer Test Facility (Pesaran 1987)

Dehumidifier Matrix	Nu_o	Nu_{mo}	Le	fRe	Nu_o/fRe
Crushed silica gel parallel plate	3.59	3.15	1.14	25.49	0.141
Microbead silica gel parallel plate	3.70	3.70	1.00	22.61	0.164
Microbead silica gel staggered parallel strip	6.68	6.30	1.06	36.87	0.181

Nu_o Mean overall heat transfer Nusselt number
Nu_{mo} Mean overall mass transfer Nusselt number
Le Mean Lewis number (= Nu_o/Nu_{mo})
f Mean friction factor
Re Mean Reynolds number

Nu_o and Nu_{mo} are measures of how fast heat and moisture are transferred from or to a matrix.

fRe is a measure of pressure drop across a matrix.

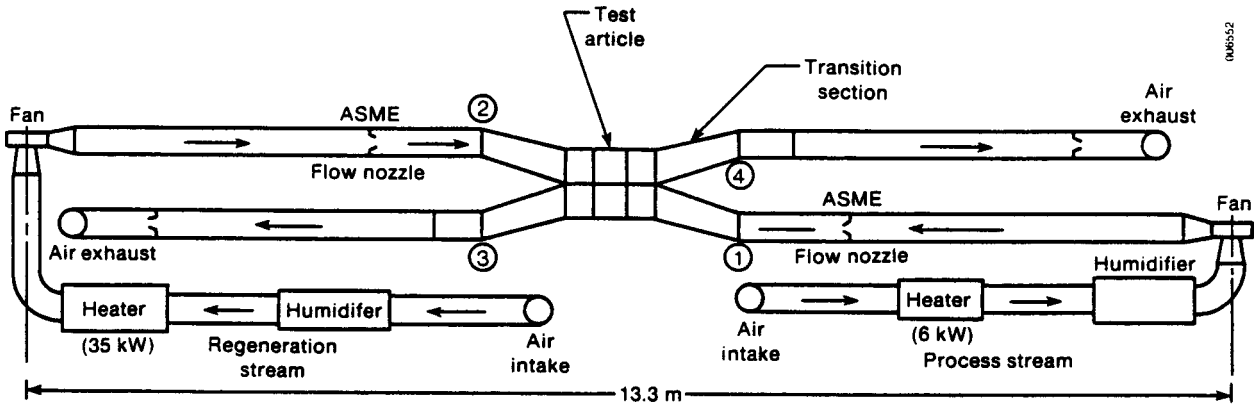

Fig. 8 Schematic of the desiccant cyclic test facility.

temperature, absolute humidity, and airflow rate. Instruments are used to monitor and record the ambient air conditions, dehumidifier inlet and outlet air conditions for both airstreams, and wheel rotational speed. Air temperatures are measured with copper-constantan thermocouple wires with an uncertainty of 0.4°C. The absolute humidities are obtained by measuring the dew-point temperatures using the chilled-mirror hygrometers and psychrometric correlations. The error in humidities is less than 3%. Capacitance-type pressure transducers measure the pressure drops across the dehumidifier and the flow nozzles with an uncertainty of less than 1%. Mass flow rates are measured with an uncertainty of less than 3% using ASME standard flow nozzles. The dehumidifier wheel is rotated by a DC servomotor turning a rubber-rimmed wheel in contact with the circumferences of the dehumidifier. An optical encoder mounted on the drive motor allows measurement of wheel rotational speed with an uncertainty of less than 1%.

After a prototype rotary dehumidifier is installed in the facility and insulated for simulation of adiabatic operation, the transient and steady state performances of the dehumidifier are obtained (Bharathan et al. 1987 and Schultz 1987). The process (adsorption) and regeneration airstreams are conditioned to achieve the desired airflow rates, and inlet air temperatures, and humidities. The dehumidifier is not rotating during this conditioning period. When the outlet air conditions of both airstreams become uniform, the dehumidifier is rotated at the desired speed and the outlet air temperatures and humidities of both process and regeneration airstreams are measured with time. This provides the transient performance. When the inlet and outlet conditions reach steady state, measurements of all the test parameters are recorded to provide the steady state data. Data are obtained for a wide range of rotational speeds. The pressure drop across the dehumidifier for both airstreams are measured as a function of airflow rate.

Two prototype test dehumidifiers were tested in the CTF (Bharathan et al. 1987 and Schultz 1987). Both had parallel plate designs for the geometry, since this geometry offers the highest heat-transfer to pressure-drop ratios among simple geometries (Kays and London 1964). One had microbead and the other had irregular-shaped silica gel particles; particles were coated on the air passages of the dehumidifier.

Figure 9 shows typical steady state test results for the microbead silica gel matrix. The process outlet air humidities are plotted against the outlet air temperatures for a range of rotational speeds. For this particular prototype and operating conditions, the optimum dehumidification occurs at about 40.6 rev/hr. The solid lines are the theoretical process

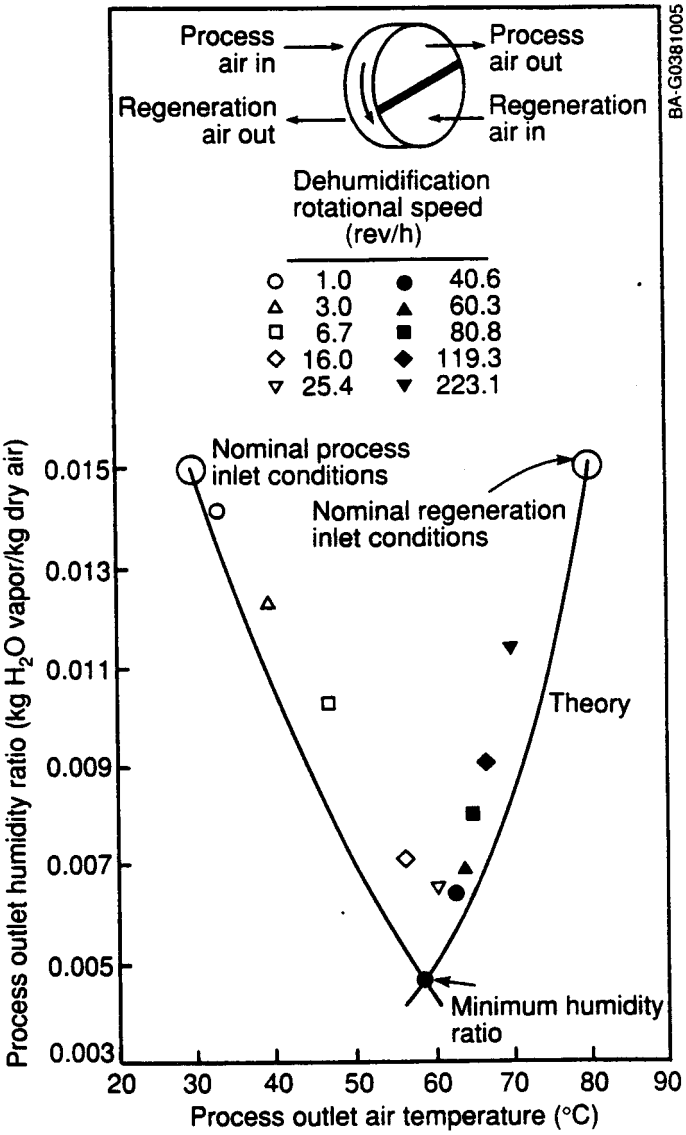

Fig. 9 Typical results from the cyclic test facility, outlet conditions for the process airstream from a microbead silica-gel/parallel-passage dehumidifier as a function of rotational speed (Bharathan et al. 1986).

lines. The overall heat and mass transfer units and pressure drops were estimated using analytical tools. Comparing the data with fully developed laminar flow models, it was found that the nonuniformity in the passage air gap in both matrices resulted in significant reduction (up to 50%) in the overall number of transfer units available for dehumidification (Bharathan et al. 1986). The tests showed that the microbead dehumidifier performed better in moisture removal than the other dehumidifier, although the microbead dehumidifier was 50% smaller in volume and had 25% less desiccant.

CONCLUDING REMARKS

SERI has four test facilities to evaluate the potential and performance of the materials, matrices, dehumidifier components. The sorption performance (moisture capacity and sorption kinetics) of desiccant films can be obtained using a quartz crystal microbalance. More than 30 desiccant polymers have been tested, and 9 promising ones were identified for further evaluation. The sorption performance of desiccant particles and composites, in context of a geometry, can be measured in the sorption test facility. More than 10 desiccants in packed bed or parallel passage geometries were tested, and the promising ones were identified. The pressure drop, and heat and mass transfer characteristics and dehumidification capability of dehumidifier matrices can be obtained in the heat and mass transfer test facility. Five desiccant/geometry combinations have been tested. The dynamic performance of a dehumidifier component can be tested in the desiccant cyclic test facility. The dehumidification capability of a dehumidifier is obtained over a wide range of operating conditions and rotational speeds. Two prototype rotary desiccant dehumidifiers were tested, and an improved design was identified. The experimental data from the facilities also were used to validate finite difference mathematical models (Pesaran 1986, Schultz 1987).

Future work involves the preparation, fabrication, characterization, testing and analyses of the new desiccant materials and matrices produced at SERI and elsewhere.

ACKNOWLEDGMENTS

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