Evaluation of the solar-assisted desiccant air-conditioning systems using periodically reactivated desiccant beds under hot and humid climates

N. Areemit and Y. Sakamoto
Department of Architecture, School of Engineering, The University of Tokyo, Japan

ABTRACT

In hot and humid regions, cooling and dehumidification are important issues of in indoor environment. In this study, the evaluation of solar-assisted desiccant air-conditioning systems utilizing periodically reactivated desiccant such as desiccant beds under hot and humid climates is performed through integrated building and equipment simulations. As a result, the periodically reactivated desiccant air-conditioning systems perform with relatively higher percentage of comfort as well as higher primary energy COP of approximately 6.05 under not extreme high enthalpy conditions. Additionally, with the addition of another desiccant bed, this allows the systems to operate during the daytime as well as nighttime. With this double desiccant beds system, primary energy COP of about 4.97 can be achieved.

1. INTRODUCTION

In hot and humid regions, cooling and dehumidification are important issues of in indoor environment. For decades, conventional air-conditioning systems have played an exceptional role in fulfilling pleasure indoor environment despite of its general drawbacks on sanitary aspects due to condensation, improper humidity control. On the other hand, although desiccant air-conditioning systems possess disadvantages such as relatively large in size of equipments and high initial cost of equipment, desiccant air-conditioning systems still provide considerable benefits on elimination of condensation, independent handle of sensible and latent cooling loads, ability to well tackling high latent cooling load, possibility of utilization of diverse energy sources, mechanical simplicity and sanitizing effects are among the merits to be mentioned.

Despite of such advantages, surprisingly a widely used desiccant wheel is relatively pricey due to the complexity. Furthermore, while desiccant wheel deals with simultaneous load, in residential building, cooling load trends to exist during nighttime when solar radiation is absence. This can be done by using simple desiccant beds regenerated and utilized over different periods of time. In this study, the evaluation of solar-assisted desiccant air-conditioning systems utilizing periodically reactivated desiccant such as desiccant beds under hot and humid climates is performed through integrated building and equipment simulations.

2. SIMULATION METHODS

2.1 Mathematical models

2.1.1 Building's envelops

The mathematical models for hygrothermal calculation were utilized due to the advantage of the incorporation of sorption process taken place in building envelopes over ordinary thermal simulation models. The main mathematical models are classified according to their functions. The governing equations for building envelops in Eqs. (1,2) and for boundary conditions in Eqs. (3,4) deal with thermal and moisture behavior of building's envelope, while the budget equations of a room plays a part in indoor air condition's calculation as shown in Eqs. (5,6).

$$\left(\frac{c\rho k}{c\rho + rv}\right)\frac{\partial X}{\partial t} = \frac{\partial}{\partial x}\left(\lambda'\frac{\partial X}{\partial x}\right) + \frac{\partial}{\partial x}\left(\frac{v}{c\rho + rv}\lambda\frac{\partial T}{\partial x}\right) \quad (1)$$

$$c\rho\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}\left(r\lambda'\frac{\partial T}{\partial x}\right) \quad (2)$$

$$\left[-\lambda\frac{\partial T}{\partial x}\right]_s = \alpha(T_o - T_s) \quad (3)$$

$$\left[-\lambda'\frac{\partial X}{\partial x}\right]_s = \alpha'(X_o - X_s) \quad (4)$$

$$\Gamma\frac{dX_r}{dt} = W_t + \rho_w G(X_o - X_r) + \sum_{i=1}^{N}\alpha'_i S_i(X_{s_i} - X_r) \quad (5)$$

$$c\Gamma\frac{dT_r}{dt} = H_t + c\rho_a G(T_o - T_r) + \sum_{i=1}^{N}\alpha_i S_i(T_{s_i} - T_r) \quad (6)$$

$$k = \rho_w\sigma\frac{\partial h}{\partial X} \qquad v = -\rho_w\sigma\frac{\partial h}{\partial T}$$

where:

T : temperature (°C)
X : absolute humidity (kg/kg DA)
x : thickness (m)
λ : thermal conductivity (kcal/m hK)
λ' : vapour permeability (kg/m h(kg/kg DA)
r : latent heat of evaporation (kcal/kg)
c : specific heat (kcal/kg K)
ρ : density (kg/m^3)
α : surface heat transfer coefficient (kcal/m^{2}hK)
α' : surface moisture transfer coefficient (kg/m^2 h(kg/kg DA)
Γ : dry air weight of room volume (kg)
G : Ventilation rate (m^3/h)
W : moisture generation (kg/h)
H : heat generation (kcal/h)
S_i : surface area of i wall (m^2)
N : number of walls
h : relative humidity (ratio)
σ : slope of the equilibrium moisture content (-)

subscript:

a : air
w : water
s : surface
o : outdoor
r : room
d : desiccant

2.1.2 Solar-assisted desiccant air-conditioning systems

Regarding the desiccant bed applications, the numerical methods were applied. While, sensible heat exchanger and direct evaporative cooler utilize the effectiveness model, solar collector uses the Hottel-Whillier steady state model.

A set of equations containing 5 equations shown in Eqs. (7) – (11) is used to described the complicated simultaneous heat and mass transfers taken place when air stream process through the desiccant matrix [1,2].

$$K_y f_v (X_d - X_a) = f_s \rho_a \frac{\partial X_a}{\partial t} + f_s \rho_a m_i + \frac{\partial X_a}{\partial z} \quad (7)$$

$$\alpha f_v (T_d - T_a) = f_s \rho_a (c_{pa} + X c_{pv}) \frac{\partial T_a}{\partial t} + f_s \rho_a m_i (c_{pa} + Y c_{pv}) \frac{\partial T_a}{\partial z} \quad (8)$$

$$K_y f_v (X_d - X) = (1 - f_s) \rho_d \frac{\partial \psi}{\partial t} - D_{sd} \left(\frac{\partial^2 \psi}{\partial z^2}\right) \quad (9)$$

$$K_y f_v H_{ad} (X_d - X_a) + \alpha f_v (T_a - T_d) = (1 - f_s) \rho_d (c_{pd} - \psi c_{pl}) \frac{\partial T_d}{\partial t} + \alpha' f_v (T_a - T_m) - \lambda \left(\frac{\partial^2 T_d}{\partial z^2}\right) \quad (10)$$

$$\kappa \frac{\partial X_d}{\partial t} + v \frac{\partial T_d}{\partial t} = \rho_d \frac{\partial \psi}{\partial t} \quad (11)$$

where:

Ky : coefficient of mass transfer (kg/m^2 s)
α : coefficient of heat transfer (kcal/m^2 s C)
f_v : ratio of desiccant surface area to volume (m^2/m^3)
f_v : ratio of flow to section areas of rotary wheel (m^2/m^2)
mi : flow rate (m^3/s)
Ds : moisture diffusivity of desiccant (kg/ms (kg/kgDA))
Had : latent heat of evaporation (J/kg)
c_{pa} : specific heat of dry air (J/kg C)
c_{pd} : specific heat of desiccant (J/kg C)
c_{pl} : specific heat of water (J/kg C)
T : time (s)
Z : depth coordinate (m)

O. A. Hougen and W. R. Marshall Jr. have given the coefficients of heat and mass transfer for the adiabatic adsorption of water vapor by silica gel, which detail is referred to [3]. The surface diffusivity is predominant in mass transfer inside desiccant material over ordinal and Knudson diffusivity, which equation can be obtained in [4]. Detail on adsorption heat for RD gel can be obtained from the study by A. A. Pasaran [5].

2.2 Building models for load calculations

A single-family standard two-story detached house oriented east-west was simplified and used as the platform for conducting the simulation calculation. Its plans and elevation are illustrated in Figure 1. In order to study the variation related to the building, the matrix of the building structures, finishing materials, insulations and air-conditioning operation patterns for space cooling load calculation, which can form 6 building patterns, is listed in Table. 1.

Table 1: List of calculation cases for the evaluation of solar-assisted periodically reactivated desiccant air-conditioning systems for residential buildings

Case	Structure	Hygroscopic finishing	Insulation	Air-conditioning operation
B-1	Wood	No	No	Full time
B-2	Wood	No	Yes	Full time
B-3	Concrete	No	No	Schedule
B-4	Wood	No	No	Schedule
B-5	Wood	No	Yes	Schedule
B-6	Wood	Yes	Yes	Schedule

The infiltration was set at constant rate of 0.5 times per hour as required by the building regulation in Japan. In addition, unlike ordinary air-conditioning systems, independent control of indoor temperature and humidity were applied in this study. Two modes of air-conditioner were set up; continuous operation of air-conditioner 24 hours a day and the part time operation of air based on the survey study by NHK, Japan. During the operation period, set indoor air temperature and relative humidity are set up at 27 °C and 50% RH.

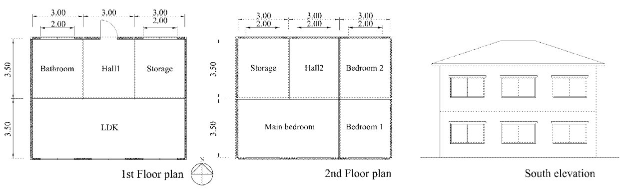

Figure 1. Plan and elevation of the detached house under study used for space cooling load calculation

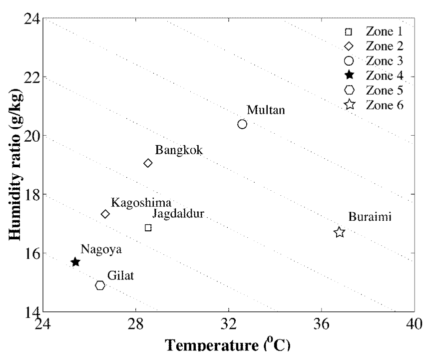

Figure 2. Variations of average climatic data of 6 climate zones under hot and humid climates

2.3 Weather data descriptions

To study the effect of climatic parameters on the system performance, the standard weather data measured from 2801 stations all over Asia-pacific regions were systematically classified and categorized by means of cluster analysis into 6 climatic zones. The mean temperature and humidity of picked up cities representing data of each climatic zone are shown in Figure 2.

2.4 Desiccant system parameters

Parameters used for the calculation of the desiccant air-conditioning systems can be relatively essential in calculation. The system parameters, such as effectiveness of direct evaporative cooler, ratio of pressure drop to flow rate, constant power draw and etc., are fixed at constant rate representing relatively high performance desiccant systems. It can be referred to the study by J. Jurinak [6] for more detail.

2.5 System cycles

The common cycle of periodically reactivated desiccant air-conditioning systems under investigation, Recirculation cycle, is considered. The diagram of this cycle is shown in Figure 3.

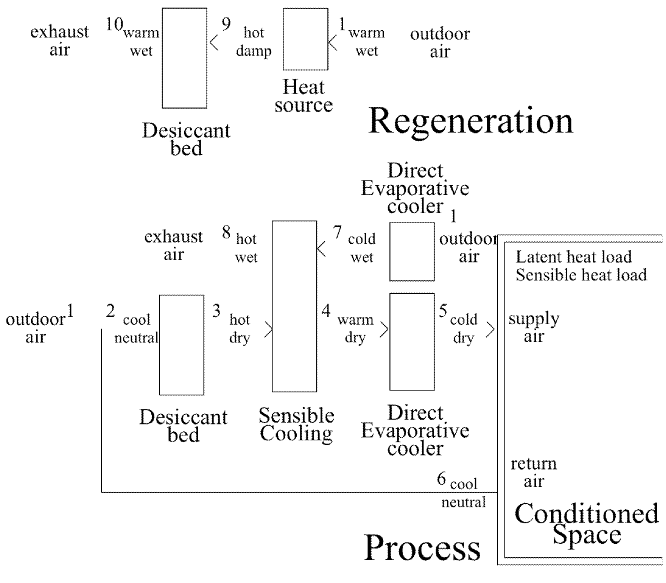

Figure 3. Schematic diagram of cycles for periodically reactivated desiccant cooling system

Instead of having regeneration and dehumidification process simultaneously taking place, it is separated into 2 processes by period of time whether it is a single bed using daytime and nighttime or double beds using one day each for regeneration and dehumidification processes. As single bed systems can only handle the nighttime load, the calculation of the single bed systems is performed under only part time operation, which emphasizes on the air-conditioning usage for bedrooms during nighttime.

2.6 Evaluation index

Desiccant air-conditioning systems apply both thermal energy for regeneration process and electrical energy for driving motors in ventilation fans and etc, which can be converted back in to energy contained in raw fuels form defined as "Primary energy". Here, the calculation of primary energy coefficient of performance (COP_p) is required, while thermal performance of the system is represented by COP_{pt}which can be referred to following equations. Both can be described by Eqs. (11-12).

$$COP_p = \frac{C_t}{\frac{Q_a}{n_{c,f}} + \frac{E_p}{n_{c,e}}} \quad \textbf{(11)}$$

$$COP_{pt} = \frac{C_t}{\frac{Q_a}{n_{c,f}} + \frac{E_p}{n_{c,e}} + Q_s} \quad \textbf{(12)}$$

where:

Ct : total cooling load obtained from difference in enthalpy between supply air and indoor condition (J)
Qa : thermal energy input (J)
Ep : electrical energy input (J)
$n_{c,f}$: conversion efficiency from fuel to thermal energy (-)
$n_{c,e}$: conversion efficiency from electricity to thermal energy (-)

3. RESULTS AND DISCUSSIONS

3.1 Single and double beds

In Figure 4, the periodically reactivated single bed desiccant air-conditioning systems produce relatively high COP_p averaged under every climatic zones at 3.60 comparing to 1.0 of conventional air-conditioning systems. Furthermore, its achievement in terms of percentage of comfort is considered to be extremely high. The results

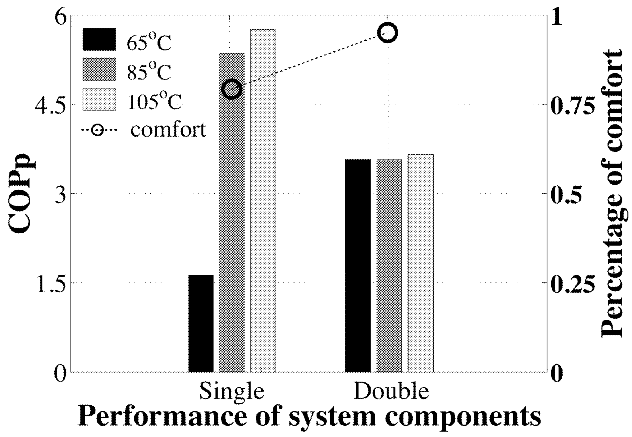

Figure 4. Distributions of seasonal COP_p of solar-assisted comparing with gas-fired periodically reactivation desiccant air-conditioning systems

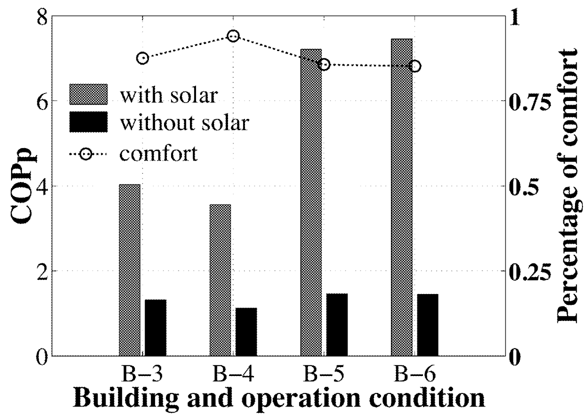

Figure 5. Distributions of seasonal COP_p of solar-assisted comparing with gas-fired periodically reactivation single bed desiccant air-conditioning systems

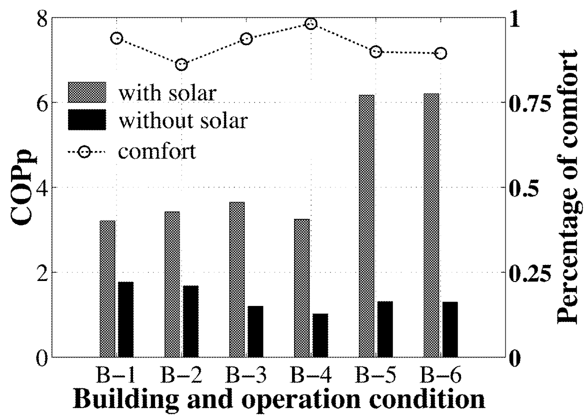

Figure 6. Distributions of seasonal COP_p of solar-assisted comparing with gas-fired periodically reactivation double beds desiccant air-conditioning systems

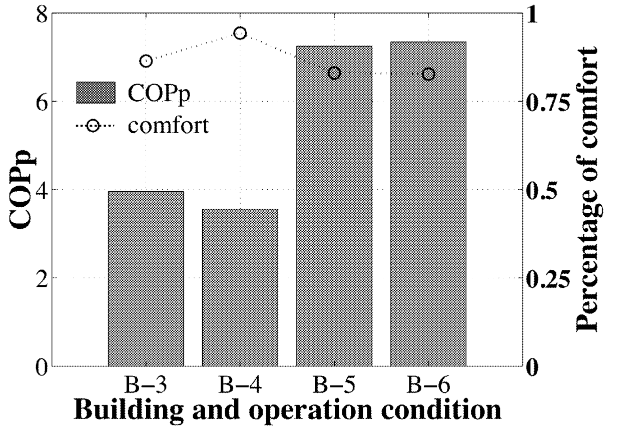

Figure 7. Distributions of seasonal COP_p of solar-assisted periodically reactivated desiccant single bed air-conditioning systems under different building and operation conditions

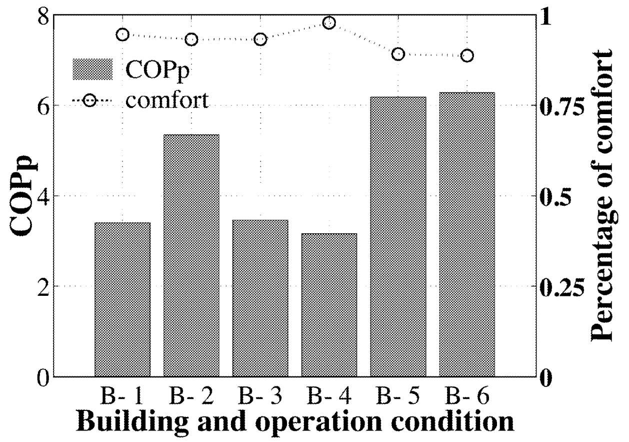

Figure 8. Distributions of seasonal COP_p of solar-assisted periodically reactivated desiccant double beds air-conditioning systems under different building and operation conditions

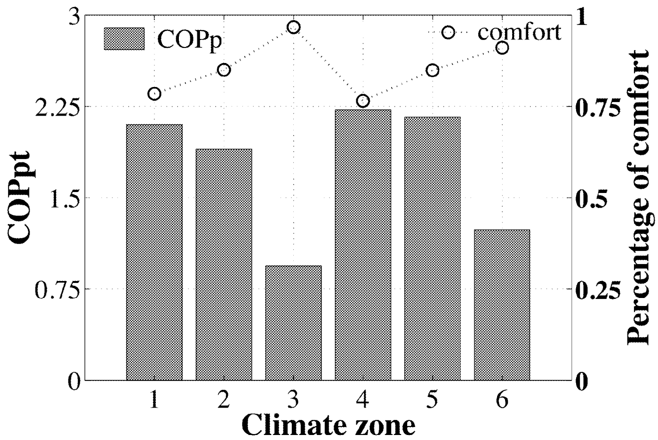

Figure 9. Distributions of seasonal COP_p of solar-assisted periodically reactivated desiccant air-conditioning systems under different climates

of the systems with double desiccant beds are still consistent with that of the single desiccant bed systems. The average COP_p at 3.5 can be achieved. In addition, regarding to regeneration temperature of additional heater when solar is absence and desiccant is not dry enough, low regeneration temperatures in single bed systems seems not sufficient to dry desiccant for nighttime use.

3.2 Solar systems

As illustrated in Figures 5 and 6, the difference in COP_p between solar-assisted and gas-fired periodically reactivated desiccant air-conditioning systems is defined. As can be expected, the solar-assisted systems produce significantly higher COP_p than gas-fired systems in all cases. In addition, the gap between solar and gas-fired systems in the periodically reactivated systems is considered to be clearly higher than that of normal systems with desiccant wheel due to the fact that it mainly utilizes solar energy. In particular of cases with well-insulated building in B-5 and B-6, the effects due to the utilization of solar energy comparatively become more obvious due to relatively low cooling load.

3.3 Building parameter

As shown in Figure 7, the distribution of COP_p under different buildings and operation conditions is compared. The COP_p resulted under B-5 and B-6, which are conditions of well-insulated building, are considered to be relatively high. This can be considered that the same free energy input is used to handle lower cooling load due to the improvement of insulation, which improve the efficiency of the systems. As shown in Figure 8, the results of the double beds systems are consistent with that of single bed systems with B-2, B-5 and B-6 having relatively high COP_p. In addition, as can be seen, the effect of building's structure, finishing material is considered to be negligible.

3.4 Climatic parameters

In order to eliminate the effect of varied solar radiation level in different climates, COP_{pt} , which counts solar energy as a input thermal energy, is utilized. As can be seen in Figure 9, illustrating the results by single bed systems, the COP_{pt} of the systems is relatively low under climatic Zone 3 and 6, which outdoor air enthalpy is comparatively high. This could be explained that as outdoor air enthalpy is high, the humidity ratio of outlet air from desiccant beds cannot efficiently dehumidified and results in less cooling capacity the systems can produce. In addition, during the daytime, the regeneration cannot be well processed the high humidity ratio of outdoor air comparatively.

As summarized in Figure 10. As a result, the periodically reactivated desiccant air-conditioning systems performs with relatively higher percentage of comfort as well as higher primary energy COP of approximately 6.05 comparing to primary energy COP of conventional systems at 1-2. However the systems are limited to nighttime operation and mild outdoor enthalpy conditions in order to achieve high primary energy COP. With the addition of another desiccant bed, this allows the systems to operate during the daytime as well as nighttime. With this double desiccant beds system, primary energy COP of about 4.97 can be achieved.

4. CONCLUSIONS

The consequences of the seasonal performance of various solar-assisted periodically reactivated desiccant air-conditioning systems for residential buildings in hot and humid regions were considered. The utilization of solar energy led us to infer that with proper operation and selection of the system, not only the advantages over the elimination of moisture-related health issues, but the solar-assisted desiccant air-conditioning systems can also deliver the energy efficiency comparable with conventional air-conditioning systems.

Therefore, with the advantages of the improvement over high-humidity and water drain issues in residential buildings under hot and humid climates, the solar-assisted desiccant air-conditioning systems using periodically reactivated desiccant beds are proved to be competitive in terms of energy efficiency with proper selections in building configurations and equipments. Thus, it can be considered to be an alternative to current conventional air-conditioning system in residential buildings.

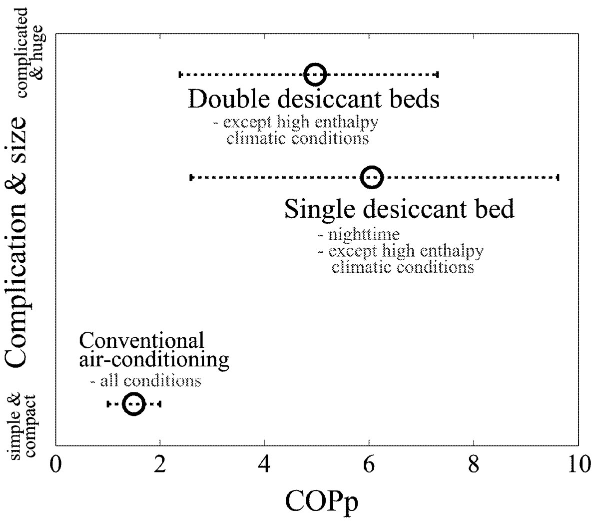

Figure 10. Summarized average primary energy coefficient of performance and system complication of various periodically reactivated desiccant air-conditioning systems

REFERENCES

1. Dai, Y. J. et al., (2001), Parameter analysis to improve rotary desiccant dehumidification using a mathematical model., International Journal of Thermal Science 40, pp. 400–408.
2. Ryuichro, Y. et al. (2006) Numerical simulation of moisture adsorption-desorption for desiccant dehumidifier.(in japanese), in: The Society of Heating, Air-Conditioning and Sanitary Engineering of Japan, Nagano, Japan, 2006, pp. 351– 354.
3. Hougen, O. A. et al. (1947), Adsorption from a fluid stream flowing through a stationary granular bed., Chemical engineering progress 43, pp. 197–208.
4. Pasaran, A. A. et al. (1987), Moisture transport in silica gel packed beds, i. theoretical study, Int. Journal of Heat and Mass Transfer 30, 6, pp. 1037–1049.
5. Pasaran, A. A. et al. (1987), Moisture transport in silica gel packed beds, ii. experimental study, Int. Journal of Heat and Mass Transfer 30, 6, pp. 1051–1060.
6. Jurnaik, J. (1982). Open cycle desiccant cooling component models as systems simulation, Ph.D. thesis, Solar energy laboratory, Monash University of Wisconsin, Madison, Wisc, USA