SERI/TP-252-2388 UC Category: 59a Preprint DE86014501

Moisture Transport in Silica Gel Packed Beds

I. Theoretical Study

Ahmad A. Pesaran (SERI) Anthony F. Mills (University of California)

August 1986

To Appear in International Journal of Heat and Mass Transfer

Prepared under Task No. 3009.10 FTP No. 01-467

Solar Energy Research Institute

A Division of Midwest Research Institute

1617 Cole Boulevard Golden, Colorado 80401-3393

Prepared for the U.S. Department of Energy Contract No. DE-AC02-83CH10093

NOTICE

۱į

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

SER

MOISTURE TRANSPORT IN SILICA GEL PACKED BEDS

I. Theoretical Study

Ahmad A. Pesaran* Solar Energy Research Institute Golden, CO 80401, USA Anthony F. Mills School of Engineering and Applied Science University of California Los Angeles, CA 90024, USA

ABSTRACT

Diffusion mechanisms of moisture within silica gel particles are investigated. It is found that for microporous silica gel surface diffusion is the dominant mechanism of moisture transport, while for macroporous silica gel both Knudsen and surface diffusion are important. A model is proposed for simultaneous heat and mass transfer in a thin packed bed of desiccant particles, which accounts for diffusion of moisture into the particles by both Knudsen and surface diffusion. Using finite difference methods to solve the resulting partial differential equations, predictions are made for the response of thin beds of silica gel particles to a step change in air inlet conditions, and compared to a pseudo gas-side controlled model commonly used for the design of desiccant dehumidifers for solar desiccant cooling applications.

^{*}At the School of Engineering and Applied Science, UCLA during the course of this work.

S221 🔅

.

.

1

.

NOMENCLATURE

a	average pore radius
Bim	mass transfer Biot number, K _G R/o _p D
A	cross section area of bed
С	specific heat
c ₁	specific heat of liquid water
^c p,e	constant pressure specific heat of humid air
c _{pl}	constant pressure specific heat of water vapor
DAR	desiccant to air ratio, $\rho_{b}AL/m_{GT}$ (dimensionless)
D	total diffusivity, definied by Eq. 11
D*	Dr/R ² (dimensionless)
DK	Knudsen diffusion coefficient
D _S	surface diffusion coefficient
Fom	mass transfer Fourier number, Dt/R ²
Ga	air mass flow rate per unit area
g	equilibrium isotherm, pm, = g(W,T)
g'(W)	derivative of equilibrium isotherm, $g'(W) = \rho (\partial m_1 / \partial W)_T$
h	enthalpy
h ₁	enthalpy of water vapor
h _c	convective heat transfer coefficient
^H ads	heat of adsorption
ID	Intermediate density (macroporous)
k	thermal conductivity
К _G	gas-side mass transfer coefficient
^K G,eff	effective mass transfer coefficient
L	length of bed

.

SE?| 🕷),

-

-

•

(

NOMENCLATURE (Continued)

^m 1	water vapor mass fraction (kg water/kg humid air)
m _G	mass flow rate of gas mixture
n	mass flux
N _{tu}	number of transfer units, $K_{G}pL/m_{G}$ or $K_{G,eff} pL/m_{G}$ (dimensionless)
P	pressure
PGC	pseudo-gas-side controlled
p	perimeter of bed
r	radial coordinate in a particle
R	particle radius
R	H ₂ O gas constant
Re	Reynolds number, 2RV/v (dimensionless)
RD	Regular density (microporous)
RH	relative humidity, P ₁ /P _{sat} (dimensionless)
Sg	specific pore surface area
SSR	solid-side resistance
t	time (s)
t*	dimensionless time, t/t (dimensionless)
T	temperature (^O C)
V	superficial velocity of air G_a/ρ
W	desiccant water content (kg water/kg dry desiccant)
Z	axial distance
z*	z/L (dimensionless)

SERI

.

.

NOMENCLATURE (Continued)

Greek

β	ρ _p D/K _C R (dimensionless)	
ε	porosity (dimensionless)	
ν	kinematic viscosity	
ρ	density of humid air	
ρ _p	particle density	
τ	duration of experimental run	
τg	tortuosity factor for intraparticle gas diffusion (dimensionless)	
τs	tortuosity factor for intraparticle surface diffusion (dimensionless)	

Subscripts

1	water vapor
2	dry air
avg	average value
Ъ	bed; bulk
e	surrounding humid air
eff	effective value
К	Knudsen diffusion
in	inlet value
0	initial value
out	outlet value

p particle

SER

NOMENCLATURE (Concluded)

- S surface diffusion
- s s-surface, in gas phase adjacent to gel particles, or dry solid phase of the bed

. .

- sat saturation
- u u-surface, in solid phase adjacent to gel particles

1.0 INTRODUCTION

TP-2388

Silica gel desiccant is widely used in industrial drying processes: generally the beds are relatively thick and can be designed using quasi-steady breakthrough methods. In recent years silica gel has been considered for solar evaporative-desiccant air conditioning systems, for which pressure drop constraints require use of thin beds (less than 15 cm thick). The operation of thin beds is inherently transient and current design procedures are based on models of the transient heat and mass transfer occurring in the bed. Such models represent the overall heat and mass transfer from the air stream to the silica gel by psuedo gas-side transfer coefficients following the early example of Bullock and Threlkeld [1].

Clark et al. [2] tested a prototype scale bed designed for solar air conditioning applications and found rather poor agreement with predictions based on the psuedo gas-side transfer coefficients model, particularly after a step change in inlet air condition. They concluded that the discrepancy was due to shortcomings of the model, since the solid-side mass transfer resistance exceeded the gas-side resistance under these conditions. The experimental data reported by Clark et al. was somewhat limited and imprecise since the bed was a large prototype design: hence Pesaran [3] performed extensive bench scale experiments on thin beds of regular density silica gel with step changes in inlet air humidity. The data obtained reliably confirmed that the solid-side resistance was indeed generally larger than the gas-side resistance, and the need for a suitable model of intro-particle moisture transport was thus made clear. In this paper we present a model which accounts for both Knudsen diffusion and surface diffusion of moisture within

SERI 🌞

the particle, and combine it with a model for the bed performance as a whole incorporating gas phase mass and heat transfer resistances. The solid-side heat transfer resistance is ignored since the characteristically small Biot number allows the assumption of negligible intra-particle temperature gradients. In part II of this series, an associated experimental program is described, and comparisons made between model predictions and experimental data.

SER

2.0 PREVIOUS WORK

The most pertinent study of moisture transport in silica gel particles is that of Kruckels [4], who performed both an experimental and theoretical study of water vapor adsorption by single isothermal silica gel particles: the experiments were performed with pure vapor to eliminate any gas-side resistance. The only resistance to mass transfer in the model was assumed to be surface diffusion in the pores. By comparing theoretical and experimental adsorption rates he concluded that the effective diffusivity inside the particles was a function of temperature, concentration and concentration gradient.

It was, however, relevant to also review the literature on other adsorbateadsorbent systems in order to identify promising approaches to modeling moisture transport in silica gel. The work of Rosen [5] is often quoted: he assumed isothermal spherical particles with a homogeneous and isotropic pore system. A linear equilibrium relation was applied at the surface of the particle. The adsorbate was assumed to move through the pores by surface diffusion, or a mechanism similar to solid-phase diffusion, with a constant diffusion coefficient. Neretnieks [6] modeled isothermal countercurrent adsorption by a fixed packed bed. Transport in the spherical particles was assumed to be by pore diffusion, solid diffusion, or a combination of both, with constant diffusion coefficients. The effect of a gas-side resistance was included. The model equations were solved numerically by use of the method of orthogonal collocation, and breakthrough curves were obtained. Schneider and Smith [7] investigated the significance of surface diffusion using the chromatographic method. The differential equations describing the

S=?| 🛞

concentration of an adsorbate flowing through a column containing spherical adsorbent particles were solved by the method of moments of the chromatographic curve. Both Knudsen and surface diffusion were considered as solid-side diffusion mechanisms, possible with constant diffusion coefficients. Isothermal particles were assumed with a linear adsorption isotherm applied locally within the particles. Experimental data for adsorption of ethane, propane and n-butane on silica gel were used to determine surface diffusion coefficients.

Carter [8] modeled transient heat and mass transfer in an adiabatic fixed bed for situations where the heat of adsorption is significant. For mass transfer both a gas-side resistance and a solid-side resistance were included, while for heat transfer only a gas-side resistance was included. A constant solidside diffusion coefficient was assumed and equilibrium was applied locally within the particle. Numerical solutions were obtained for adsorption of water vapor on activated alumina, and compared with experimental data from a full scale plant. Reasonable agreement was obtained and discrepancies were attributed to inaccurate equilibrium isotherms and surface diffusion coefficient inputs. Meyer and Webber [9]studies the adsorption of methane from helium carrier gas by beds of activated carbon particles, both experimentally and theoretically. Their model includes both gas-side and solid-side (Knudsen diffusion) resistances for mass transfer, and gas-side and solid-side (conduction) resistances for heat transfer. A general equilibrium adsorption relation was applied within a spherical particle. A constant Knudsen diffusion coefficient was used. Discrepancies between predictions and experiment were attributed to inaccuracies in experimentally determined diffusion coefficients for methane in activated carbon.

3. MODELING OF INTRA-PARTICLE MOISTURE TRANSPORT

Water vapor can diffuse through a porous medium by ordinary, Knudsen and surface diffusion. For silica gel at atmospheric pressure, the contribution by ordinary (Fick's Law) diffusion is shown in Appendix A to be negligible, and only the latter two mechanisms of diffusion need to be considered. An equation describing conservation of moisture in a single spherical particle is developed here for the cases where either or both of the two diffusion mechanisms are important. The diffusion rates for each mechanism are compared for both Regular Density (RD) and Intermediate Density (ID) silica gel particles. RD gel has a microporous structure with average pore radius of 11 Å while ID gel is a macroporous material and has an average pore radius of 68 Å. (Note that the H-O bond length in a water vapor molecule is 0.958 Å with a bond angle of 104.45 degrees [10] and the distance between the two H atoms is 1.514 Å).

Consider a spherical particle of silica gel with initial gel water content $W_0 = f(r)$, and a uniform temperature T_0 , which is suddenly exposed to humid air with water vapor mass fraction $m_{1,e} = f(t)$. Assuming low mass transfer rates, water vapor is transferred from the bulk air stream to the particle surface at a rate

$$n_{1,s} = K_{G}(m_{1,s} - m_{1,e})$$
(1)

Water molecules are assumed to move through pores by both Knudsen and surface diffusion, while adsorption takes place on the pore walls. The adsorption-

SE71 🌦

desportion process is assumed to be rapid with respect to diffusion, and thus the local vapor concentration ρm_1 and the local gel water content W are in equilibrium. The differential equation governing H₂O conservation is

$$\varepsilon_{p} \frac{\partial(\rho m_{1})}{\partial t} + \rho_{p} \frac{\partial W}{\partial t} = -\frac{1}{r^{2}} \frac{\partial}{\partial r} (r^{2} n_{1})$$
(2)

where n_1 is the mass flux of H_2O through the porous particle and consists of Knudsen diffusion, surface diffusion, and convective contributions.

The rate of Knudsen diffusion through the particle is

$$n_{1,K} = -\rho D_{K,eff} \frac{\partial m_1}{\partial r}$$

and the rate of surface diffusion is

$$n_{1,S} = - \rho_p D_{S,eff} \frac{\partial W}{\partial r}$$

The effective Knudsen diffusivity, $D_{K,eff}$, and the effective surface diffusivity, $D_{S,eff}$, are discussed in Appendix A. Since Knudsen and surface diffusion are parallel processes, they are additive if the interactions between them are ignored. Adding the contributions to the mass flux of H₂O,

$$n_1 = -\rho_p D_s, eff \frac{\partial W}{\partial r} - \rho D_K, eff \frac{\partial m_1}{\partial r} + m_1 n_1$$

where the third term on the right hand side is the convection of water vapor through the pores assuming that the air is stationary. If $m_1 << 1$, as is the case in the present study ($m_1 < 0.03$), convection can be ignored, and

SERI 🐞

TP-2388

$$n_1 = -\rho_p D_{S,eff} \frac{\partial W}{\partial r} - \rho D_{K,eff} \frac{\partial m_1}{\partial r}$$
(3)

Substituting Eq. (3) in Eq. (2) yields the differential equation,

$$\varepsilon_{p} \frac{\partial (\rho m_{1})}{\partial t} + \rho_{p} \frac{\partial W}{\partial t} = \frac{1}{r^{2}} \frac{\partial}{\partial r} [r^{2}DS, eff \rho_{p} \frac{\partial W}{\partial r}]$$

+
$$\frac{1}{r^2} \frac{\partial}{\partial r} [r^2 D_{K,eff} \rho \frac{\partial m_1}{\partial r}]$$
 (4)

which requires two initial conditions and two boundary conditions.

The initial conditions are

$$W(r,t=0) = W_{o}(r); \rho m_{1}(r,t=0) = \rho m_{1o}(r)$$
 (5a,b)

while the boundary conditions are

zero flux at the particle center,
$$n_1\Big|_{r=0} = 0$$
 (6)

species continuity at surface,
$$n_1|_{r=R} = K_G(m_{1,s}-m_{1,e})$$
 (7)

Also local equilibrium is assumed between vapor and absorbed phase, thus ρm_1 and W within the particle are related through the equilibrium condition,

$$pm_1(r,t) = g[W(r,t),T]$$
 (8)

SERI 🏽

Finally, continuity of gas phase concentrations requires

$$m_1 (r=R,t) = m_{1,s}(t)$$
 (9)

By setting either $D_{S,eff}$ or $D_{K,eff}$ equal to zero the limit cases of dominant Knudsen diffusion or dominant surface diffusion can be obtained.

<u>Generalized Diffusion Equation</u>: The above equations can be simplified by assuming an isothermal particle, which is reasonable for this study since the Biot number of the silica gel particles is generally less than 0.15 [11]. The number of unknowns can be reduced by eliminating ρm_1 using the equilibrium relations, Eq. (8) and the chain rule of differentiation to obtain

$$\frac{\partial}{\partial t} (\rho m_1) = \left(\frac{\partial (\rho m_1)}{\partial W}\right)_T \frac{\partial W}{\partial t} = g' (W) \frac{\partial W}{\partial t}$$

$$\frac{\partial}{\partial r} (\rho m_1) = \left(\frac{\partial (\rho m_1)}{\partial W}\right)_T \frac{\partial W}{\partial r} = g' (W) \frac{\partial W}{\partial r}.$$

Since $m_1 << 1$, and the particle is taken to be isothermal, ρ can be assumed to be constant inside the particle; hence

$$\frac{\partial(\rho m_1)}{\partial r} \simeq \rho \frac{\partial m_1}{\partial r}$$

Substituting the above equations into Eq. (4) and rearranging gives

$$\frac{\partial W}{\partial t} = \frac{1}{\left(\frac{\varepsilon_{p}g'(W)}{\rho_{p}} + 1\right)} \frac{1}{r^{2}} \frac{\partial}{\partial r} \left\{r^{2}\left[D_{S,eff} + D_{K,eff} \frac{g'(W)}{\rho_{p}}\right] \frac{\partial W}{\partial r}\right\}$$
(10)

· · · · · · · · · ·

SERI

g' (W) varies from 0 to 0.4 kg/m³ for both RD and ID gel [11], ε_p is less than unity and ρ_p is 1129 and 620 kg/m³ for RD and ID gel, respectively. Thus $\varepsilon_p g'$ (W)/ ρ_p is at most of order 5 × 10⁻⁴; it is negligible compared to unity and will be ignored. Physically this corresponds to neglecting the gas phase storage term $\varepsilon_p \Im(\rho m_1)/\Im$ t in Eq. (4). We now define a total diffusivity D,

$$D = D_{S,eff} + D_{K,eff} \frac{g'(W)}{\rho_p}$$
(11)

where D is a function of both gel water content W and particle temperature. Equations (5) through (10) then becomes

$$\frac{\partial W}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left[r^2 D \frac{\partial W}{\partial r} \right]$$
(12)

I.C.
$$W(r,t=0) = W_0(r)$$
 (13)

B.C. 1
$$\frac{\partial W}{\partial r}\Big|_{r=0} = 0$$
 (14)

B.C. 2
$$-\rho_p D \frac{\partial W}{\partial r}\Big|_{r=R} = K_G(m_{1,s}-m_{1,e})$$
(15)

Coupling (or equilibrium) condition: $m_{1,s}(t) = f[W(r=R,t),T,P]$ (16)

The above set of equations applies to any combination of Knudsen and surface diffusion. Equations (11) to (16) will be used in the analysis of silica gel bed performance presented later.

<u>Comparison of Surface and Knudsen Diffusion Fluxes in a Particle</u>: The ratio of Knudsen to surface diffusion fluxes in a gel particle is

SERI 🏽

$$\frac{n_{1,K}}{n_{1,S}} = \frac{D_{K,eff} g'(W)/\rho_p}{D_{S,eff}}$$
(17)

If we substitute Eqs. (A-4) and (A-8) we obtain

$$\frac{n_{1,K}}{n_{1,S}} = \frac{\tau_{S} \varepsilon_{p}}{\tau_{g} \rho_{p}} \frac{D_{K}}{D_{S}} g' (W)$$

This ratio depends on the internal structure of the particle (average pore radius, surface area, tortuosity factors), isotherm slope and temperature. The results of calculations for this ratio show [11] that the dominant mechanism in RD gel is surface diffusion, while both surface and Knudsen diffusion should be considered for ID gel. This conclusion is consistent with the conclusion arrived at in Appendix A for a single pore. In fact, assuming the Wheeler [12] porous model of straight and cylindrical pores, it can be shown [11] that Eq. (17) and Eq. (A-11) are identical.

4. MODELING OF SILICA GEL PACKED PARTICLE BEDS

The differential equations governing the transient response of a packed bed of desiccant particles are presented in this section. These equations are obtained by applying the principles of mass, species, and energy conservation in both phases. Figure 2 shows an idealized picture of the physical phenomena in the gas phase. The species conservation equation in the gas phase neglecting axial and radial diffusion is

$$\varepsilon_{b}A \frac{\partial(\rho m_{1})_{e}}{\partial t} + \frac{\partial(m_{1}, e^{\dot{m}_{G}})}{\partial z} = n_{1}, sp \qquad (18)$$

while overall mass conservation requires that

$$\varepsilon_{b}A \frac{\partial \rho_{e}}{\partial t} + \frac{\partial m_{G}}{\partial z} = n_{1,s}p$$
(19)

Combining Eqs. (22) and (23) gives

$$\epsilon_b A \rho_e \frac{\partial m_{1,e}}{\partial t} + \dot{m}_G \frac{\partial m_{1,e}}{\partial z} = n_{1,s} (1-m_{1,e})p$$
 (20)

It can be shown [11] that the storage term $\epsilon_b A \rho_e \frac{\partial m_{1,e}}{\partial t}$ is negligible for thin beds. Assuming low mass transfer rates the final form of Eq. (20) is

$$\dot{m}_{G} \frac{\partial m_{1,e}}{\partial z} = K_{G} (m_{1,s} - m_{1,e}) (1 - m_{1,e})p$$
 (21)

The species conservation equation for the solid phase was developed in Section 3. For spherical particles assuming radial symmetry the general form of the equation is Eq. (12),



$$\frac{\partial W}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(Dr^2 \frac{\partial W}{\partial r} \right)$$
(22a)

where D, the total diffusivity defined by Eq. (11), is a function of gel water content W. Note that if the mass transfer problem is treated as a "lumped capacitance" model, as has been done by many investigators, e.g. [1,13,14], in their pseudo gas-side controlled models, the solid-phase species conservationequation becomes

$$A\rho_b \frac{\partial W_{avg}}{\partial t} = - K_{G,eff}(m_{1,s}-m_{1,e})p \qquad (22b)$$

where $K_{G,eff}$ is an effective mass transfer coefficient, accounting for both ______ gas-side and solid-side resistances. Equations (21) and (22a) are coupled through the equilibrium relation applied at the particle surface,

$$m_{1e}(z,t) = f[W(r=R,z,t), T_e(z,t), P]$$
 (23)

The initial and boundary conditions for Eq. (22a) are

I.C.
$$W(r,z,t=0) = W_0$$
 (24)

B.C. 1
$$\frac{\partial W}{\partial r}\Big|_{r=0} = 0$$
 (25)

B.C. 2
$$-\rho_p D \frac{\partial W}{\partial r}\Big|_{r=R} = K_G[m_{1,s}(z,t)-m_{1,e}(z,t)]$$
 (26)

while the boundary condition for Eq. (21) is

$$m_{1,e}$$
 (z=0,t) = $m_{1,in}$ (27)



The average water content of a particle is give by

$$W_{avg} = \frac{\int_0^R 4\pi r^2 W \rho_p dr}{\frac{4}{3} \pi R^3 \rho_p}$$
(28)

Referring to Fig. 2, the gas-phase energy conservation equation is

$$\frac{\partial}{\partial z} \left(\dot{m}_{\rm G} h \right) = p \left[h_{\rm C} (T_{\rm s} - T_{\rm e}) + n_{1,\rm s} h_{1,\rm s} \right]$$
(29)

where axial and radial conduction and storage term have been neglected and the bed is assumed to be adiabatic. Assuming isothermal particles a "lumpedcapacitance" model can be used for the solid phase. Then energy conservation in the solid phase is

$$A \rho_b \frac{\partial h_b}{\partial t} = - p [h_c (T_s - T_e) + n_{1,s} h_{1,s}]$$
 (30)

Assuming low mass transfer rates and using

 $h_b = \int_0^W h_{1,u} dW' + h_{solid}$

$$H_{ads}(W_{avg}) = h_{1,s}-h_{1,u}$$

$$h = m_1 h_1 + (1-m_1)h_2$$

$$c = \frac{\partial h}{\partial T}$$

S=?| 🏽

equations (29) and (30) can be rewritten in terms of temperatures as

$$c_{p,e^{\hat{m}_{c}}} = -p [h_{c}+c_{p1}K_{G}(m_{1,s}-m_{1,e})] (T_{e}-T_{s})$$
 (31)

$$A\rho_{b}c_{b} \frac{\partial T_{s}}{\partial t} = p \left[h_{c}(T_{e}-T_{s}) - H_{ads}K_{c}(m_{1}, s-m_{1}, e)\right] \qquad (32)$$

The initial condition for Eq. (32) is

$$T_{s}(z,t=0) = T_{0}$$
 (33)

while the boundary condition for Eq. (31) is

$$T_{e}(z=0,t) = T_{in}$$
 (34)

Equations (21), (22a), (23), (28), (31) and (32) are a set of coupled nonlinear equations with six unknowns: W(r,z,t), $W_{avg}(z,t)$, $m_{l,s}(z,t)$, $T_s(z,t)$, $m_{l,e}(z,t)$ and $T_e(z,t)$. These can be solved with the given boundary and initial conditions.

<u>Auxiliary Data</u>: Data are required for K_{G} , h_{c} , D, $c_{p,e} c_{b}$, H_{ads} and the equilibrium relation. Based on a survey of the available literature on mass transfer in packed particle beds [3] the following correlations for the gasside transfer coefficients are adopted,

TP-2388

$$K_{\rm G} = 1.70 \ {\rm G}_{\rm a} \ {\rm Re}^{-0.42} \ {\rm kg/m^2S}$$
 (35)

$$h_c = 1.60 G_a Re^{-0.42} c_{p,e} W/m^2 K$$
 (36)

For the psuedo gas-side controlled model $K_{G,eff}$ and h_c are give by the Hougen and Marshall correlations [15] of Ahlberg's experimental data [16] since these are in wide use.

$$K_{G,eff} = 0.704 G_a Re^{-0.51} kg/m^2 S$$
 (37)

$$h_c = 0.683 G_a Re^{-0.51} c_{p,e} W/m^2 K$$
 (38)

The total diffusivity can be obtained using Eqs. (11) and the expressions give in Appendix A. The specific heats c_{p.e} and c_{b.}are given by

$$c_{p.e} = 1884 m_{1.e} + 1004 (1-m_{1.e}) J/kg K$$
 (39)

$$c_b = 4186 W_{avg} + 921 J/kg K$$
 (40)

Equilibrium isotherms were obtained by fitting fourth degree polynomials to the manufacturer's data [11] for Regular Density (Davison, Grade 01) and Intermediate Density (Davison, Grade 59):

for RD gel

RH =
$$0.0078 - 0.05759 W + 24.16554 W^2 - 124.478 W^3 + 204.226 W^4$$
 (41)

S=?! «

for ID gel

RH = 1.235 W + 267.99 W² - 3170.7 W³ + 10087.16 W⁴ W
$$\leq$$
 0.07
(42
RH = 0.3316 + 3.18 W W > 0.07

The relation between water vapor mass fraction and relative humidity, RH, is

 $m_{1} = \frac{0.622 \text{ RH} \times P_{sat} (T)}{P_{rotal} - 0.378 \text{ RH} \times P_{sat} (T)}$

The heat of adsorption for RD gel is

 $H_{ads} = -12400 W + 3500 W \le 0.05$ $H_{ads} = -1400 W + 2950 W > 0.05$

and for ID gel is

 $H_{ads} = -300 W + 2095 W \le 0.15$ $H_{ads} = 2050 W > 0.15$ (44)

Method of Solution: The above set of equations was put in dimensionless form and solved numerically. Three nondimensional parameters were involved:

$$N_{Lu} = \frac{K_{G}pL}{\dot{m}_{G}} ; \quad DAR = \frac{\rho_{b}AL}{\dot{m}_{G}\tau} ; \quad \beta = \frac{\rho_{p}D}{K_{G}R}$$

)



The Crank-Nicholson scheme was used for Eq. (22a), while the implicit Euler method was used for Eq. (32) and Eq. (22b). A fourth-order Runge-Kutta technique was used for the spatial equations, Eqs. (21) and (31). For further details of the numerical procedure see [11]. A computer code called DESICCANT was developed which is capable of producing numerical solution to the following transient problems:

- i) step change in surrounding water vapor concentration of a single isothermal silica gel particle [Eq. (22a)].
- ii) step change in the inlet conditions to a fixed packed bed of silica gel with solid side resistance (SSR) model [Eqs. (21), (22a), (23), (28), (31) and (32)].
- iii) step change in the inlet conditions to a fixed packed bed of silica gel with pseudo gas-side controlled (PGC) model [Eqs. (21), (22b), (23), (31) and (32)]. Note that for this case $N_{tu} = K_{G,eff} pL/\dot{m}_{G}$.

5.0 RESULTS AND DISCUSSION

The numerical solutions of the diffusion equation for a single particle, Eq. (12), for Regular Density (RD) and Intermediate Density (ID) silica gels are discussed first. Next, the bed performance using the theoretical models, i.e., solid side resistance (SSR) and pseudo gas-side controlled (PGC), will be presented for RD and ID silica gels for both adsorption and desorption cases. Note that the major difference between these two models is the use of diffusion equation, Eq. (22), in the SSR model and use of the "lumped capacitance" equation, Eq. (22a), in the PGC model. The SSR model includes both gas side and diffusion resistances inside the particles; the PGC model is a lumped capacitance model. Adsorption occurs when the bed is initially dry relative to the inlet air, and moisture is transferred to the silica gel. Desorption occurs when the inlet air is dry relative to the initial condition of the bed, and moisture is transferred from the silica gel particles.

<u>Numerical Solutions of the Diffusion Equation in an Isothermal Particle</u>: The numerical solutions to the diffusion equation for an RD and an ID particle are presented in Figs. 3 and 4, respectively. The particle has an initial water content of W_0 , and at t=0 there is a step change in the water vapor mass fraction of the surroundings to $m_{1,e}$. The figures show the gel water content as a function of mass tranfer Fourier number for adsorption cases. The Fourier number was estimated based on initial D. The result for an RD particle, Fig. 3, shows that the difference between curve 1 (surface plus Knudsen diffusion) and curve 2 (surface diffusion only) is very small, and thus confirm that the contribution of Knudsen diffusion can be neglected for



RD gel. On the other hand, Fig. 4 shows that the contribution of Knudsen diffusion cannot be neglected for ID gel. Note that the curves of W_{avg} versus Fo_m for each mechanism cannot be simply added, since the problem is a nonlinear one. It should be noted that the same value of $D_{o,eff}$ (= 1.6 x 10⁻⁶) for both ID and RD gel was used to estimate surface diffusivity from Eq. (A-8). This value of $D_{o,eff}$ was obtained as a best estimate through comparison of experimental and theoretical results, as explained in Ref. [11,21]. The results shown in Figs. 3 and 4 are general over a wide range of temperature (20<T<50°C) and humidity (<0.03 kg/kg humid air).

The local concentration profiles in RD and ID particles at different times are plotted in Figs. 5 and 6, respectively. It is observed that usually the gel water content at the surface reaches about 90% of its final equilibrium value when t* reaches 0.1-0.15. The shape of the profiles in both gels are the same. However, the penetration of water into ID gel is faster than that of RD gel mainly because the total diffusivity, D, of ID gel is much larger than that of RD gel (about 4-20 times greater).

Numerical Solutions for Bed Performance Using SSR and PGC Models: The range of parameters (i.e., initial bed conditions, air velocity, inlet air conditions, etc.) which were used to generate the numerical solutions in this section are typical of those that are encountered in the operation of solar desiccant cooling systems. The numerical solutions were obtained for a bed of initially uniform conditions (W_0, T_0) with a step change in the inlet air conditions $(T_{in}, m_{1,in})$ at time t=0. It should be noted that, hereafter, whenever the SSR model is used for RD gel only surface diffusion is considered in the particles while for ID gel both surface and Knudsen diffusions are included in SSR model.

SE71 🏽

Typical theoretical results using both the model with solid side resistance (SSR model) and pseudo-gas side controlled model (PGC model) are presented in Figs. 7 through 12. Table 1 summarizes the pertinent parameters. The mass transfer Biot number, Bi_m, in Table 1 indicates the relative importance of the solid side and gas side mass transfer resistances. The lower Biot number for ID gel is mainly due to higher total diffusity D in the particles. Note that the dimensionless parameter β is reciprocal of Bi_m . In the figures, the outlet air temperature (T_{out}) and water vapor mass fraction $(m_{1,out})$ after the step change in the inlet conditions to the bed, are shown as a function of dimensionless time t/τ . Duration of an experiment, τ , is about half of the cycle time for fixed silica gel beds and τ has a fundamental relevance for making time dimensionless. Since both gas and solid side resistances are considered here, the Fourier number is not an appropriate time scale. Figs. 7 and 8 are typical results for adsorption on RD silica gel beds, Figs. 9 and 10 are typical results for adsorption on ID silica gel, and results for desorption from RD silica gel are presented in Figs. 11 and 12. Theoretical predictions of the SSR model in these figures were obtained using D_{s.eff} from Eq. (A-8) with $D_{0,eff} = 1.6 \times 10^{-6}$.

The general trend of the predicted results from both models for adsorption cases can be explained as follows: T_{out} increases rapidly to a maximum and gradually decreases at a rate depending on the air flow rate; $m_{1,out}$ also increases rapidly at first, but rather than reaching a maximum, the rate of increase simply becomes less. The change in slope of $m_{1,out}$ occurs after T_{out} reaches its peak. The reasons for this behavior can be explained as follows. Immediately following the step change, the dry bed adsorbs H_2O and liberates heat at a high rate; consequently the bed temperature and T_{out}

TP-2388

11.1111.4

ł

 $\ell \rightarrow$

13 110

1.1.1910

1.000

Table 1. Bed and Flow Conditions for the Theoretical Soluti

	Run	Gel	Process	R	L	Wo	Т _о	T _{in}	^m l,in	v	т	N _{tu} ‡	Bim	DAR
				$(mx10^{-3})$	(mx10 ⁻³)	(kg/kg)	(°C)	(°C)		(m/s)	(s)			
•	1	RD	Adsorption	1.94	77.5	0.0417	23.3	23.3	0.0100	0.21	1800	22.65	1145	0.1285
	2	RD	Adsorption	1.94	75.0	0.045	22.1	22.1	0.0088	0.55	1500	14.25	2401	0.0547
	3	ID	Adsorption	1.94	77.5	0.0088	23.6	23.7	0.0097	0.45	1200	16.85	175	0.0500
	4	ID	Adsorption	1.94	77.5	0.005	24.4	24.5	0.0063	0.67	1200	14.21	222	0.0330
26	5	RD	Desorption	2.60	50.0	0.368	25.0	25.0	0.0051	0.40	1800	7.59	342	0.0420
	6	RD	Desorption	2.60	50.0	0.260	25.4	25.4	0.0007	0.67	1200	6.12	723	0.0390

3 . A . A

2

<u>ا</u>

{ F

 \ddagger This value of N_{tu} is for SSR model, N_{tu} for PGC model is about 1/3.4 of this value. *Based on initial value of D.

1 . 1

SERI 🍥

increase rapidly, and $m_{l,out}$ increases rapidly from a value much lower than $m_{l,in}$. The bed gradually loses its adsorptive capacity due to the increase in gel water content and bed temperature, and the rate of increase of $m_{l,out}$ decreases as a result. The maximum in T_{out} is reached when the cooling effect of the air flow balances the heat of adsorption being released, and thereafter the reduced rate of adsorption causes T_{out} to decrease. The reverse of the above explanation is valid for the desorption cases.

Generally the initial rates of increase of $m_{1,out}$ predicted by the SSR model are steeper than those predicted by the PGC model. This feature can be explained as follows. The PGC model has a constant overall mass transfer resistance chosen to best approximate the adsorption process on an average basis. The SSR model has an overall resistance which increases as the adsorption process proceeds and moisture has to diffuse further into the gel particle. Thus, initially, the overall resistance of the SSR model is lower than that of the PGC model, adsorption rates are higher, and the outlet concentration predicted by the SSR model increases faster than that predicted by the PGC model. During the latter stages of adsorption the situation is reversed so that the total amount of water adsorbed would be the same for both models.

In general the shape of the $m_{1,out}$ and T_{out} curves predicted by the SSR model are not the same for adsorption versus desorption. This interesting feature is due to the concentration dependence of the surface diffusion coefficient, and the fact that the initial gel water content for a typical desorption case is much higher than for an adsorption case. Sladek's equation, Eq. (A-7) shows that D_S increases with W Hence, for all other pertinent parameters the

same, the SSR model predicts a higher initial rate of desorption than adsorption. The PGC model does not have this feature.

The equilibrium capacity of ID gel is lower than RD gel, as one can calculate from Eqs. (41) and (42). Thus, a bed of ID gel loses its adsorption capacity faster than a bed of RD gel with similar bed and air inlet conditions. This can be observed from comparison of numerical solutions from RD gel (Figs. 7 and 8) and ID gel (Figs. 9 and 10). The numerical predictions will be compared with the experimental results in Part II of this study [21] to evaluate the suitability of the models.

Fig. 13 shows the variation of average gel water content and bed temperature along the bed at various times of a typical adsorption case on RD gel using the SSR model. W_{avg} decreases monotonically along the bed, but the variation of T_s is more complex, associated with movement of the location of maximum adsorption rate along the bed with time.

S=2|

6.0 SUMMARY AND CONCLUSIONS

The magnitude of different diffusion mechanisms into two types of silica gel particles were examined. It was found that in Intermediate Density silica gel with a mean pore radius of 68A, both surface and Knudsen diffusion are important modes of moisture transport, while in Regular Density silica gel with a mean pore radius of 11A, only surface diffusion needs to be considered. A generalized diffusion equation was developed and was incorporated in a simultaneous heat and mass transfer model to predict the transient performance of a packed bed of silica gel. The heat and mass transfer model was solved numerically using finite difference methods. The transient responses of silica gel beds to step change in inlet air conditions were predicted with this new model and were compared with the predictions of the widely used pseudo-gas-side controlled model. The new model is more faithful to the true physics of the problem, so it is likely that it will give better agreement with experimental results. Comparison with experiment will be reported in Part II of this series [21].

ACKNOWLEDGMENTS

This work was supported by a grant from the Solar Energy Research Institute/U.S. Department of Energy, Grant No. DE-FG02-80CS84056. The Technical Monitor was T. Penney. Computer time was supplied by the Campus Computing Network of the University of California, Los Angeles. The Publication Development Branch of the Solar Energy Research Institute assisted in preparing this paper.

SER

REFERENCES

- 1. Bullock, C. E., and J. L. Threlkeld, Dehumidification of Moist Air by Adiabatic Adsorption, Trans. ASHRAE, 72, part I, 301-313 (1966).
- 2. Clark, J. E., A. F. Mills, and H. Buchberg, Design and Testing of Thin Adiabatic Desiccant Beds for Solar Air Conditioning Applications, J. Solar Energy Engineering, 103, 89-91 (May 1981).
 - 3. Pesaran, A. A., "Air Dehumidifcation in Packed Silica Gel Beds," M.S. Thesis, School of Engineering and Applied Science, University of California, Los Angeles, (1980).
 - 4. Kruckels, W. W., On Gradient Dependent Diffusivity, Chem. Eng. Sci., 28, 1565-1576 (1973).
 - 5. Rosen, J. B., Kinetics of a Fixed Bed System for Solid Diffusion into Spherical Particles, J. Chem. Phys., 20, 387-393 (1952).
 - 6. Neretnieks, I., Adsorption in Finite Bath and Countercurrent Flow with Systems Having a Nonlinear Isotherm, Chem. Engr. Sci., 31, 107-114 (1976).
 - 7. Schneider, P., and J. M. Smith, Chromatographic Study of Surface Diffusion, AIChE J., 14, No. 6, 886-895 (November 1968).
 - 8. Carter, J. W., A Numerical Method for Prediction of Adiabatic Adsorption in Fixed Beds, Trans. Inst. Chem. Engrs., 44, 1966, pp. T253-T259.

30

TP-2388

SERI 🍥

- 9. Meyer, O. A., and T. W. Weber, Nonisothermal Adsorption in Fixed Beds, AIChE J., 13, No. 3, 457-465 (1967).
- 10. Weast, R. C., CRC Handbook of Chemistry and Physics P. F-168, CRC Press, Inc., Florida (1985).
- 11. Pesaran, A. A., "Moisture Transport in Silica Gel Particle Beds," Ph.D. Dissertation, School of Engineering and Applied Sciences, University of California, Los Angeles, (1983).
- 12. Wheeler, A., Reaction Rates and Selectivity, in Catalysis, II, (P. H. Emmett, ed.), 109-120, Reinhold Publishing Co., New York (1955).
- 13. Nienberg, J. W., "Modeling of Desiccant Performance for Solar-Desiccant-Evaporative Cooling Systems," M.S. Thesis, School of Engineering and Applied Science, University of California, Los Angeles, (1977).
- 14. Pla-Barby, F. E., and G. C. Vliet, Rotary Bed Solid Desiccant Drying: An Analytical and Experimental Investigation, ASME/AIChE 18th National Heat Transfer Conference, San Diego, CA (1979) (ASME paper 79-HT-19).
- 15. Hougen, O. A., and W. R. Marshall, Jr., Adsorption from a Fluid Stream Flowing through a Stationary Granular Bed, Chem. Eng. Prog., 43, No. 4, 197-208 (April 1947).



- 16. Ahlberg, J. E., Rates of Water Vapor Adsorption for Air by Silica Gel, Ind. Eng. Chem., 31, 988-992 (August 1939).
- 17. Edwards, D. K., V. E. Denny, and A. F. Mills, Transfer Processes (2nd ed.), Hemisphere/McGraw-Hill Book Company, Inc., New York, (1979).
- 18. Flood, E. A., R. H. Tomlinson, and A. E. Legger, The Flow of Fluids through Activated Carbon Rods, Can. J. Chem. Engr., 30, 389-396 (1952).
- 19. Gilliland, E. R., R. F. Baddour, and J. L. Russel, Rates of Flow through Microporous Solids, AIChE J., 4, No. 1, 90-96 (March 1958).
- 20. Sladek, K. J., E. R. Gilliland, and R. F. Baddour, Diffusion on Surfaces. II. Correlation of Diffusivities of Physically and Chemically Adsorbed Species, Ind. Eng. Chem. Fundam., 13, No. 2, 100-105 (1974).
- 21. Pesaran, A. A., and A. F. Mills, Moisture Transport in Silica Gel Particle Beds II. Experimental Study, International Journal of Heat and Mass Transfer, in press.

SERI

APPENDIX A. DIFFUSION IN POROUS MEDIA

Ordinary diffusion, as described by Fick's law, occurs when the molecules of the gas collide with each other more frequently than with pore walls of a porous medium. For water vapor-air mixtures a useful formula for ordinary diffusion coefficient is [17]

$$D_{H_20,air} = 1.735 \times 10^{-9} \frac{(T + 273.15)^{1.685}}{P} m^2/s$$
 (A-1)

where T is the gas temperature in degrees Celsius and P is in atmospheres.

In the limit of large Knudsen number (Kn = λ/a , where λ is the mean free path and a is the pore radius) the gas molecules collide more often with pore walls than with each other and the diffusion of mulecules is described by the equations of free molecule flow [18]. A Fick's law type expression can be obtained for this type of flow if a Knudsen diffusion coefficient, D_K, is defined. For water-vapor diffusion in straight cylindrical pores of radius a, a dimensional equation for D_K is [17]

$$D_{\rm K} = 22.86 (T+273.15)^{1/2} a m^2/s$$
 (A-2)

where a is in m. Table A-1 compares Knudsen and ordinary diffusion coefficients in water vapor-air mixtures for various values of pore radius. Note that combined ordinary and Knudsen diffusion may be approximately represented by assuming additive resistances [17], that is

$$\frac{1}{D_1} = \frac{1}{D_{H_2}O_{,air}} + \frac{1}{D_K}$$
(A-3)

SERI 🐞

We see in Table A-1 that Knudsen diffusion is dominant for pore sizes smaller than about 200 Å. Since most of the pores of silica gel are less than 100 Å, it is clear that ordinary diffusion can be ignored in usual silica gel applications.

Equation (A-2) is, strictly speaking, valid only for long, uniform radius capillaries, and should be modified for application to real porous media. It can be shown that [11] effective Knudsen diffusion coefficient is related to Knudsen diffusion by

$$D_{K,eff} = \frac{\varepsilon_p}{\tau_g} D_K$$
 (A-4)

where ϵ_p is the particle porosity (volume void fraction) which accounts for the reduction of free area for diffusion due to presence of solid phase and τ_g in gas tortuosity factor which accounts for the increase in diffusional length due to tortous paths of real pores. Note that the effective ordinary diffusion can also be obtained by a similar equation to Eq. (A-4).

Surface diffusion is the transport of adsorbed molecules on the pore surface. A number of possible mechanisms for movement of adsorbed molecules on surfaces is proposed, e.g. [4,18,19]. Kruckel [4] studied the surface diffusion of water vapor through isothermal RD silica gel particles. He expressed the surface rate in terms of Fick's law and considered the submonolayer concentration range (concentrations up to about half of the saturation loading of silica gel particles), and proposed that the mechanism of surface diffusion to be one of activated hopping molecules in a random walk process. He proposed a formula with several paramaters: but since the theoretical

SE2! 🐲

estimation of these parameters was difficult, they were calculated by a nonlinear least squares fit between the mathematical model and experimental data at 40° C. The resulting formula for the surface diffusion coefficient can be extrapolated to other temperatures using the assumption of Arrhenius type behavior,

$$D_{S} = 1.287 \times 10^{-8} \exp\left[-811.30 \frac{W}{(T+273.15)}\right] \left[1 + 3112W \frac{\tanh\left(0.265 \times 10^{-2} \frac{\partial W}{\partial r}\right)}{\left(\frac{\partial W}{\partial r}\right)}\right] \frac{m^{2}}{s}$$
(A-5)

and shows a decrease of D_S with increasing W.

This formula requires considerbable computational effort, and is only valid for RD gels at low concentrations. A simpler formula which can be used for both RD and ID silica gel at both high and low concentrations was therefore sought.

Sladek et al. [20] proposed a simpler formula which is valid for both low and high surface coverages. They assumed a mechanistic hopping model with the assumption that the jumping frequency is a function of surface concentration (through the heat of adsorption) and obtained the following expression for the surface diffusion coefficient

$$D_{s} = D_{o} \exp[-aH_{ads}/R(T + 273.15)] m/s^{2}$$
 (A-6)

They later correlated some available data on surface diffusion of various adsorbates into different adsorbents (not H_2O - silica gel system) with this equation and found that D_0 should be set at 1.6 × 10⁻⁶ m²/s and a = 0.45/b

SERI 🐞

where b is obtained from the type of adsorption bond. For silica gel, b is unity so the surface diffusivity becomes

$$D_{\rm S} = D_{\rm o} \exp[-0.974 \times 10^{-3} (H_{\rm ads}/(T + 273.15))] m^2/s$$
 (A-7)

where an approximation to D_0 is $1.6 \times 10^{-6} \text{ m}^2/\text{s}$. However, as we will see in Part II of this study, D_0 can be obtained by matching the experimental and the theoretical results of transient response of packed beds of silica gel.

The surface diffusion coefficients given above are valid for smooth surfaces, and should be modified to account for rough walls of the porous media. Since surface diffusion is a surface phenomenon the reduction of the area normal to the direction of flux due to the presence of solid phase has no role in effective surface diffusivity.

It can be shown [11] that

$$D_{S,eff} = \frac{1}{\tau_{s}} D_{S} = D_{o,eff} \exp[-0.947 \times 10^{3}(H_{ads}/(T + 273.15))]$$
 (A-8)

where τ_s is surface tortuosity factor which accounts for the increase in diffusional length due to tortous paths of real pores. Note that $D_{o,eff}$ is D_o/τ_s .

In the remainder of this section we compare the Knudsen and surface diffusion rates in a single pore. Consider a cylindrical and isothermal pore of radius a. The vapor diffusion rate due to Knudsen diffusion, \dot{m}_{K} , through the pore in axial direction z is

SERI 🏽

$$\dot{m}_{K} = \pi a^{2} (-D_{K}^{\rho} \frac{\partial m_{1}}{\partial z})$$
 (A-9)

and due to surface diffusion, mg on the surface of the pore is

$$\dot{m}_{\rm S} = 2\pi a (-D_{\rm S} \frac{\partial C_{\rm S}}{\partial z})$$
 (A-10)

Since C_s , surface concentration, is related to gel water content, W, and specific surface area, S_g , through $C_s = W/S_g$, the ratio of Knudsen diffusion and surface diffusion rates is

$$\frac{m_{K}}{m_{S}} = \frac{a}{2} \frac{D_{K}}{D_{S}} S_{g\rho} \left(\frac{\partial m_{1}}{\partial W}\right)_{T}$$
(A-11)

If we assume that the rates of adsorption and desorption of molecules are both large compared with the surface migration rates, the surface C_s and pore concentrations (ρm_1) will be almost in equilibrium, and hence will be related by the equilibrium adsorption isotherm, or

$$\rho m_1 = g(W,T,P)$$

The ratio of rates can be calculated knowing the properties of the gel. Table A-2 contains the properties of both RD and ID gel and shows the results of the calculation of rate ratios. We see that surface diffusion dominates in a pore with RD gel characteristics while both mechanisms are important for a pore with ID gel characteristics.

SERI 🕷

Table A-1. Comparison of Knudsen and Ordinary Diffusion Coefficients in Water Vapor-Air Mixtures for Various Values of Pore Radius (T=40°C, P=1 atm)

			D _{K,H2} 0
а	D _K ,H ₂ 0	D _{H2} 0,air	
(Å)	(m^2/s)	(m^2/s)	D _{H2} 0,air
11	4.45×10 ⁻⁷	2.79×10 ⁻⁵	0.0159
68	2.75×10 ⁻⁶	2.79×10 ⁻⁵	0.099
100	4.04×10 ⁻⁶	2.79×10^{-5}	0.145
200	8.08×10 ⁻⁶	2.79×10 ⁻⁵	0.290
1000	4.04×10 ⁻⁵	2.79×10 ⁻⁵	. 1.450

SERI 🐞

Table A-2. Surface and Knudsen Diffusion Rate Comparison in

a Pore of Silica Gel at 30⁰C and 1 Atmosphere [11]

	Regular Density	Intermediate Density	· .
Equilibrium Relation	Eq. (41)	Eq. (42)	, =.,
Heat of Adsorption	Eq. (43)	Eq. (44)	
Surface Diffusivity	Eq. (A-7)	Eq. (A-7)	
Knudsen Diffusivity	Eq. (A-2)	Eq. (A-2)	
٥ _p	1129 kg/m ³	620 kg/m ³	· · · · · ·
$\tau_s = \tau_g$	2.8	2.0	
Pore Surface Area	$S_g = 7.8 \times 10^5 \text{ m}^2/\text{kg}$	$S_g = 3.40 \times 10^5 \text{ m}^2/\text{kg}$	
Average Pore Radius	$a = 11 \text{ Å} = 11 \times 10^{-10} \text{ m}$	$a = 68 \text{ \AA} = 68 \times 10^{-10} \text{ m}$	•
Range of Water Content	0.01 - 0.3 kg/kg	0.005 - 0.15 kg/kg	-
Range of Ratio of		- · ·	· • •
Knudsen to Surface			
Diffusion Rates	0.023 - 0.060	0.6 - 2.0	

SERI 🕷



2. Idealized Picture of the Physical Phenomena in the Gas Phase of the Packed

Bed

SERI 🏽





SERI



4. W_{avg} versus Mass Transfer Fourier Number for Various Mechanisms of Diffusion for an ID Particle

SERI 🕷



5. Concentration Profile in an RD Particle with Surface Diffusion

SERI 💮



TP-2388

6. Concentration Profile in an ID Particle with Surface and Knudsen Diffusions





^{7.} Comparison of PGC and SSR Models for Adsorption on RD Gel, Run 1



8. Comparison of PGC and SSR Models for Adsorption on RD Gel, Run 2

SERI 🕷



^{9.} Comparison of PGC and SSR Models for Adsorption on ID Gel, Run 3

S=?! 💓



10. Comparison of PGC and SSR Models for Adsorption on ID Gel, Run 4





11. Comparison of PGC and SSR Models for Desorption on RD Gel, Run 5



12. Comparison of PGC and SSR Models for Desorption on RD Gel, Run 6

SERI 🕷



13. Variation of W_{avg} and T_s with z* at Various t* Using SSR Model for Adsorption on RD Gel