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EFFECT OF MOLECULAR WEIGHT DIFFERENCE BETWEEN SEVERAL GASES ON GAS DIFFUSION BEHAVIORS IN AIR FLOW THROUGH PACKED BED[1]

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Abstract

The purpose of this study is to clarify that diffusion behavior of several kinds of gases in air flow through packed bed in order to understand diffusion behavior of hydrogen in blast furnace. Cold model experiments at room temperature were carried out to investigate the diffusion behavior of He and CH_4 gases in air flow through the packed bed. Effect of molecular species difference on gas diffusion behavior was appeared clearer in the condition of smaller air flow velocity than bigger one from this comparison. In other words, gas diffusion behavior could ignore difference of molecular species under enough large gas flow condition.

Key words: Gas diffusion; Effective diffusivity; Packed bed; Blast furnace.

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1 INTRODUCTION

Hydrogen has strong possibility of alternative for reducing agent as green energy source instead of fossil fuel in ironmaking process. When hydrogen uses for reduction reaction of iron oxide, only water would be generated as result of reduction. Effect of hydrogen utilization on reduction behavior of iron oxide has been researched by many researchers.[1-3] From their reports, it has been showed that hydrogen has an advantage about reduction rate of iron oxide when it is compared with carbon monoxide. When practical utilization of hydrogen in blast furnace will be tried, mass transfer behavior of hydrogen under the upward gas flow should be correctly understood. However, from point of view about mass transfer of hydrogen under ironmaking condition in blast furnace there is unfortunately not enough reports.[4] The purpose of this study is to clarify that diffusion behavior of several kinds of gases in air flow through packed bed in order to understand diffusion behavior of hydrogen in blast furnace.

2 MATERIALS AND METHODS

Cold model experiments at room temperature were carried out to investigate the diffusion behavior of several kinds of gases, they are different molecular species, in air flow through the packed bed. He and CH_4 were chosen as tracer gases for investigation of effect of difference of molecular species on their diffusion behavior.
Figure 1 shows a schematic diagram of an experimental apparatus to investigate the diffusion behavior of the gases into the packed bed. The packed bed was made of a tube filled with glass beads, their specific diameter were 2.0 and 4.0mm. The dimensions of the packed bed were 100mm diameter and 383mm in height. A gas injection nozzle for He and CH_4 as tracer gases was inserted in a center from bottom of the tube. The nozzle's inner diameter was 3mm and it could move up and down. A sampling tube for tracer gases was located just above top end surface of the packed bed. The tube's inner diameter was 1mm and it could move in a radial direction. This sampling tube was connected to a quadrupole mass spectrometer for measurement of tracer gas concentration in carrier gas. Ar gas as carrier gas was injected from bottom at specific flow velocities from 0.085 to 0.42 m/s. Flow velocities of tracer gases were same as carrier gas in order to make steady-state condition in the packed bed. Hereinafter in this study, this carrier gas flow velocity is defined as superficial gas flow velocity of tracer gas.

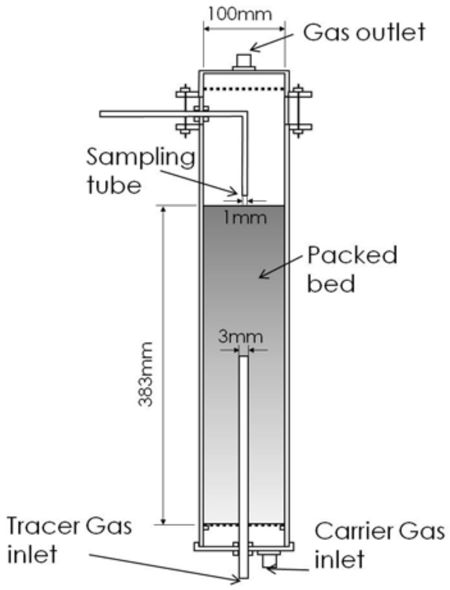

Figure 1. Schematic diagram of experimental apparatus.

3 RESULTS

The effect of superficial gas flow velocity on He and CH_4 diffusion behaviors are shown in figures 2 and 3, respectively. From comparison of these figures, it was found that CH_4 diffusion behavior showed no dependency on gas flow velocity though He showed clear dependency on it. This result indicated that gas species had superficial gas flow velocity dependency on their diffusibility in packed bed.

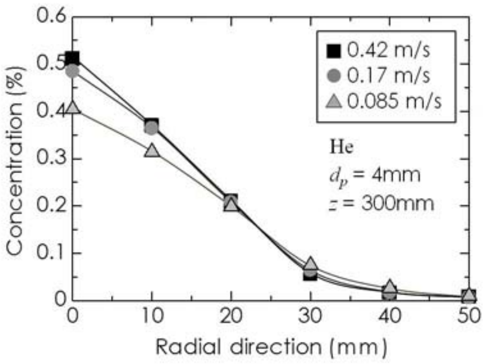

Figure 2. Effect of superficial gas flow velocity on He gas distribution.

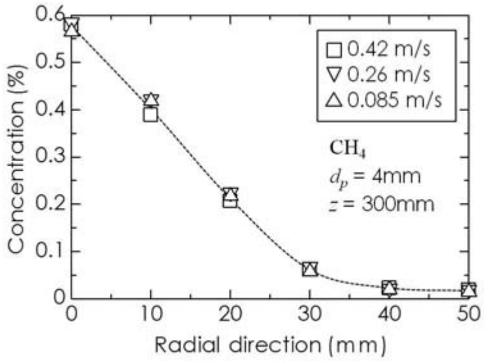

Figure 3. Effect of superficial gas flow velocity on CH_4 gas distribution.

A comparison about He gas diffusion behaviors between different size of particles, 2 and 4mm, is shown in figure 4. Through a comparison of their profiles, a clear difference between them was recognized that larger particle showed bigger diffusibility in radial direction. This result could roughly be explained by an idea of gas branching difference caused from difference of particle size as shown in Figure 5.

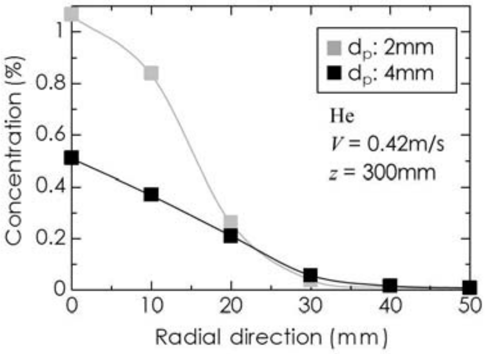

Figure 4. Effect of packing particle size on gas distribution.

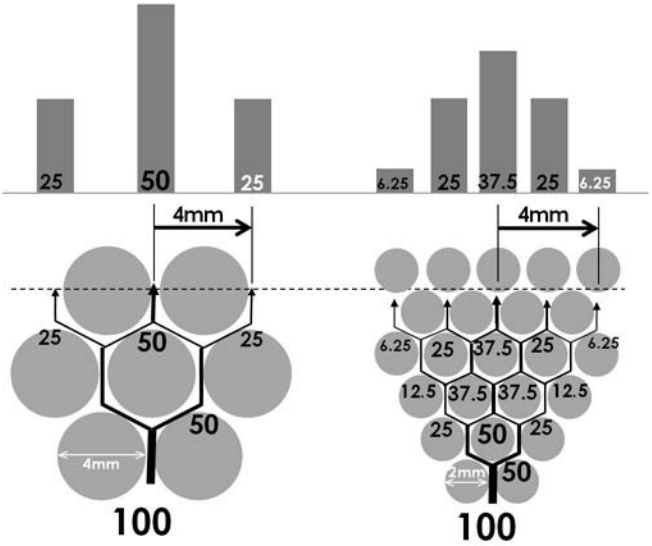

Figure 5. Schematic illustration of gas branching difference in packed bed caused by size of packing particle.

Figures 6 and 7 show gas diffusion behaviors of He and CH_4 under 0.42m/s and 0.085m/s superficial gas flow velocity, respectively. In case of 0.085m/s condition, relatively small superficial gas flow velocity, difference of their diffusion behaviors between two kinds of gases was clearly bigger than that of gas flow velocity, 0.42m/s. Difference between their gases diffusion behaviors could be appeared clearer in the condition of smaller superficial gas flow velocity than larger one from this comparison.

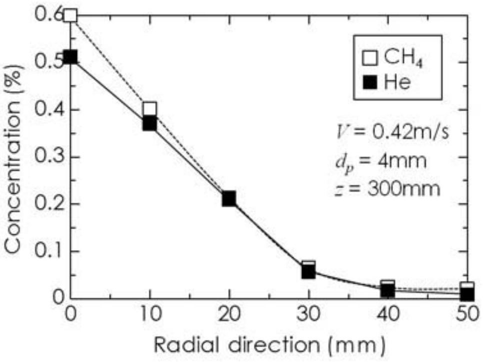

Figure 6. Effect of gas molecular species on gas distribution under large superficial gas flow velocity.

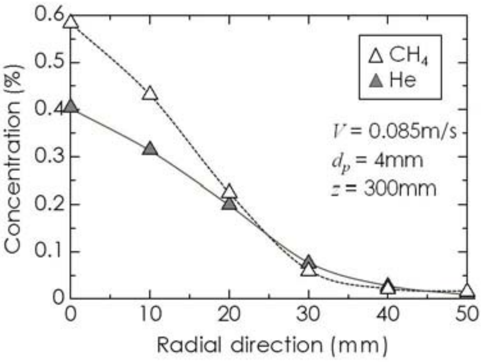

Figure 7. Effect of gas molecular species on gas distribution under small superficial gas flow velocity.

4 DISCUSSIONS

The basic differential equation[5,6] for mass transfer, which considers diffusion in the radial direction only and bulk flow in the axial direction, is written as Equation (1).

$$\frac{\partial}{\partial R}\left(D_e R\frac{\partial C}{\partial R}\right)=uR\frac{\partial C}{\partial z} \tag{1}$$

Angular symmetry is assumed. The following boundary conditions are imposed:

- at $z = 0$, the plane of the injection tube top $C(r, 0) = C_f$, for $0 < R < r_0$ and $C(r, 0) = 0$, for $r_0 < R < R_0$
- at the tube wall $\frac{\partial C(R_0, z)}{\partial R}=0$
- at the tube center $\frac{\partial C(0, z)}{\partial R}=0$

On the assumption that D_e and u are independent of position, analytical solution is shown as the solution of Equation (2) in the form of an infinite Fourier-Bessel series.

$$\frac{C}{C_A}\frac{C_A}{C_M}=1+\frac{2}{r_0}\sum_{n=1}^{\infty}\frac{1}{\beta_n}\frac{J_1(\beta_n r_0)}{J_0{}^2(\beta_n R_0)}J_0(\beta_n R)\exp(-\beta_n^2 z/\alpha) \tag{2}$$

All of the other terms of equation (2), except α, can be known from experimental condition and results. α can be estimated by the curve fitting technique between the experimental concentration data and equation (2).

Using this α value, the average Peclet number and the effective diffusivity can be calculated from Equation (3).

$$Pe = d_p \frac{V}{D_e} = d_p \alpha \qquad (3)$$

Figure 8 shows relationships between superficial gas flow velocity and effective diffusivities of He gas in packed bed made from 2mm particle and 4mm particle. It was clearly found linear relationship between effective diffusivity and gas flow velocity. Gradient difference of the linear relations between 2mm particle's packed bed and 4mm's one was obviously found in this figure. It could be thought that this tendency came from difference of packing structure caused by size difference of packed particles.

Figure 9 shows difference of effective gas diffusivities between He and CH_4 when same packed bed was used. Both of them also show linear relationship between effective diffusivity and gas flow velocity, and have same gradients. Same tendency about their gradients could be understood from their experimental condition, which used same packed bed. On the other hand y-intercepts in Figures 8 and 9 have different tendencies. In figure 8, effective diffusivities in packed beds of 2mm and 4mm particles are same value when gas flow didn't exist. In Figure 9, effective diffusivities of He and CH_4 show different values when gas flow velocity was 0m/s as shown in y-intercepts of them. Basically, effective diffusivity consists of not only molecular diffusivity but also inter-diffusivity. From figures 8 and 9, y-intercepts show dependency on not packing structure but duffusivity difference between He and CH_4. Interdiffusion coefficient of He and CH_4 in air flow have been reported as 0.624 x 10^{-4} m^2/s and 0.219 x 10^{-4} m^2/s, respectively.[7] Although the coefficients did not completely correspond with y-intercept values, both of them showed He's value is 3 times bigger than CH_4's value.

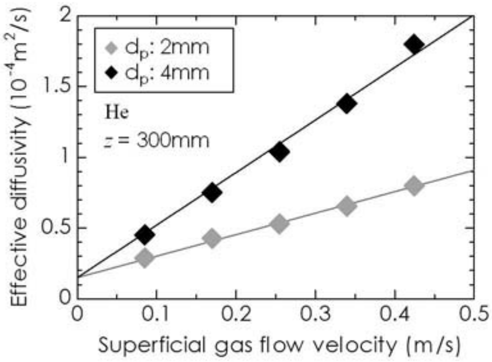

Figure 8. Effect of packing particle size on effective diffusivity.

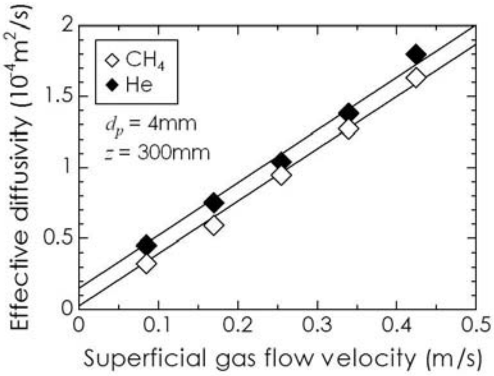

Figure 9. Effect of gas molecular species on effective diffusivity.

For application of this study's results to blast furnace operation, gas diffusion behavior in packed bed was evaluated using dimensionless numbers, particle Reynolds number and Peclet number.

The particle Reynolds number could be calculated by Equation (4).

$$\mathrm{Re}_{par} = \frac{\rho_g d_p V}{\mu_g} \qquad (4)$$

Peclet numbers could be derived from calculated values of effective diffusivity with using equation (3).

Figure 10 shows relationship between Re$_{par}$ and Pe. From this figure, it was found that both Pe of He and CH$_4$ converged to constant value, about 10, when Re$_{par}$ became bigger. In other words, Pe was independent on kinds of diffused gas under the condition with enough big Re$_{par}$, more than about 100. Generally, it is thought that particle Reynolds number of gas flow in blast furnace is more than 100. Therefore, Peclet number in blast furnace is constantly about 10 without dependency of kinds of gas. This result of discussion means Peclet number of H_2 could be also about 10 in blast furnace. When H_2 injection into blast furnace is discussed, Peclet number describes flux ratio of upward air flow divided by H_2 diffusion in a radial direction. That is to say, good diffusion of H_2 in blast furnace could be not expected from this discussion. When H_2 gas would be tried to inject into blast furnace, we have to carefully consider effective ways of injection of H_2.

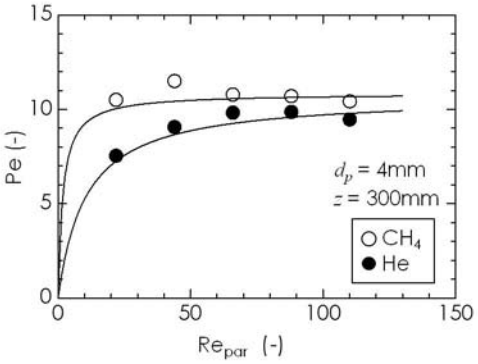

Figure 10. Relationship between particle Reynolds number and Peclet number. (d_p=4mm, z=300mm).

5 CONCLUSIONS

Diffusion behavior of several kinds' gases in air flow through packed bed was investigated and following results were obtained.

- Effective diffusivity increased linearly to the gas flow velocity. Gradient of this relationship was due to packing structure of packed bed. Value of effective diffusivity at 0m/s gas flow velocity was explained by interdiffusion coefficient.
- Effective diffusivity increased when bigger size of packed particle was used in packed bed.
- Gas diffusion behavior could ignore difference of molecular species under enough superficial large gas flow velocity condition. In other words, Peclet number in blast furnace is constantly about 10 without dependency of kinds of gas because Reynolds number of gas flow in blast furnace is more than 100.

LIST OF SYMBOLS

C: concentration in Air (mol/m^3)
C_A: measured average concentration (mol/m^3)
C_f: concentration of pure He or CH_4 in injection tube (mol/m^3)
C_M: integral average concentration (mol/m^3)
C_0: concentration at column center (mol/m^3)
D_e: effective diffusivity (m^2/s)
d_p: particle diameter (m)
R: radial distance from center of bed (m)
R_0: column radius (m)
r_0: radius of injection tube (m)
z: height of packed bed above injection tube (m)
u: superficial point velocity (m/s)
V: superficial gas flow velocity (m/s)
α: ratio of V/D_e (m^{-1})
$\beta_n r_0$: roots of $J_1(\beta_n r_0) = 0$
ρ_g: density of Air (kg/m^3)
μ_g: viscosity of Air (Pa･s)

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