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A model for the temperature effect on onset velocity of turbulent fluidization of Geldart type A particles

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Abstract−This study proposes a model to predict the temperature effect on the onset velocity of turbulent fluidization (u_c) of Geldart type A particles. It was found that void splitting could occur in the whole bed when the initial bubble size at the distributor (d_{bo}) was greater than the maximum stable bubble size (d_{bmax}) or the equilibrium bubble size (d_{beq}). The proposed model was successful to fit the trend of temperature effect on the u_c. When the bubble growth was limited by the d_{bmax}, the u_c increased with an increase of temperature. However, when the d_{beq} was smaller than d_{bmax}, the u_c decreased with an increase of temperature because the minimum fluidizing velocity and thus the d_{beq} decreased. The u_c increased initially and decreased later when the d_{beq}/d_{bmax} starting with the ratio >1 decreased to the ratio <1 as temperature increased. The present model predicted the trend properly that any other existing correlations could not be able to reflect.

Key words: Model, Temperature Effect, Transition Velocity, Onset Velocity, Turbulent Fluidized Bed

INTRODUCTION

The turbulent fluidization regime is commonly considered to lie between bubbling fluidization and the fast fluidization regime. The turbulent regime is known to result from disappearance of large voids by predominance of void splitting over void coalescence. Turbulent fluidization is commonly utilized in industrial fluidized-bed reactors due to vigorous gas-solids contacting, favorable bed-to-surface heat transfer, high solids hold-ups, and limited axial mixing of gas [1].

Although extensive results have been reported to quantify the onset velocity of turbulent fluidization (u_c), the effect of temperature on it is not clear yet for Geldart type A particles [2,3]. The u_c increased with temperature for Geldart type A and B particles in the study of Cai et al. [4,5]. However, they measured the static pressure in the middle of bed height that was improper to reflect the property of the whole bed. Chehbouni et al. [2] reported that the u_c decreased with an increase of temperature in the bed of FCC particles (Geldart type A; 78 μm, 1,450 kg/m^3). These results were related to the effect of temperature on bubble size, which was significantly different for fine and large particle diameters. Moreover, no published correlation could predict adequately those experimental data. The u_c in the bed of sand particles (Geldart type B; 250 μm, 2,560 kg/m^3) increased with an increase of temperature. According to the study of Peeler et al. [3], as temperature increased, the u_c decreased after an initial increase in the bed of sand particles (Geldart type B; 130 μm, 4,400 kg/m^3) using N_2 as fluidizing gas and decreased in the bed of alumina particles (Geldart type A; 70 μm, 2,800 kg/m^3) using N_2 or He as fluidizing gas. None of the reported correlations for estimating u_c satisfactorily predicts this behavior.

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This study is to propose a model for temperature effect on transition velocity to turbulent fluidization (u_c) of Geldart type A particles. Two cases of void splitting were considered for the fluidized bed of Geldart group A and AB particles. One is that the equilibrium bubble diameter is smaller than the maximum stable bubble diameter. Then the u_c decreased with an increase of temperature. Another is that the equilibrium bubble diameter is greater than the maximum stable bubble diameter. Then the u_c increased with temperature.

MODEL

The void size in a bubbling or slugging bed is limited by the maximum stable bubble size according to the study of Harrison et al. [6]. The bubble size in the bed of Geldart type A particles is controlled additionally by equilibrium bubble size because bubble splitting occurs [7]. Therefore, bubble breakup could occur in the whole bed when the initial bubble size at the distributor is greater than the smaller one of the maximum stable bubble size and the equilibrium bubble size.

At the usual gas velocity of turbulent bed including the bed of Chehbouni et al. [2] and Peeler et al. [3], which were considered in this study, the bubble diameter formed initially at the distributor is bigger than the pitch of the distributor nozzle so given by the following correlation for the porous plate distributor [8,9].

$$d_{bo} = \frac{3.685(u - u_{mf})^2}{g} \tag{1}$$

Harrison et al. [6] proposed the following relationship for the maximum stable bubble size:

$$\frac{d_{b\,max}}{d_p} = 1.32 \frac{\rho_p - \rho_g}{\rho_g} \frac{\frac{\rho_p}{\rho_p - \rho_g} - \varepsilon_{mf}}{1 - \varepsilon_{mf}} \tag{2}$$

Since $\frac{\frac{\rho_p}{\rho_p-\rho_g}-\varepsilon_{mf}}{1-\varepsilon_{mf}}$ is nearly unity in most gas fluidized beds, the simplified form gives

$$d_{b\,max}=1.32\frac{\rho_p-\rho_g}{\rho_g}d_p \tag{3}$$

When this relationship is applied to the initial bubble size (Eq. (1)) formed at the distributor as a criterion to begin bubble breakup throughout the bed, the onset velocity of turbulent fluidization u_c is

$$u_c=u_{mf}+0.5985\left(\frac{d_p(\rho_p-\rho_g)g}{\rho_g}\right)^{0.5} \tag{4a}$$

$$\frac{d_p u_c\rho_g}{\mu}=\frac{d_p u_{mf}\rho_g}{\mu}+0.5985\left(\frac{d_p^3\rho_g(\rho_p-\rho_g)g}{\mu^2}\right)^{0.5} \tag{4b}$$

$$Re_c=Re_{mf}+0.5985\,Ar^{0.5} \tag{4c}$$

The Re_{mf} can be given by the correlation of Wen and Yu [10]:

$$Re_{mf}=[(33.7)^2+0.0408\,Ar]^{0.5}-33.7 \tag{5}$$

Then, the onset condition of turbulent fluidization is in another form:

$$Re_c=[(33.7)^2+0.0408\,Ar]^{0.5}-33.7+0.5985\,Ar^{0.5} \tag{6}$$

When the bubble growth is limited by the maximum stable bubble size, the onset velocity of turbulent fluidization u_c increases with an increase of temperature as can be seen in Eq. (4a).

The equilibrium bubble size can be given by following correlations of Choi et al. [7]:

$$d_{beq}=\frac{6.792k(u-u_{mf})}{f_s^*} \tag{7}$$

$$k=\frac{u-(u/u_{mf})^{0.620}u_{mf}}{u-u_{mf}} \tag{8}$$

$$f_S^*=6.47\times10^{-4}\left(\frac{u}{u_{mf}}\right)^{0.454}\frac{g}{u_{mf}} \tag{9}$$

The k is bubble flow fraction of excess gas velocity and the f_s^* splitting frequency of a single bubble. The equilibrium bubble size is considered now that the bubble splitting is important in the bed of Geldart type A particles. When Eq. (7) is applied to the initial bubble size (Eq. (1)) formed at the distributor as a criterion to start the bubble breakup throughout the bed, the onset velocity of turbulent fluidization is

$$\left(\frac{u_c}{u_{mf}}\right)^{2.454}-2\left(\frac{u_c}{u_{mf}}\right)^{1.454}-2849\left(\frac{u_c}{u_{mf}}\right)+2849\left(\frac{u_c}{u_{mf}}\right)^{0.62}+\left(\frac{u_c}{u_{mf}}\right)^{0.454}=0 \tag{10}$$

The solution is

$$\frac{u_c}{u_{mf}}=217.5 \tag{11}$$

Therefore, if the bubble growth is limited by the equilibrium bubble size, the u_c decreases with an increase of temperature because the minimum fluidizing velocity and thus the equilibrium bubble size decrease.

Combining Eqs. (3) and (7) to (9) gives

$$\frac{d_{beq}}{d_{b\,max}}=7953\frac{Re_{mf}^2}{Ar}\left\{\frac{\left(\frac{u}{u_{mf}}\right)-\left(\frac{u}{u_{mf}}\right)^{0.62}}{\left(\frac{u}{u_{mf}}\right)^{0.454}}\right\} \tag{12}$$

First, the bubble size in the bed of Geldart type A, B and D particles is limited by the maximum stable bubble size. The bubble size in the bed of Geldart type A particles is controlled additionally by the equilibrium bubble size because the bubble splitting is important. The bubble splitting frequency in the bed of Geldart type B and D particles is so low that the equilibrium bubble size is greater than the stable bubble size and thus no real limitation to the bubble growth. Therefore, bubble breakup occurs in the entire bed if the initial bubble size formed at the distributor is greater than the smaller one of the maximum stable bubble size and the equilibrium bubble size.

RESULTS AND DISCUSSION

Fig. 1 shows the ratio of the equilibrium bubble diameter to the maximum stable bubble diameter, d_{beq}/d_{bmax} calculated by Eq. (12) at $u=u_c$ which was measured by Chehbouni et al. [2] and Peeler et al. [3]. The d_{beq}/d_{bmax} for the bed of sand and FCC particles was smaller or greater than unity, whereas for the bed of alumina particles smaller than unity. Therefore, this result confirms that bubble breakup in the bed could be caused by the initial bubble size formed at the distributor greater than the maximum stable bubble size or the equilibrium bubble size. The present discussion did not consider the data of Chehbouni et al. [2] obtained from sand beds because the $d_{beq}/d_{bmax}>1$ for those beds. The bubble splitting frequency in the bed of Geldart type B and D particles is so low that the equilibrium bubble size is greater than the stable bubble size and thus no real limitation to the bubble growth.

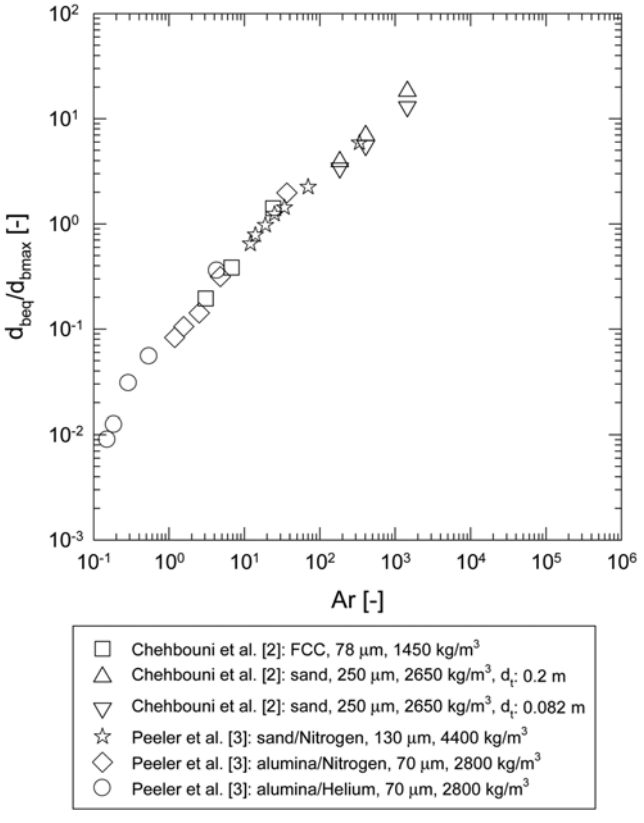

Fig. 1. d_{beq}/d_{bmax} versus Ar at u_c.

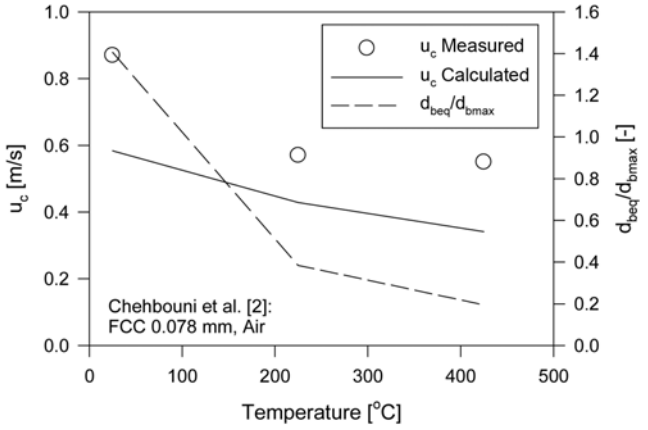

Fig. 2. Effect of temperature on u_c and d_{beq}/d_{bmax} (Chehbouni et al. [2]; FCC 0.078 mm, air).

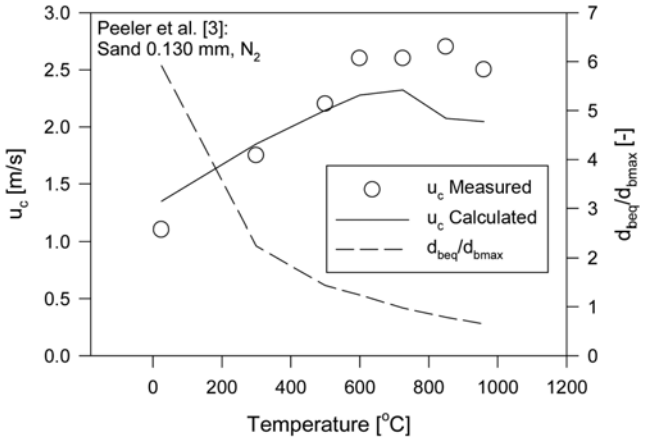

Fig. 3. Effect of temperature on u_c and d_{beq}/d_{bmax} (Peeler et al. [3]; sand 0.130 mm, N_2).

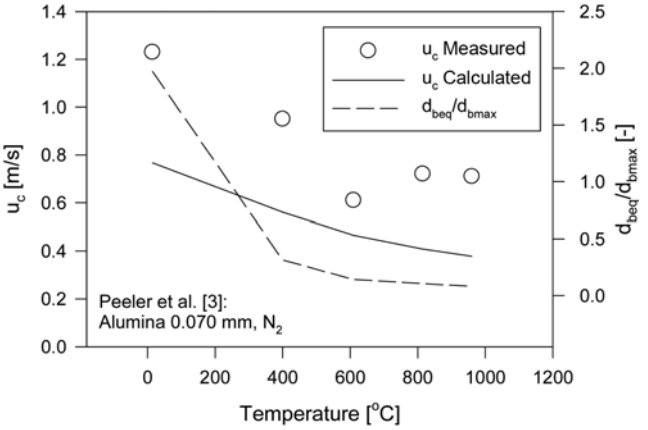

Fig. 4. Effect of temperature on u_c and d_{beq}/d_{bmax} (Peeler et al. [3]; alumina 0.070 mm, N_2).

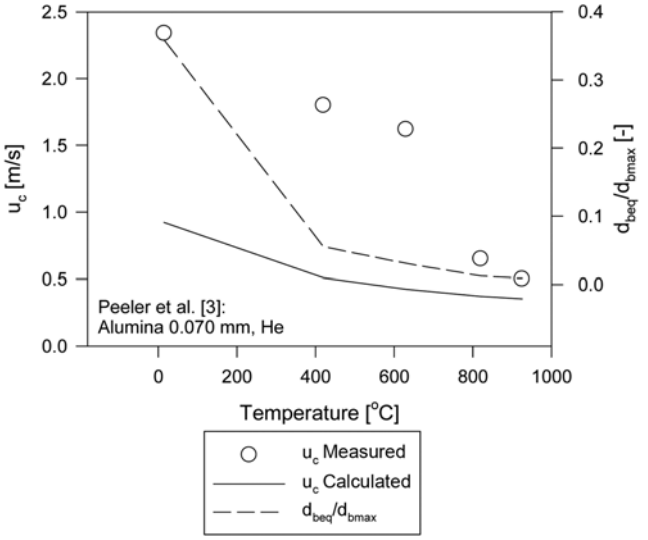

Fig. 5. Effect of temperature on u_c and d_{beq}/d_{bmax} (Peeler et al. [3]; alumina 0.070 mm, He).

Fig. 2 shows the comparison of the present model with data measured by Chehbouni et al. [2]. The maximum stable bubble diameter is greater than the equilibrium bubble diameter at temperature> 104 °C. So the u_c was determined by Eq. 4(a) for temperature<104 °C and Eq. (11) for temperature>104 °C. The present model could predict the temperature effect on the u_c reasonably well that decreased with an increase of temperature. However, the equilibrium diameter seemed to be somewhat underestimated so that the present model underestimated the u_c.

Fig. 3 shows a comparison of the present model with the data of Peeler et al. [3], which were measured in sand beds using N_2 gas as fluidizing gas. The u_c initially increased but decreased later as temperature increased. The d_{beq}/d_{bmax} was predicted greater than unity at temperature<725 °C so the u_c was determined by Eq. (4a). However, the d_{beq}/d_{bmax} was predicted smaller than unity at temperature >725 °C so Eq. (11) determined the u_c. The present model could predict the measured trend well. It was the trend that any other existing correlations could not follow reasonably [3].

Fig. 4 compares the present model with the data of Peeler et al. [3], measured in the alumina bed using N_2 gas as fluidizing gas. The d_{beq}/d_{bmax} was predicted greater than unity at temperature<238 °C so the u_c was determined by Eq. (4a). However, the d_{beq}/d_{bmax} was predicted smaller than unity at temperature>238 °C so Eq. (11) determined the u_c. So the u_c looked just decreasing with an increase of temperature. The present model could predict the measured trend well at the same condition.

Fig. 5 compares the present model with the data of Peeler et al. [3], measured in the alumina bed using He gas as fluidizing gas. The d_{beq}/d_{bmax} was predicted smaller than unity within the tested temperature range. The u_c decreased with an increase of temperature. The present model predicted the trend properly. But it underestimated the u_c considerably at temperatures 15 °C, 420 °C and 630 °C and could not follow the unlikely big decrease (0.97 m/s) between 630 °C and 820 °C.

Fig. 6 shows the relationship between u_c and u_{mf} when $d_{beq}<d_{bmax}$. Eq. (11) was in reasonable agreement with the data of Chehbouni et al. [2] and Peeler et al. [3], except for some data of the alumina-He system at 15 °C, 420 °C, and 630 °C. The present knowledge hardly seemed to explain the reason for the disagreement, only the present model seemed to underestimate the u_c because the equilibrium diameter was underestimated. It is evident that further study

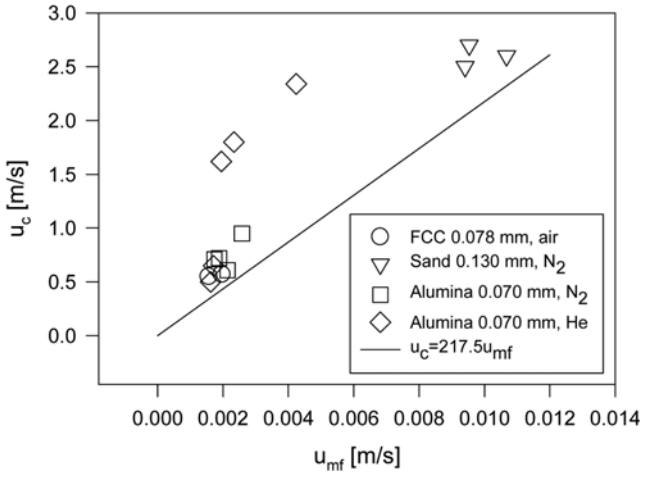

Fig. 6. u_c versus u_{mf} [2,3].

is needed to improve the model accuracy.

CONCLUSIONS

This study proposes a model to predict the temperature effect on the u_c of Geldart type A particles. The present study found that bubble breakup in the whole bed could be caused by the $d_{bo}>d_{bmax}$ or d_{beq}. The present model was successful to fit the trend of temperature effect on the u_c. When the bubble growth was limited by the d_{bmax}, the u_c increased with an increase of temperature. However, when $d_{beq}<d_{bmax}$, the u_c decreased with an increase of temperature because the minimum fluidizing velocity and thus the equilibrium bubble size decreased. The u_c increased initially and decreased later when the d_{beq}/d_{bmax} starting with a ratio>1 decreased to a ratio<1 as temperature increased. The present model predicted the trend properly that any other existing correlations could not reflect. The present model seemed to underestimate the u_c because the d_{beq} was underestimated. Further study is needed to improve the model accuracy.

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NOMENCLATURE

Ar : Archimedes number, $\frac{d_p^3\rho_g(\rho_p-\rho_g)g}{\mu^2}$

d_{beq} : equilibrium bubble diameter [m]
d_{bmax} : maximum stable bubble diameter [m]
d_{bo} : initial bubble diameter formed at the distributor [m]
d_p : particle diameter [m]
d_t : column diameter [m]
f_s^* : splitting frequency of a single bubble [1/s]
g : gravitational acceleration, 9.8 [m/s^2]
k : bubble flow fraction of excess gas velocity ($u-u_{mf}$) [-]
Re_c : particle Reynolds number at the onset condition of turbulent fluidization, $(d_p u_c \rho_g)/\mu$ [-]
Re_{mf} : particle Reynolds number at minimum fluidization, $(d_p u_{mf} \rho_g)/\mu$ [-]
u : gas velocity [m/s]
u_c : onset velocity of turbulent fluidization [m/s]
u_{mf} : minimum fluidizing velocity [m/s]
ε_{mf} : bed voidage at minimum fluidization condition [-]
ρ_g : gas density [kg/m^3]
ρ_p : solid density [kg/m^3]
μ : gas viscosity [Pa·s]

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