



Bed expansion behavior and sensitivity analysis for super-high-rate anaerobic bioreactor*

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Abstract: Bed expansion behavior and sensitivity analysis for super-high-rate anaerobic bioreactor (SAB) were performed based on bed expansion ratio (E), maximum bed sludge content (V_{pmax}), and maximum bed contact time between sludge and liquid (τ_{max}). Bed expansion behavior models were established under bed unfluidization, fluidization, and transportation states. Under unfluidization state, E was 0, V_{pmax} was 4867 ml, and τ_{max} was 844–3800 s. Under fluidization state, E , V_{pmax} , and τ_{max} were 5.28%–255.69%, 1368–4559 ml, and 104–732 s, respectively. Under transportation state, washout of granular sludge occurred and destabilized the SAB. During stable running of SAB under fluidization state, E correlated positively with superficial gas and liquid velocities (u_g and u_l), while V_{pmax} and τ_{max} correlated negatively. For E and V_{pmax} , the sensitivities of u_g and u_l were close to each other, while for τ_{max} , the sensitivity of u_l was greater than that of u_g . The prediction from these models was a close match to the experimental data.

Key words: Anaerobic bioreactor, Expansion behaviors, Bed expansion ratio, Fluidization state, Sensitivity analysis
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1 Introduction

A range of high-rate anaerobic fluidized-bed (AFB) reactors such as upflow anaerobic sludge blanket (UASB), upflow-staged sludge bed (USSB), expanded granular sludge bed (EGSB), internal circulation (IC), and inverse anaerobic fluidized bed (IAFB) reactors, and two high-rate anammox reactors [sequencing batch reactor (SBR) and an upflow biofilter (UBF)] have been investigated (Lettinga *et al.*, 1991; Lens *et al.*, 1998; Chen *et al.*, 2009; Pereboom and Vereijken, 1994; Sownmeyan and Swaminathan, 2008a; Jin *et al.*, 2008). At the industrial scale, AFB reactor can bear very high loading rates, up to

40 g COD/(L·d) (Heijnen *et al.*, 1989). Our preliminary laboratory scale studies revealed that the ability of AFB reactor was even greater than that. The organic loading rate (OLR) and volumetric biogas production (VBP) of the spiral automatic circulation (SPAC) reactor in our laboratory could reach up to 306 g COD/(L·d) and 131 L/(L·d) (Zheng *et al.*, 2008; Chen *et al.*, 2008), respectively. However, high OLR and VBP can result in high bed expansion ratio that changes not only bed sludge content but also contact time between sludge and liquid. A bed sludge content correlates positively with reaction rate, while it is opposite when it comes to bed contact time between sludge and the generation yield of reactants. The objective of this study was to investigate bed expansion behavior of super-high-rate anaerobic bioreactor (SAB) along with its relation with superficial liquid velocity and superficial gas velocity. Such investigation may be of some interest for further optimizing the operations and designs of such reactors.

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2 Materials and methods

2.1 Bed expansion behavior model

Bed expansion behavior in reactors results from synergistic effect of superficial liquid velocity (u_l , led by OLR) and superficial gas velocity (u_g , led by VBP), which includes bed unfluidization, fluidization, and transportation states. The fluid superficial velocity (u) in bed can be obtained according to the vector relation: $\mathbf{u}=\mathbf{u}_l+\mathbf{u}_g$. Generally, we consider $u=u_l+u_g$ because directions of \mathbf{u} , \mathbf{u}_l and \mathbf{u}_g are all up. When u is low, the drag force for granular sludge in the bed is less than its weight; therefore, the bed is under unfluidization state. When u is larger than minimum fluidization velocity (u_{mf}), the drag force approaches to the weight. Consequently, the granular sludge begins to loosen, bed porosity increases, and the bed expands and comes into fluidization state. When u further increases to the minimum transportation velocity (u_{mt}), the drag force for granular sludge in the bed is more than its weight, the bed enters transportation state, and washout of the granular sludge occurs. When SAB experiences three expansion states, its behavior can be expressed through its characteristics: bed expansion ratio (E), maximum bed sludge content (V_{pmax}), and maximum bed contact time between sludge and liquid (τ_{max}).

2.1.1 Bed expansion ratio

Bed expansion ratio E can be calculated using the following equation:

$$E=(H_{gls(ls)}-H_u)/H_u\times 100\%, \quad (1)$$

where $H_{gls(ls)}$ represents the bed expansion height (mm) at gas-liquid-solid tri-phasic or liquid-solid bi-phasic condition; H_u represents the sludge height (mm) under unfluidization state.

If the total sludge mass loaded into the reactor remains constant, Eq. (2) can be established:

$$H_{gls(ls)}A\varepsilon_s=H_uA(1-\varepsilon_0), \quad (2)$$

where A is the cross-sectional area (mm^2) of the reactor column, ε_0 is bed porosity in the beginning (dimensionless), and ε_s is the granular sludge holdup (dimensionless). The bed expansion ratio can be transformed into Eq. (3) using Eqs. (1) and (2):

$$E=(1-\varepsilon_0-\varepsilon_s)/\varepsilon_s\times 100\%. \quad (3)$$

Thus, E for SAB is a function of ε_0 and ε_s , which vary with OLR and VBP. So E under the tri-phasic state of SAB is different.

1. E for the unfluidization state

When superficial liquid velocity u_l is less than the minimum superficial fluidization velocity u_{mf} , the bed is under unfluidization state, where the sludge holdup keeps constant and the bed expansion ratio is zero. Based on statics equilibrium principles (Huang and Wu, 1996), u_{mf} can be expressed under the liquid-solid bi-phasic condition as follows:

$$u_{mf}=\frac{\varepsilon_0^3d_p^2(\rho_p-\rho_l)g}{150\mu(1-\varepsilon_0)}, \quad (4)$$

where d_p (mm) is particle diameter, ρ_p (g/cm^3) is particle density, ρ_l (g/cm^3) is liquid density, g (cm/s^2) is acceleration of gravity, and μ [$\text{g}/(\text{cm}\cdot\text{s})$] is dynamic viscosity.

2. E for the fluidization state

When the superficial liquid velocity u_l is between the minimum fluidization velocity u_{mf} and the minimum transportation velocity u_{mt} , the bed is under fluidization state. The following relationship holds among individual holdups:

$$\varepsilon_g+\varepsilon_l+\varepsilon_s=1, \quad (5)$$

in which ε_g , the gas holdup (dimensionless), can be calculated using the correlation equation proposed by Chern *et al.* (1984) as follows:

$$\varepsilon_g=0.098(u_l/10)^{-0.98}(u_g/10)^{0.7}. \quad (6)$$

In the present study, large bioparticles ($d_p=\Phi 1.14$ mm) were observed in the SAB. Thus, the generalized model was simplified by setting $x=0$ (ignoring the friction resistance caused by liquid wake) as a common assumption (Yu and Rittmann, 1997; Wu *et al.*, 2006), as shown in the following equation:

$$\varepsilon_1=\left(\frac{u_l-ku_g}{v_i}\right)^{1/n}(1-\varepsilon_g-k\varepsilon_g)^{1-(1/n)}+k\varepsilon_g, \quad (7)$$

where n is bed-expansion index (dimensionless) and k

is mean volume ratio of wakes to bubbles (dimensionless). k can be calculated using the following equation:

$$k=0.211(u_t/10)^{1.293}(u_g/10)^{-0.739}. \quad (8)$$

v_i (mm/s) represents terminal settling velocity of a particle (with diameter d_p) in the reactor with equivalent diameter D :

$$v_i = u_t 10^{-d_p/D}, \quad (9)$$

where u_t (mm/s) represents terminal settling velocity of a particle without wall effect.

If both u_g and ε_g are set at zero, Eq. (7) can be simplified to:

$$u_t = v_i \varepsilon_1^n. \quad (10)$$

n of Eq. (10) and u_t of Eq. (9) can be obtained by using the correlation equations proposed by Khan and Richardson (1987; 1989), as shown in the following equations:

$$\frac{4.8-n}{n-2.4} = 0.043Ga^{0.57} [1 - 1.24(d_p/D)^{0.24}], \quad (11)$$

$$u_t = \frac{\mu}{\rho_1 d_p} (2.33Ga^{0.018} - 1.53Ga^{-0.016})^{13.3}, \quad (12)$$

where μ [g/(cm·s)] represents dynamic viscosity, and Ga represents Galileo number (dimensionless) and $Ga = \rho_1 d_p^3 (\rho_p - \rho_1) g / \mu^2$.

Thus, k , n , and v_i must be calculated first, followed by the calculation of ε_g using Eq. (6) and the calculation of ε_1 using Eq. (7). Thereafter, the bed expansion ratio E can be calculated using Eqs. (3) and (5).

3. E for the transportation state

When superficial liquid velocity u_1 is larger than the minimum superficial transportation velocity u_{mt} , the bed is under transportation state. u_{mt} can be calculated theoretically under liquid-solid bi-phasic condition, as shown in the following equation:

$$u_{mt} = (1 - \varepsilon_s) u_t. \quad (13)$$

Thus, the bed-expansion ratio E can also be calculated using Eqs. (5)–(12) theoretically if the height of the bed is high enough because the transportation state is just a critical state of the fluidization state.

2.1.2 Maximum bed sludge content

If bed expansion ratio remains constant, sludge content is maximized when the effective volume of the bed is filled with granular sludge. Thus, the maximum bed sludge content V_{pmax} can be expressed as follows:

$$V_{pmax} = V_0 \varepsilon_s, \quad (14)$$

where, V_0 (ml) represents the effective volume of the bed.

Thus, V_{pmax} can be calculated using Eq. (14) and Eqs. (5)–(12).

2.1.3 Maximum bed contact time between sludge and liquid

If bed expansion ratio remains constant, the sludge content increases, and the maximum bed contact time between sludge and liquid τ_{max} will become long. The τ_{max} is maximum at the maximum sludge content. Under these conditions, τ_{max} can be expressed in the following form:

$$\tau_{max} = H_0 A \varepsilon_1 / u_t A = H_0 \varepsilon_1 / u_t, \quad (15)$$

where H_0 (mm) represents the height of the bed.

Thus, τ_{max} can be calculated using Eq. (15) and Eqs. (5)–(12).

2.2 Experimental set-up

The schematic diagram of the experiment is presented in Fig. 1. The anaerobic bioreactor was fed with an aqueous solution of sulfuric acid (0.5%, w/w). Gas generation was performed by chemical reaction between sulfuric acid and saturated sodium bicarbonate. The bioreactor had five ports evenly distributed along the bed height to simulate biogas production, i.e., CO₂ effervescence, of SAB. The bed was filled with anaerobic granular sludge to a height as per requirement of the experiment. Anaerobic granular sludge in SAB was adopted to simulate the working condition of processes.

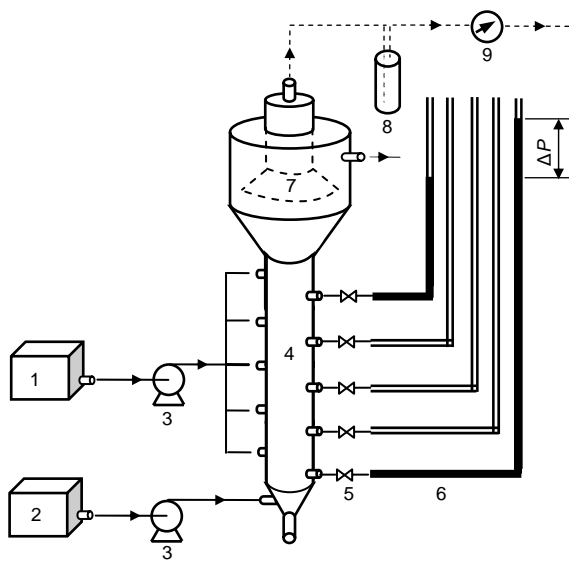


Fig. 1 Sketch of experimental apparatus

1: tank for saturated NaHCO₃; 2: tank for H₂SO₄ (0.5%, w/w); 3: pump; 4: reactor; 5: valve; 6: L-type tube; 7: tri-phasic separator; 8: water seal; 9: wet gas-flow meter

2.3 Anaerobic granular sludge and correlative parameters

Anaerobic granular sludge loaded into SAB was collected from a papermaking wastewater treatment plant. The granular sludge averaged $\Phi 1.14$ mm in diameter (d_p) and had a dry density (ρ_p) of 1.052 g/cm³. The SAB (Fig. 1) had the following dimensions: bed (column) diameter (D) $\Phi 100$ mm, bed height (H_0) 1000 mm, and separation unit diameter and height $\Phi 280$ mm and 300 mm, respectively. The upper and lower end diameters of tri-phasic separator equipped in separation unit were $\Phi 50$ mm and $\Phi 180$ mm, respectively. The working and column volumes of reactor were 20000 ml and 7850 ml, respectively. The total volume and height of reactor were 28000 ml and 1600 mm, respectively. Other characteristics were: liquid dynamic viscosity $\mu=8.6 \times 10^{-3}$ g/(cm·s), liquid density $\rho_l=1000$ g/cm³, incipient bed porosity $\varepsilon_0=0.38$, acceleration of gravity $g=980$ cm/s², and ranges of superficial liquid and gas velocities (u_l and u_g) 0–1.83 mm/s and 0–0.67 mm/s, respectively.

2.4 Analytical procedures

The granular sludge was observed and photographed under microscope (Leica DFC300FX, Germany), and its diameter was analyzed by supporting image analysis software (Leica Qwin V3, Germany).

The density of granular sludge and the incipient bed porosity were determined according to Summerfelt (2006). The superficial liquid velocity could be calculated by the influent volume in relation to gas production time. The superficial gas velocity was determined by gas flow meter (BSD 0.5, China) and the liquid dynamic viscosity was determined by rotating viscometer (NDJ-1, China). The height of granular sludge in bed was determined by a ruler with precision of 1 mm.

3 Results and discussion

3.1 Bed expansion behavior under unfluidization state

OLR of bioreactor was low when bed expansion behavior was studied under unfluidization state. The minimum fluidization velocity $u_{mf}=0.45$ mm/s could be calculated according to Eq. (4), where $\varepsilon_0=0.38$, $d_p=\Phi 1.14$ mm, $\rho_p=1.052$ g/cm³, $\rho_l=1000$ g/cm³, $g=980$ cm/s², and $\mu=8.6 \times 10^{-3}$ g/(cm·s). The granular sludge held nearly still when superficial velocity u was lower than 0.45 mm/s, and bed expansion ratio E was 0. According to Eq. (14), the maximum bed sludge content $V_{pmax}=4867$ ml could be calculated, where $V_0=7850$ ml, $\varepsilon_0=0.38$, and $\varepsilon_s=1-\varepsilon_0$. By using Eq. (5), where we could ignore the gas holdups ($\varepsilon_g=0$) because the OLR under the unfluidization state was very low and the gas production was very few, we have $\varepsilon_l=1-\varepsilon_s$. Together with $\varepsilon_0=1-\varepsilon_s=0.38$ and $H_{glS}=H_{umax}=1000$ mm, Eq. (15), the maximum bed contact time between sludge and liquid (τ_{max}) under bed unfluidization state, could be replaced in the following equation:

$$\tau_{max}=380/u_l. \quad (16)$$

According to Eq. (16), influence curve of u_l to τ_{max} is shown in Fig. 2. From Fig. 2, τ_{max} decreased from 3800 s to 844 s as u_l increased from 0.1 mm/s to 0.45 mm/s (with hydraulic retention time between 10000 s and 2222 s).

3.2 Bed expansion behavior under fluidization state

OLR of bioreactor was high or even super-high when bed expansion behavior was studied under

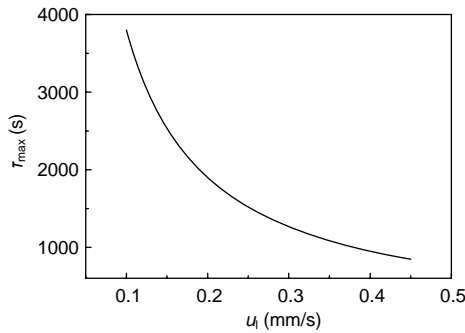


Fig. 2 Influence of superficial liquid velocity on maximum bed contact time between sludge and liquid under unfluidization state

fluidization state. When u was above the minimum fluidization velocity 0.45 mm/s, the unfluidization state of granular sludge was changed into the fluidization state.

3.2.1 Influence of superficial liquid velocity on bed expansion behavior under fluidization state

By combining the Eqs. (3), (5), (6), (9) and (10) where the estimation of n and u_t values is based on Eqs. (11) and (12), respectively, having $\varepsilon_0=0.38$, $d_p=\Phi 1.14$ mm, and $D=\Phi 100$ mm, the bed expansion ratio under liquid-solid bi-phasic fluidization state ($\varepsilon_g=0$) can be translated as follows:

$$E = (0.435u_l^{0.29} - 0.38) / (1 - 0.435u_l^{0.29}) \times 100\% . \quad (17)$$

On the basis of Eq. (17) and the bed expansion ratio model of the fluidization state, Fig. 3a depicts the influence of superficial liquid velocity on bed expansion ratio and the maximum bed sludge content. The bed expansion ratio model is a close match to the experimental data. The plot indicates that bed expansion ratio E increased from 0 to 42.7% and from 11.7% to 47.4% under $u_g=0$ and $u_g=0.12$ mm/s, respectively, as u_l increased. On the contrary, the maximum bed sludge content decreased as u_l increased, in which values decreased from 4867 ml to 3411 ml and from 4295 ml to 3293 ml under $u_g=0$ and $u_g=0.12$ mm/s, respectively. Fig. 3b depicts the effect of superficial liquid velocity on maximum bed contact time between sludge and liquid; the τ_{max} decreased from 726 s to 263 s and from 767 s to 266 s under $u_g=0$ and $u_g=0.12$ mm/s as u_l increased.

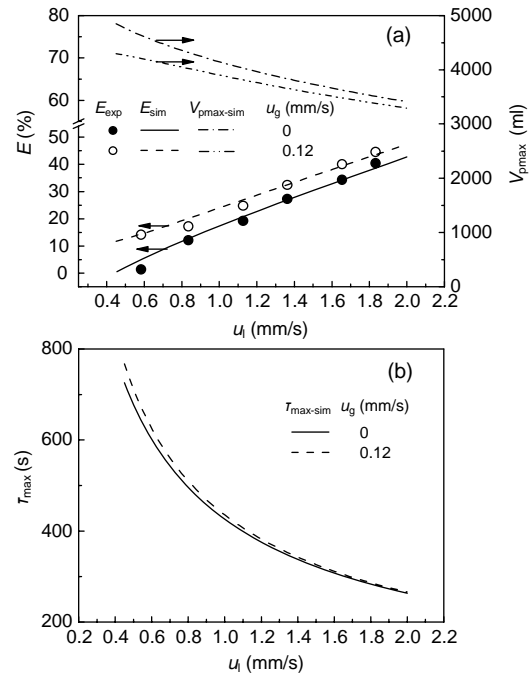


Fig. 3 Influence of superficial liquid velocity on bed expansion ratio and maximum bed sludge content (a) and maximum bed contact time between sludge and liquid (b) under fluidization state

3.2.2 Influence of superficial gas velocity on bed expansion behavior under fluidization state

Fig. 4a depicts the effect of superficial gas velocity on bed expansion ratio and the maximum bed sludge content. A reasonable agreement existed between the experimental data and the bed expansion ratio model. What can be seen in this plot is that bed expansion ratio E increased as u_g was increased for two data sets, in which values increased from 16.3% to 52.7% and from 22.2% to 42.9% under $u_l=0.51$ mm/s and $u_l=0.84$ mm/s, respectively. In contrast, the maximum bed sludge content decreased from 4187 ml to 3187 ml and from 3982 ml to 3407 ml under $u_l=0.51$ mm/s and $u_l=0.84$ mm/s as u_g increased. Meanwhile, Fig. 4b depicts the effect of superficial gas velocity on the maximum bed contact time between sludge and liquid τ_{max} ; τ_{max} decreased from 662 s to 561 s and from 476 s to 432 s under two data sets ($u_l=0.51$ mm/s and $u_l=0.84$ mm/s) as u_g increased.

3.2.3 Influence of superficial liquid and gas velocities on bed expansion behavior under fluidization state

The influence curves of superficial liquid and gas

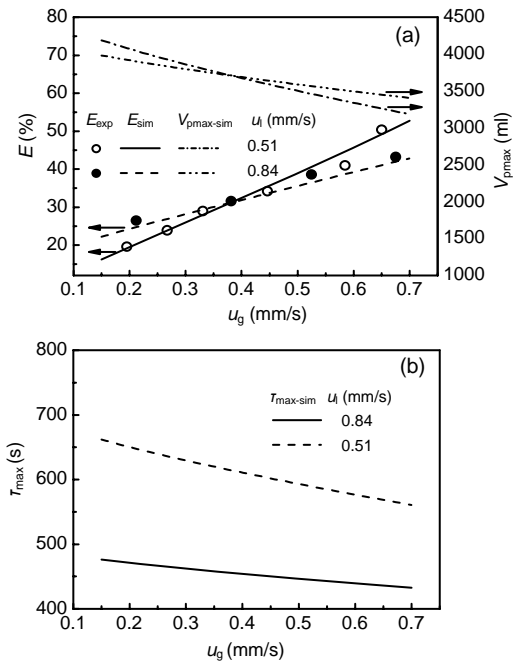


Fig. 4 Influence of superficial gas velocity on bed expansion ratio and maximum bed sludge content (a) and maximum bed contact time between sludge and liquid (b) under fluidization state

velocities on bed expansion behavior are shown in Fig. 5. Bed expansion ratio E increased from 5.28% to 159.55%, while the maximum bed sludge content V_{pmax} decreased from 4559 ml to 1878 ml and the maximum bed contact time between sludge and liquid τ_{max} decreased from 732 s to 110 s when $u_g=0.10$ mm/s. Bed expansion ratio E decreased initially, and then increased with the increase of u_l , varying from 255.69% to 62.20% when $u_g=0.20$ mm/s. Similar to the result of E , V_{pmax} and τ_{max} increased first, and then decreased as u_l increased, varying from 1368 ml to 3001 ml and from 385 s to 104 s, respectively. Hence, when u_l and u_g were varied synchronously, the changed range of bed expansion ratio E changed from 255.69% to 5.28%, the maximum bed sludge content V_{pmax} changed from 1368 to 4559 ml (as shown in the shaded part of Fig. 5a), and the maximum bed contact time between sludge and liquid τ_{max} changed from 104 s to 732 s (as shown in the shaded part of Fig. 5b). Fig. 5 also shows that when superficial liquid velocity u_l was larger, bed expansion behavior under different u_l and u_g tended to be more uniform. When superficial liquid velocity u_l was close to the minimum transportation velocity u_{mt} , values for E ,

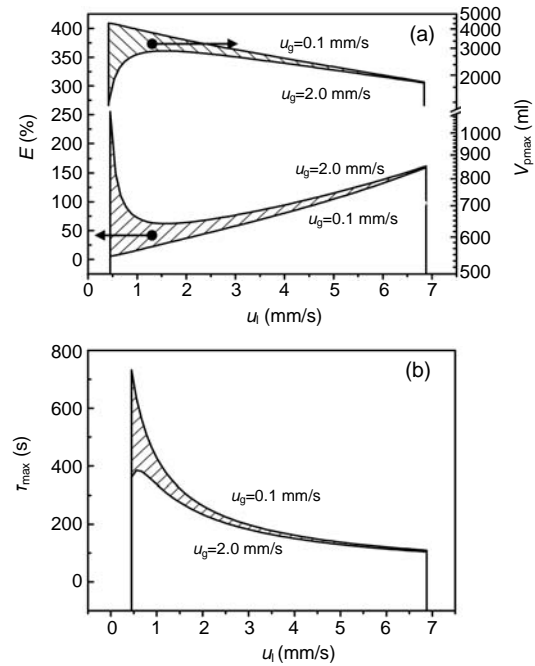


Fig. 5 Influence of superficial liquid and gas velocities on bed expansion ratio and maximum bed sludge content (a) and maximum bed contact time between sludge and liquid (b) under fluidization state

V_{pmax} and τ_{max} approached 160%, 1860 ml and 104 s (with hydraulic retention time between 145 s and 2222 s), respectively.

3.3 Bed expansion behavior under transportation state

Bed expansion behavior changes into transportation state when superficial liquid velocity u_l of bioreactor exceeds the upper limit. According to Eq. (13) and combining Eqs. (5)–(12), where u_t was based on Eq. (12) and ε_s was based on Eqs. (5)–(11), together with corresponding parameters, the minimum transportation velocity u_{mt} 6.88 mm/s was obtained. When superficial velocity u exceeded 6.88 mm/s, the fluidization state of granular sludge transitioned into the transportation state. Thus, washout of the granular sludge occurred and destabilized the SAB. Thereby, values for E , V_{pmax} , and τ_{max} have no utility values in practice under the transportation state.

3.4 Parametric sensitivity analyses of bed expansion behavior under fluidization state

SAB can operate effectively and stably under bed fluidization state, which can maintain a fixed bed

expansion ratio and provide good hydrodynamic behavior (Diez Blanco *et al.*, 1995; Sowmeyan and Swaminathan, 2008b). Therefore, the sensitivity analyses of main parameters (X) such as u_l and u_g for bed expansion behavior under fluidization state were performed on the basis of the following parameter values: $u_l=2.00$ mm/s, $u_g=2.00$ mm/s, $d_p=\Phi 1.14$ mm, $D=\Phi 100$ mm, $\rho_p=1.052$ g/cm³, and ε_g , k , v_i , n , and u_t obtained by using Eqs. (6), (8), (9), (11) and (12), respectively. E , V_{pmax} and τ_{max} were regarded as object values, where u_l and u_g varied within a range of $\pm 50\%$. When $u_l=1.00$ – 3.00 mm/s and $u_g=1.00$ – 3.00 mm/s, sensitivities (S_R) of E , V_{pmax} and τ_{max} can be calculated using Eq. (18) in the following form (Zheng and Feng, 2006):

$$S_R = \frac{Y_i - Y_b}{Y_b} \bigg/ \frac{X_i - X_b}{X_b}, \quad (18)$$

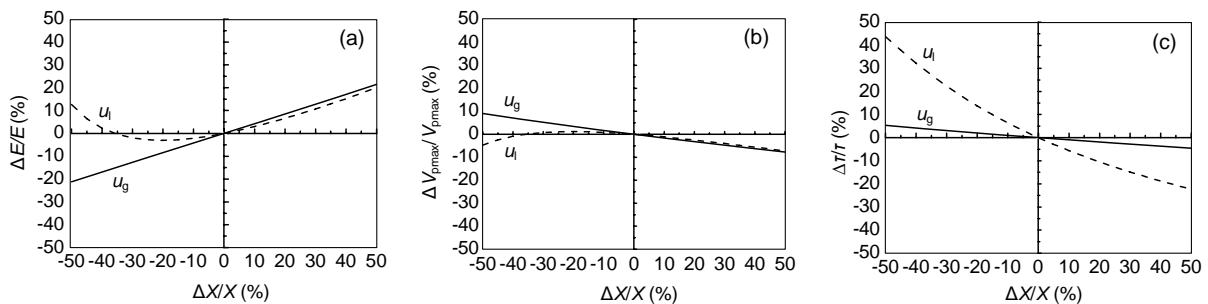


Fig. 6 Parametric sensitivity analyses of bed fluidization state on bed expansion ratio (a), maximum bed sludge content (b), and maximum bed contact time between sludge and liquid (c)

4 Conclusion

Bed expansion behavior of SAB was systematically investigated by analysis of the results obtained in this research. Under unfluidization state, u was less than 0.45 mm/s; E was 0; V_{pmax} was 4867 ml, and τ_{max} was 844–3800 s (with hydraulic retention time 2222–10000 s). Under fluidization state, u ranged 0.45 mm/s to 6.88 mm/s; and E , V_{pmax} , and τ_{max} were 5.28%–255.69%, 1368–4559 ml, and 104–732 s (with hydraulic retention time between 145 s and 2222 s), respectively. Under transportation state, u was larger than 6.88 mm/s and washout of granular sludge occurred and destabilized the SAB. The predictions from these models agreed well with the experimental data; thus, they may be used to optimize the operations and designs of SAB. Under bed

fluidization state of SAB, E correlated positively with u_g and u_l , while V_{pmax} and τ_{max} correlated negatively with u_g and u_l . For E and V_{pmax} , the sensitivities of u_g and u_l were close to each other, while for τ_{max} , the sensitivity of u_l was more than that of u_g .

where S_R represents sensitivity (dimensionless); Y_i represents E , V_{pmax} , or τ_{max} of different parameters; Y_b represents the basic value of E , V_{pmax} , or τ_{max} ; X_i represents the different parameter values; X_b represents the basic parameter value. It is evident from Fig. 6 that, for bed expansion ratio E and the maximum bed sludge content V_{pmax} , the sensitivities of superficial liquid and gas velocities were close to each other (Figs. 6a and 6b), while for the maximum bed contact time between sludge and liquid τ_{max} , the sensitivity of superficial liquid velocity was higher than that of superficial gas velocity (Fig. 6c), which guided us to better operate the SAB. For example, if we wanted to enhance removal efficiency of the SAB by prolonging τ_{max} , we took some measures to reduce the superficial liquid velocity firstly as soon as possible, but not the superficial gas velocity.

fluidization state of SAB, E correlated positively with u_g and u_l , while V_{pmax} and τ_{max} correlated negatively with u_g and u_l . For E and V_{pmax} , the sensitivities of u_g and u_l were close to each other, while for τ_{max} , the sensitivity of u_l was more than that of u_g .

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