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Brief communication

Prediction of flooding velocity in a trickle bed

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1. Introduction

Flooding is a kind of hydrodynamic phenomenon to be prevented in the operation of packed-columns which are extensively used in absorption and distillation, and in empty tubes mainly used in reflux condensers where the condensate moves downward countercurrently with respect to the uprising vapor. However, flooding has not been studied so much in a trickle bed reactor up to now, since trickle beds are usually packed with small size catalysts of less than 5 mm, which gives relatively small flow passages of less than 3 mm and leads to a strong interfacial friction between the upward moving gas and the downward moving liquid, and thus flooding occurs easily. Therefore, trickle-bed reactors are normally operated in the concurrent flow direction to avoid flooding. However, with the rapid development of advanced reaction engineering technology such as catalytic distillation, countercurrent hydrodesulfurization in production of ultra clean diesel fuel (Cheng et al., 2004), etc., countercurrent operation of a trickle bed has become an important subject to be studied.

Since there is no available flooding prediction model for a trickle bed, the results derived from the study of vertical tubes and packed-columns should be considered as the starting point. This is in spite of the difference between a trickle bed and an empty tube; yet a trickle bed can be simplified to a certain degree as a bundle of tubes. Moreover, on the other hand, the flooding velocity

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in narrow channels with hydraulic diameter even down to 3 mm could be accurately predicted (Souidi and Bontemps, 2001). Therefore, to predict the flooding velocity in a trickle bed, the flooding prediction models that have been established both in a tube and in a packed-column should be considered first, and then find a proper method to improve it once the model prediction deviates from the experimental data obviously.

2. The flooding model

2.1. Evaluation on the current models

2.1.1. The tube model

Tube diameter is the most important parameter related to flooding. Jayanti et al. (1996) and Vijayan et al. (2001) have found from analytical and experimental studies that flooding in a small diameter tube of less than 30 mm is induced by the upward transport of waves, whereas in large diameter tubes with diameters above 65 mm it is due to the entrainment and carry over of droplets. Fiedler et al. (2002) studied the flooding in small-scale passages with hydraulic diameter between 3 and 10 mm and used the Wallis equation to relate the flooding velocities of the two fluids

$$(u^*_{\mathrm{G,fl}})^{1/2} + C_1(u^*_{\mathrm{L,fl}})^{1/2} = C_2 \tag{1}$$

where, $C_1 = 1$ and $C_2 = 0.725$ are determined from flooding experiments for a vertical tube, and $u^*_{\mathrm{G,fl}}$ and $u^*_{\mathrm{L,fl}}$ are the dimensionless superficial flooding velocities of the gas and liquid phases defined as follows:

$$u^*_{\mathrm{G,fl}} = \frac{u_{\mathrm{G,fl}}\rho_{\mathrm{G}}^{1/2}}{[gd_{\mathrm{h}}(\rho_{\mathrm{L}} - \rho_{\mathrm{G}})]^{1/2}} \tag{2}$$

$$u^*_{\mathrm{L,fl}} = \frac{u_{\mathrm{L,fl}}\rho_{\mathrm{L}}^{1/2}}{[gd_{\mathrm{h}}(\rho_{\mathrm{L}} - \rho_{\mathrm{G}})]^{1/2}}. \tag{3}$$

In above equations, d_{h} is the hydraulic diameter of the tube in m, $u_{\mathrm{G,fl}}$ and $u_{\mathrm{L,fl}}$ are the superficial flooding velocities of the gas and the liquid fluids in m s^{-1} ρ_{G} and ρ_{L} denote the gas and liquid density in kg m^{-3}, g is gravitational acceleration in m s^{-2}. To employ Eqs. (1)–(3) to predict the flooding velocity in a trickle bed, the tube hydraulic diameter d_{h} should be defined as the equivalent trickle bed diameter:

$$d_{\mathrm{h}} = \frac{4\varepsilon}{a} \tag{4}$$

where a is the volumetric external surface area of the packing based on the volume of the reactor, and ε is the void faction of the trickle bed.

2.1.2. The packed-column model

Flooding in packed-columns has been described by several empirical and theoretical flooding models. The former one includes the well recognized GPDC (generalized pressure drop correlation) method proposed by Sherwood et al. (1938) and improved largely by Eckert (1966), Kessler and Wankat (1988) and Leva (1992). Among the theoretical models are the Suspended-Droplet model by Mackowiak (1990) and the Double-Film model by Hutton et al. (1974). However, these methods cannot be conveniently used since the flooding cannot be predicted a priori from the geometrical properties of the packing. In overcoming this limitation, Kuzniewska-Lach (1999) has developed a flexible and fairly accurate correlation based on a variety of literature data, especially that of Mackowiak (1990). For the air–water system, the flooding velocity of the gas was predicted through the following equation:

$$u_{\mathrm{G,fl}} = A\varepsilon\left(\frac{a}{\varepsilon^3}\right)^B \tag{5}$$

where A and B are empirical parameters determined from Eqs. (6) and (7), a is the specific surface area of the packing per unit column volume, and ε the void fraction of the column.

$$A = 1\,608\,932u_{\mathrm{L,fl}}^3 - 7486.1u_{\mathrm{L,fl}}^2 + 237.3u_{\mathrm{L,fl}} + 15.2 \tag{6}$$

$$B = -144.6u_{\mathrm{L,fl}}^2 - 9.5u_{\mathrm{L,fl}} - 0.273 \tag{7}$$

It is realized from Eq. (5) that, at a given liquid flow rate, the flooding gas velocity is only determined by the packing property which is characterized by the packing factor a/ε^3.

2.1.3. Experimental evaluation of the two models

A plexiglass column of ID 0.28 m and 2.0 m in height was used to provide experimental data to evaluate the validity of the two flooding models. Two kind of packing materials which are quite different in geometry, i.e., ceramic Raschig rings and ceramic spheres, were used so as to cover a wide variety of packing properties. The size of the Raschig ring was measured to be 6 mm × 4 mm × 4 mm (outside diameter × inside diameter × height), and the diameter of the spherical particle was 4.47 mm. Detailed information about the packing and the trickle bed is listed in Table 1.

Table 1
Packings used in the trickle bed (this work)

Packing type*	a (m^2/m^3)	ϵ	α/ε^3 (m^2/m^3)	d_p (mm)	d_h (mm)
Ceramic sphere	778.40	0.42	10506.43	4.50	2.16
Ceramic short Raschig ring	865.80	0.63	3462.55	6 mm × 4 mm	2.91
Mixed packing 1	955.42	0.45	10484.72	Not defined	1.88
Mixed packing 2	789.62	0.60	3655.65	Not defined	3.04
Mixed packing 3	847.09	0.61	3731.99	Not defined	2.88

* The packings are defined as: (ceramic sphere) nominal diameter of 4.50 mm; (ceramic short Raschig ring) 6 mm in outside diameter and 4 mm in length; (mixed packing 1) composed of 30.54 vol% spheres and 69.46 vol% Raschig rings; (mixed packing 2) Composed of 53.69 vol% spheres and 46.31 vol% Raschig rings; (mixed packing 3) composed of 76.85 vol% spheres and 23.15 vol% Raschig rings.

Herskowitz and Smith (1978) suggested from their experimental work that, if the bed-to-particle diameter ratio is larger than 18, the liquid flow distribution over the cross section of the bed can be regarded uniform. Therefore, our flooding data were obtained under this ideal hydrodynamic condition. As such, the uncertainty factor could be reduced to the minimum which could properly enable the flooding data analysis and model evaluation. In this work, the gas flooding velocity was defined as the point at which liquid begins to accumulate over the top of packing layer, and it was found to be consistent with the pressure drop method and the liquid holdup method.

Unfortunately, it was shown from Fig. 1 that the flooding prediction from both models deviates substantially from the experimental data. Yet, the packed-column flooding model obviously yields a much less discrepancy than does the tube model. It therefore implies that the geometrical similarity of the packed-column is an important factor in providing a reasonable basis for flooding behavior study in a trickle bed.

2.2. Modification of the packed-column flooding prediction model

It is reasonable to believe that the most possible reason for the deviation of the flooding velocity prediction from the experimental measurement may be due to the "channel size effect", since the real channel size available for fluid flow in a trickle bed is possibly much different from that in a packed-column or in an empty tube. To verify this speculation, the equivalent packed bed diameter d_h was calculated from Eq. (4) and was listed in Tables 1 and 2. It is found the value of d_h in a trickle bed is in the range of 1–3 mm, while in a packed-column it is between 10 and 50 mm. Therefore, considering the geometrical similarity between a trickle bed and a packed-column, the discrepancy in flooding velocity prediction of a trickle bed by using the packed-column model should be ascribed to the very large difference in the value of d_h. It is known flooding can be accurately predicted by the empty tube model down to 3 mm, which is of the same order in channel size in a trickle bed. The discrepancy induced by applying the empty tube model to a trickle

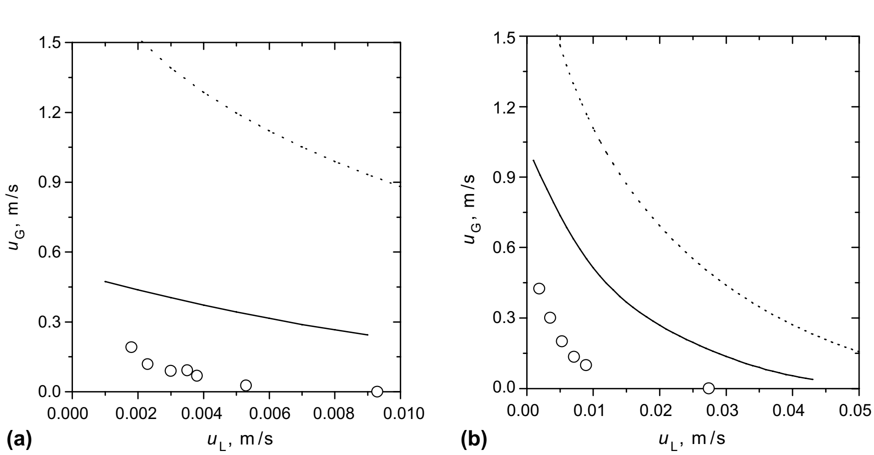

Fig. 1. Evaluation of literature correlations for flooding prediction in a trickle bed: (a) ceramic sphere and (b) short Raschig ring. (---) Tube model, (—) packed-column model and (○) experimental data.

Table 2
Packing geometrical parameters for a packed-column (from Mackowiak, 1990)

Packing type	a (m^2/m^3)	ϵ	α/ε^3 (m^2/m^3)	d_p (mm)	d_h (mm)
Metallic Pall ring	360.00	0.94	439.01	15.00	10.40
	215.00	0.94	257.21	25.00	17.53
	215.00	0.96	246.07	25.00	17.79
	145.00	0.95	170.19	35.00	26.15
	110.00	0.95	127.49	50.00	34.62
	105.00	0.97	115.05	58.00	36.95
	78.00	0.96	88.16	80.00	49.23
Plastic Pall ring	220.00	0.89	312.07	25.00	16.18
	160.00	0.90	215.86	35.00	22.63
	110.00	0.92	141.26	50.00	33.45
Ceramic Pall ring	220.00	0.73	565.53	25.00	13.27
	120.00	0.77	262.85	50.00	25.67
Ceramic Raschig ring	550.00	0.65	2002.73	8.00	4.73
	292.00	0.67	984.02	15.00	9.14
	177.00	0.69	531.83	25.00	15.66
	140.00	0.71	391.16	35.00	20.29
	98.00	0.73	251.92	50.00	29.80
Metallic Raschig ring	350.00	0.92	449.47	15.00	10.51
	220.00	0.92	282.53	25.00	16.73
	150.00	0.93	186.48	35.00	24.80
	110.00	0.95	128.30	50.00	34.55

bed is apparently caused by the differences in geometrical structure rather than in the channel size. Because of this we will not adopt the empty tube flooding model in the model modification study that is presented in the next paragraph.

As observed from Table 1, the flow channel size in a trickle bed is small—between 1 and 3 mm. Therefore the influence of liquid film thickness on the flow space reduction will be considerable (Cheng and Yuan, 1999). To exactly express the variation of flow space under liquid flow condition, the real bed void fraction ε' was introduced by subtracting the liquid holdup h_t from the void fraction ε of the dry bed

$$\varepsilon' = \varepsilon - h_t, \tag{8}$$

where the total liquid holdup h_t was estimated according to Stichlmair et al. (1989)

$$h_t = 0.555\left(\frac{au_L^2}{g\varepsilon^{4.65}}\right)^{1/3} \tag{9}$$

The effect of liquid holdup on the bed void fraction is shown in Fig. 2. It is found that as the liquid flow rate increases, the decrease in ϵ' is negligible for the large size packings, but it is significant for the small size ones.

By substituting ε in Eq. (5) for ε' as defined in Eq. (8), a modified flooding prediction equation is obtained for the trickle bed:

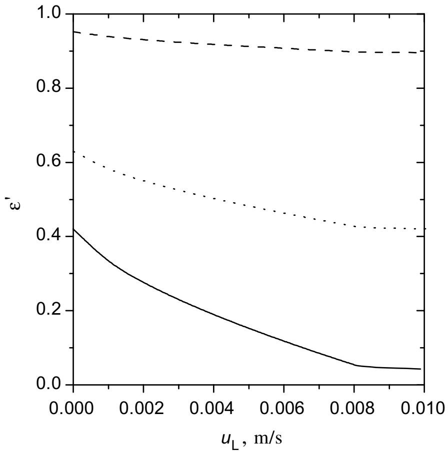

Fig. 2. Influence of liquid holdup on the void fraction of a packed bed. Symbol of lines: (—) ceramic sphere of 4.47 mm; (···) ceramic Raschig ring of 6 mm × 4 mm × 4 mm and (---) metallic Pall ring of 50 mm.

$$u_{G,fl} = A\varepsilon'\left(\frac{a}{\varepsilon'^3}\right)^B \tag{10}$$

2.3. Evaluation on the trickle bed flooding prediction model

The validity of Eq. (10) was first checked by flooding experiments packed with small size packings of the same kind, i.e., a ceramic sphere of 4.3 mm, or a short Raschig ring of 6 mm × 4 mm × 4 mm. It is found from Fig. 3 that the modified packed-column model Eq. (10) gives a fairly good prediction. To further evaluate the validity of Eq. (10), three kind of packing mixtures composed of ceramic spheres and short Raschig rings in different ratios were packed

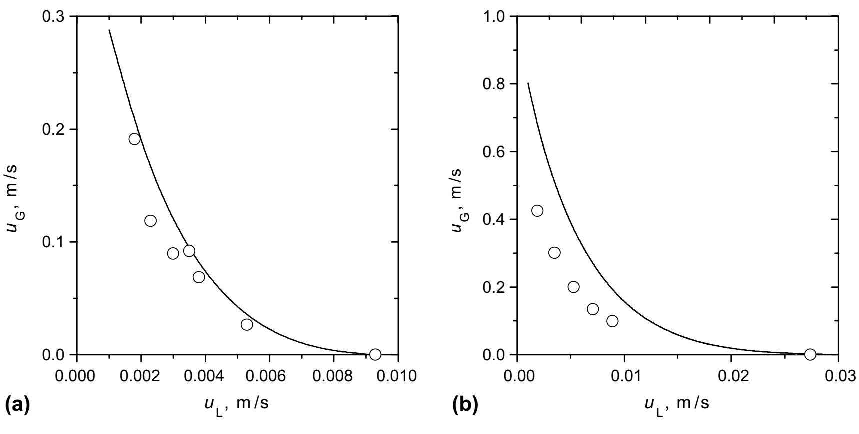

Fig. 3. Flooding velocity prediction in a trickle bed with the same kind of packing: (a) ceramic sphere and (b) short Raschig ring. (—) Packed-column model; (○) experimental data.

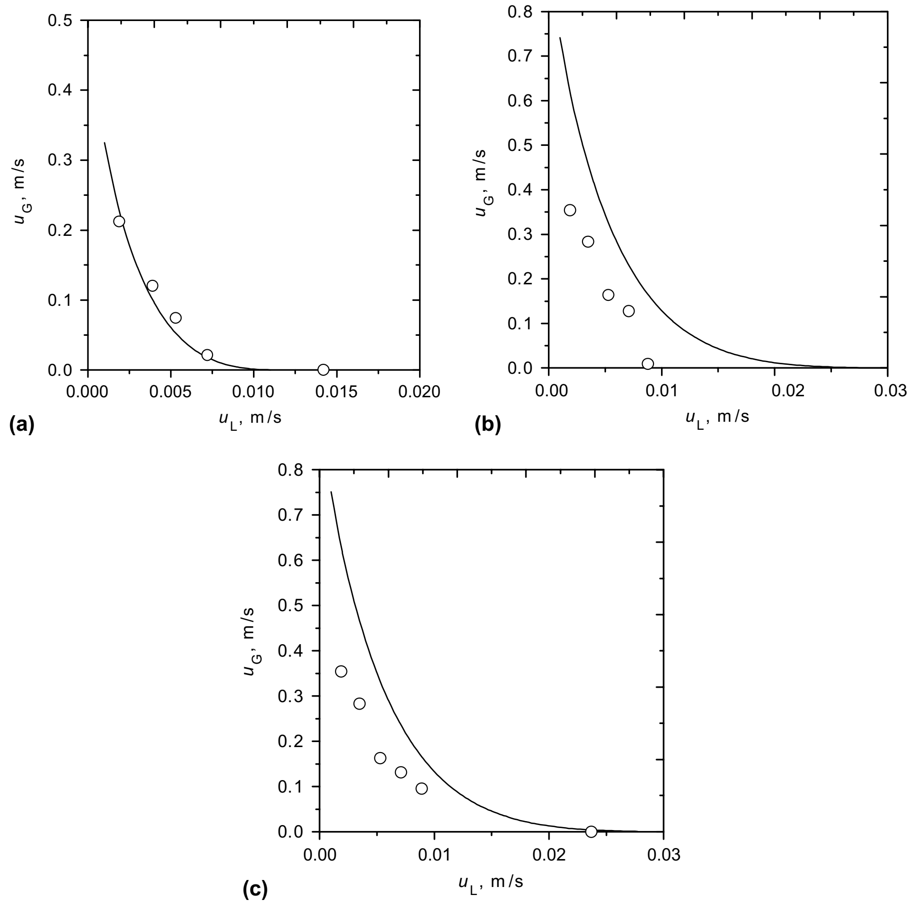

Fig. 4. Flooding velocity prediction in a trickle bed with different kind of packings: (a) 30.54 vol% spheres and 69.46 vol% Raschig rings; (b) 53.69 vol% spheres and 46.31 vol% Raschig rings and (c) 76.85 vol% spheres and 23.15 vol% Raschig rings.

again in the trickle bed, and the results are shown in Fig. 4. Apparently the flooding velocity prediction by the modified packed-column model Eq. (10) still works well, notwithstanding the differences in the bed packing geometry. This implies that the flooding model developed in this work is suitable to a wide variety of packings used in trickle-bed reactors.

3. Conclusions

The present work considered the empty tube model and the packed-column model as a basis for development a reliable model for flooding prediction in a trickle bed. Two kinds of geometrical effects were identified by means of experimental comparison with the model predictions. These effects are further incorporated into the modeling proposed in this paper:

1. *The geometrical similarity effect*. A packed column is more similar to a trickle bed than an empty tube. Therefore flooding can be better predicted with the packed-column model, which was therefore chosen as the basis for flooding prediction in a trickle bed.
2. *The geometrical size effect*. In spite of the geometrical similarity between a trickle bed and a packed column, the geometrical sizes of the two beds are much different. The influence of the liquid holdup on the flow space reduction, which was negligible in a packed column, was found significant in a trickle bed. A modified trickle bed flooding model having a decent predictive capacity has been developed by accounting for this geometrical size effect.

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