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Dynamic holdup in a countercurrent gas - flowing solids - packed bed contactors

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Abstract: Equations for the prediction of the holdup of dynamic solids in countercurrent gas – flowing solids – packed bed contactors are presented in this paper. The correlations do not require the use of parameters that need to be determined by experimental measurements in the actual system of interest. They could be used for a wide range of operational conditions, different packing types and a variety of flowing solids materials. The equations are compared with all available experimental data from the literature.

Keywords: multiphase contactors, gas – flowing solids – packed bed contactors, gas – trickle solids flow, dynamic solids holdup.

INTRODUCTION

The basic idea of countercurrent flow and contacting of gas and fine solids through packed beds was patented in 1948[1] and the first industrial realization occurred in 1965 (Compagnie de Saint Gobain).[2] In countercurrent gas – flowing solids – fixed bed contactors, the gas is introduced at the bottom and fine solid particles at the top of the column and they flow counter-currently inside a packed bed of solids.

Several advantages of this type of column have been reported[3–17]: low pressure drop, high heat and mass transfer rates and low axial mixing in both phases. Over the years researchers have paid considerable attention to the fluid dynamics of such systems,[3–14] and the heat and mass transfer.[8,15–17] Westerterp and colleagues[18,19] proposed the use of fine solids as a regenerative adsorbent, flowing through a bed of catalyst for methanol synthesis. Similar approaches were investigated in the work of Verver and van Swaaij for the catalytic oxidation of hydrogen sulfide,[20] and in the work of Kiel *et al.*, for the regenerative desulfurization of flue gases.[17,21]

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Fuid dynamic parameters are essential for the application of this type of multiphase contactor. Pressure drop, flowing solids holdup, residence time and backmixing are some of the properties that need to be reliably predicted for equipment design. In previous studies, three flow regimes were observed, as in gas – liquid systems: preloading, loading and flooding. The preloading and loading regimes differ in the concentration of flowing solids and in the dependence of pressure drop on the gas flow rate. When the terminal velocity of the gas approaches the velocity of the flowing solids, a sudden increase in the pressure drop occurs, together with an accumulation of solids at the top of the bed, which is characteristic of flooding.

Previous studies resulted in semi-empirical descriptions[6,10,23] or strictly empirical correlations[22] for the fluid dynamics parameters. Moreover, many of the authors tested their models on a limited number of experimental results, often just using their own experimental data.

There are many reasons for the lack of a fundamental theoretical equation, or a well tested empirical correlation. The complexity of the multiphase flow, with all the interactions between the phases is a major difficulty for the establishment of a reliable theoretical model. Accounting for the effects of particle shape, size, roughness, bed porosity distribution, *etc*., causes additional problems. The objective of this study was to obtain a reliable correlation for the prediction of dynamic holdup, based on all available data from the literature. Quantifying the dynamic solids holdup is an important step in the overall design of the equipment, because it is usually assumed that this is an active portion of the flowing solids when this serve as an adsorbent or catalyst. This correlation should be based on variables which are known in advance, without experiments, and should be easy to use.

DYNAMIC HOLDUP CORRELATION

The holdup of flowing solids is usually divided into two portions: dynamic and static. The latter represents the fraction of fine particles that rest on the packing elements. After shutting down the solids and gas flows, these particles will remain in the bed. Dynamic holdup represents the fraction of flowing solids that is suspended in the gas stream between the packing elements. These fine solid particles will flow out after the inlets for the gas and flowing solid are closed.

In most of the previous studies, the models for the prediction of dynamic holdup were semi-empirical. Roes and van Swaaij[6] proposed a model which was based on the mean particle velocity. They assumed that in the preloading zone the particle velocity is constant, as well as a slip velocity in the loading zone. Further studies[10,23] showed that this assumption was not correct. For the loading zone, Westerterp and Kuczynski[10] presumed that there are two contributions to dynamic holdup: the constant content of the trickles and the freely suspended ones. The fault of this model is that the contribution of freely suspended trickles are difficult to determine. Kiel[23] developed a model based on momentum balance of the solid particles. All the variables in their equation could be easily determined, except

TABLE I. Studies of the hydrodynamics of gas – flowing solids – packed bed contactors

No.	Symbol	Author	Column diameter/m	Packing type and size/mm	Void fraction of pack.	Solids phase type and size/μm	Solid mass flux kg/m^2s	Superficial gas velocity/m s^{-1}
1.	◇	Predojević[12]	0.111	Raschig rings, 12*12*2.4	0.61	Sand, 253	0.16–2.5	0.06–0.46
2.	■			Raschig rings, 30*30*2.3	0.85			
3.	▲			cer. beads, 19	0.47			
4.	×			Pall rings, 23*8*0.1	0.96			
5.	✱			Raschig rings, 12*12*2.4	0.61	Propant, 642	0.14–2.5	
6.	●			Raschig rings, 30*30*2.3	0.85			
7.	+			Cer. beads, 19	0.47			
8.	–			Pall rings, 23*8*0.1	0.96			
9.	○	Roes and van Swaaij[6;7]	0.076	Raschig rings, 10*10*1	0.80		1.1–6.0	0.02–0.19
10.	□			Pall rings, 15*15*2	0.86		1.3–6.0	0.02–0.23
11.	◆			Cylindrical screans 10*10*0.5	0.97			0.02–0.17
12.	Δ	Kiel[23]	0.10* 0.10	Regularly stacked packing, 3	0.61	Glass beads, 490	0.1–1	0.2–1
13.	—					Glass beads, 740	0.43–1	0.5–1
14.	◘	Verver and van Swaaij[20]	0.10* 0.10	Regularly stacked packing, 15*15		FCC, 70	0.03–0.8	0.08–0.2
15.	⊕ ∗	Benali[24]	0.114	Pall rings, 25*25	0.85	Zirconium, 1320	2.5–8.5	6.8–24.9

* All experimental data points in loading zone

for two empirical parameters: the initial solids velocity and a 'hydrodynamic effectiveness factor'. Although these models wee fundamentally based, they always required several empirical parameters for the prediction of dynamic houldup. Moreover, all of the these authors tested their models only on their own experimental results (the same results that were used to obtain the empirical parameters).

In this work, correlations for dynamic holdup are proposed which contain only variables that are known in advance. These are: superficial gas velocity, flowing solids flux, density and viscosity of the gas, density and mean diameter of the flowing solids column diameter, packing equivalent diameter and porosity of the bed. These operational conditions and system properties were grouped in dimensionless numbers.

The gas flow regime through the packed bed is presented, as usual, by particle the Reynolds number of the particles. The settling of the flowing solids under gravity and the gas resistance are presented by Archimedes number. A new dimensionless group was introduced to take into account the ratio of the kinetic energy of the flowing solids to the kinetic energy of the gas:

$$\frac{\rho_s u_s^2}{\rho\, u_g^2} \tag{1}$$

The velocity of the flowing solids can be found from:

$$u_s = \frac{S}{\rho_s} \tag{2}$$

so that the dimensionless number is:

$$\frac{S^2}{\rho_s \rho_g u_g^2} \tag{3}$$

The equivalent diameter of a packing particle takes into account the size and shape of the particles together with porosity and wall effects:

$$d_{eq} = \frac{6(1+\varepsilon)}{a + 4/D} \tag{4}$$

The sources of available experimental results are presented in Table I. On the basis of 542 experimental data points the following equation was obtained:

$$\beta_{dyn} = 6560.7\ Re_p^{1.29}\ Ar^{-1.01} \left(\frac{S^2}{\rho_s \rho_g u_g^2} \right)^{0.521} (d_s/d_{eq})^{2.57}\,(1-\varepsilon)^{1.52}\,\varepsilon^{0.933} \tag{5}$$

The comparison between the predicted and experimental data is presented in Fig. 1. Over a wide range of conditions, different dimensions of equipment, flowing parti-

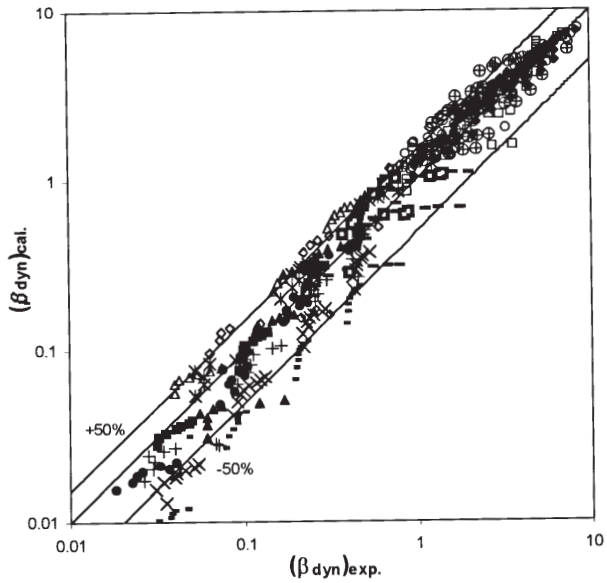

Fig. 1. Comparison of the predicted (Eq. (5)) and experimental values for dynamic holdup. (Symbols in Table I).

cles and packing elements of different shape, the equation gives good agreement with the experimental results with an average error of 26.9 %.

However, it can be seen from Fig. 1 that the correlation is better for higher values of dynamic holdup than for lower ones, which are somewhat underpredicted. The lower values mostly correspond to the preloading zone, and the higher ones to the loading zone. So, it could be argued that better predictions could be obtained with sep-

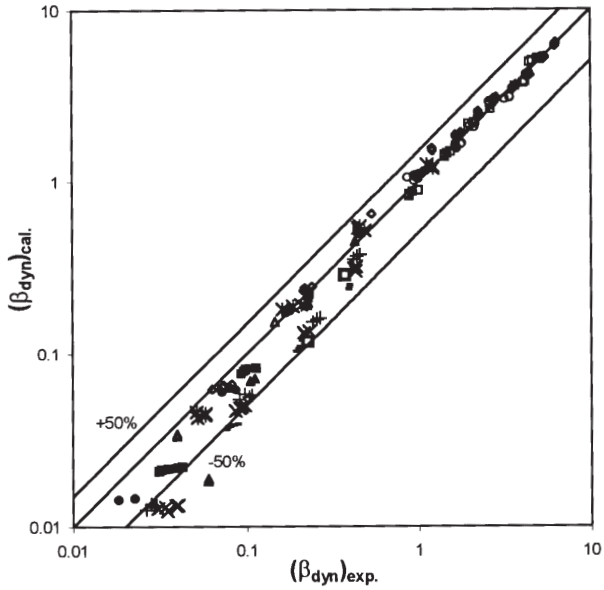

Fig. 2. Dynamic holdup for the preloading zone. Comaprison of the predicted (Eq. (7)) and experimental values. (Symbols in Table I).

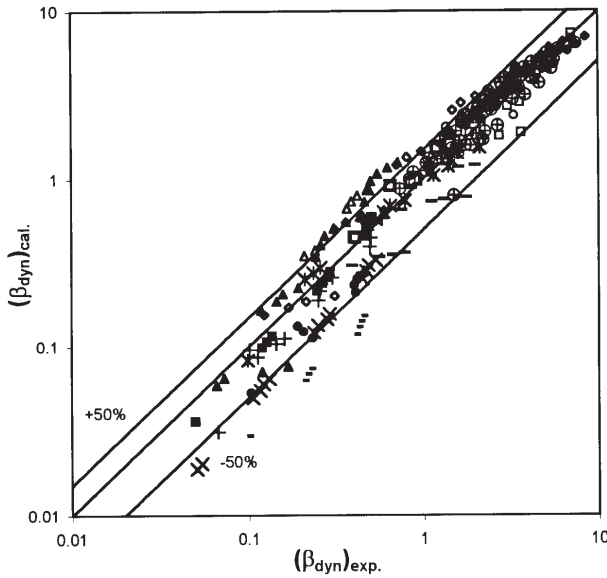

Fig. 3. Dynamic holdup for the loading zone. Comparison of the predicted (Eq. (8)) and experimental values. (Symbols in Table I).

arate equations for the preloading and loading regions. A similar approach was used by Predojević *et al.*[22] for predicting pressure drop, and the following equations was offered for the loading point:

$$Re_{\text{load}} = 0.1289\, Ar^{0.48}\, (d_s/d_{\text{eq}})^{-1.11}\, (G/S)^{0.23} \cdot \varepsilon^{0.85} \tag{6}$$

After dividing the experimental data into zones using Eq. (6), some of the experimental results which were too close to the loading point were disregarded. These experimental points, which represent some kind of transition zone, could introduce considerable error into the data fitting.

For the preloading zone, on the basis of 183 experimental data points, following equation was obtained:

$$\beta_{\text{dyn.p}} = 2196.2\ Re_{\text{p}}^{1.21}\ Ar^{-0.88}\left(\frac{S^2}{\rho_s \rho_g u_g^2}\right)^{0.582} (d_s/d_{\text{eq}})^{2.41}\ (1-\varepsilon)^{1.42}\ \varepsilon^{0.279} \tag{7}$$

The agreement with experimental resuls was good, as is shown in Fig. 2, with an average error of 20.1 %. This percentage was notably lower than the average error of 28.1 % obtained using the unique correlation (5) for the preloading zone, only.

For the loading regime, 270 data points were correlated to give:

$$\beta_{\text{dyn,l}} = 15570.7\ Re_{\text{p}}^{1.57}\ Ar^{-1.24}\left(\frac{S^2}{\rho_s \rho_g u_g^2}\right)^{0.509} (d_s/d_{\text{eq}})^{2.93}\ (1-\varepsilon)^{1.46}\, \varepsilon^{-1.45} \tag{8}$$

As it can be seen in Fig. 3, the agreement with the experimental results is good, with an average error of 26.4 %. However, this error is very similar to the one acquired using the unique Eq. (5), which was 26.0 % for loading zone points. From Fig. 3 it can be concluded that the error is again higher for the lower holdup values. Hence, the use of the partial correlation is benificial only for the preloading zone. For the loading zone, both the unique and separated equation give similar results. Taking into account some uncertainties and discontinuity around loading point, Eq. (7) could be recommended for the preloading regime far enough away from the transitional zone, *i.e.*, the loading point.

CONCLUSION

Correlation (5) can be efficiently used for the prediction of the holdup of dynamic solids in countercurrent gas – flowing solids – packed bed contactors. For the preloading regime alone, Eq. (7) gives somewhat better predictions. The proposed correlations are based only on parameters which are known in advance, so they do not require any measurements in the system of interest. Taking into account the wide range of operating conditions and the great variety of packing elements and flowing solids, the predictions of these equations are in very good agreement with the experimental results.

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NOMENCLATURE

a – Surface area of packing per unit bed volume, m^2 / m^3
Ar – Archimedes number for a particle of flowing solid ($= d_s^3 (\rho_s - \rho)\ \rho\ g / \mu^2$)
D – Diameter of column, m
d_s – Diameter of a particle of flowing solids, m
d_{eq} – Equivalent diameter of a packing particle ($= 6 (1 - \varepsilon) / (a + 4/D)$), m
G – Mass flux of gas, kg/m^2s
g – Acceleration of gravity, m/s^2
Re_p – Particle Reynolds number ($= u_g\, d_{eq}\, \rho/\mu$)
S – Mass flux of flowing solids, $kg / (m^2s)$
u_g – Superficial gas velocity, m/s
u_s – Particle velocity, m/s
β_{dyn} – Dynamic solids holdup
ε – Void fraction of the packed bed
μ – Gas dynamic viscosity, kg / (m s)
ρ – Gas density, kg / m^3
ρ_s – Skeletal density of the flowing solids particles, kg/m^3

ИЗВОД

ДИНАМИЧКИ САДРЖАЈ ПОКРЕТНЕ ЧВРСТЕ ФАЗЕ У СУПРОТНОСТРУЈНИМ КОНТАКТОРИМА ГАС – ЧВРСТО – ЧВРСТО

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У раду су представљене корелације за предсказивање динамичког садржаја покретне чврсте фазе у супротнострујним контакторима гас – чврсто – чврсто. Изрази искључиво садрже променљиве које су познате унапред, тј. није неопходно њихово експериментално одређивање. Корелације се могу применити у широком опсегу оперативних услова, за различите типове паковања и разноврсне материјале покретне чврсте фазе. Предложене корелације су тестиране поређењем са експерименталним резултатима доступним из литературе.

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