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A correlation for predicting solids holdup in the dilute pneumatic conveying flow regime of circulating and interconnected fluidised beds

Yusif Alghamdi [a], Zhengbiao Peng [a], Kalpit shah [a], Behdad Moghtaderi [a], Elham Doroodchi [a,b,*]

[a] Priority Research Centre for Frontier Energy Technologies & Utilisation, The University of Newcastle, Callaghan, NSW 2308, Australia
[b] Priority Research Centre for Advanced Particle Processing and Transport, The University of Newcastle, Callaghan, NSW 2308, Australia

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ABSTRACT

Theoretical modelling, design and operation of circulating and interconnected fluidized beds require an accurate prediction of solids holdup in the fully developed pneumatic conveying flow regime of the riser (i.e. the upper section of the riser). Existing empirical and semi-empirical solids holdup correlations have exhibited limited accuracy and application range. In this study, an empirical correlation was developed to predict the solids holdup at the upper section of the riser in circulating and interconnected fluidized beds with an improved level of accuracy for a broad range of operating conditions and riser dimensions. The correlation is based on a group of dimensionless quantities, which are typically used to describe the hydrodynamics of gas-solids fluidized beds, taking into account gas and particle properties, riser dimensions, and solid circulation rate. The reduced solids flux phenomenon also has been considered directly by introducing a system dependent exponent in the correlation. The correlation predicted 90% of the experimental data with an average deviation of 15%. The correlation is applicable for particle Reynolds numbers between 3.7 and 366.

1. Introduction

The performance of circulating and interconnected fluidized beds including chemical looping combustors (CLC) is largely influenced by the solids holdup distribution in the riser and the solid circulation rate (SCR) throughout the system. These two parameters hydrodynamically govern the transportation of metal oxide particles and hence the gas and solid residence time [1–5], and thermally dictate the energy transfer and overall chemical reaction rate [6–9]. Moreover, the erosion rate of particle surface is also significantly affected by the solids holdup distribution in the riser [6–9].

In general, the SCR expression of Kunii and Levenspiel [10,11] derived from the definition of the solids flux of particulate flow, can be employed to predict the solids holdup at the upper section of the riser, ϕ_t,

$$\phi_t = \frac{G_s}{\rho_p (u_g - u_t)} \tag{1}$$

where G_s is the solid circulation rate, u_g and u_t are the gas velocity and particle terminal velocity, respectively, and ρ_p is the particle density. Kunii and Levenspiel expression [11] has been developed for an ideal case or at a very high riser superficial gas velocity [10], when all the solids in the fully developed region (i.e. ϕ_t at the upper section of the riser) are flowing upwards, and hence exiting the riser (i.e. $\phi_t = \phi_s$, where ϕ_s is the solid concentration that circulating out of the riser). In practice, however, due to the reduced solid flux in the riser [12] and the riser exit geometry or shape [13], particle backflow is often encountered near the wall. Hence the amount of solids that are circulating out of the riser is just a fraction of the solids within the upper section of the riser [5,12], therefore, $\phi_s < \phi_t$. Subsequently, using Kunii and Levenspiel [11] expression could underestimate the solids holdup predictions at the upper section of the riser.

The phenomenon of reduced solid flux is mainly related to the gas-solid two-phase flow characteristics in the riser and is often described as a function of riser dimensions and the superficial gas velocity [12,14]. Rhodes et al. [12] developed a semi-empirical model to predict the so-called reduced solids flux profile within the riser, based on which the fraction of solids moving downward near the wall and the fraction of solids circulating out of the riser could be calculated [5]. They identified two separate regions, namely the core region with dilute upward flowing solids (i.e. the annular flow) and the region near the wall with dense downward flowing solids. Hence, in both fully developed and partially developed riser flow, risers exhibited some degree of reduced solids flux, and accordingly, ϕ_t/ϕ_s in practice should be >1. Besides, the size of this annular region and hence the reduced solids flux were found to be strongly dependent on the riser dimensions and the two-phase flow characteristics. Also, the riser exit geometry or shape affects the amount of the solids exiting the riser [13]. Specifically, a small portion of particles that flowing upward will collide with the exit

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[*] Corresponding author at: Priority Research Centre for Frontier Energy Technologies & Utilisation, The University of Newcastle, Callaghan, NSW 2308, Australia.
E-mail address: elham.doroodchi@newcastle.edu.au (E. Doroodchi).

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wall and bounce back, hence contributing to the overall layer of the reduced solid flux phenomenon especially near the riser exit.

Ouyang and Potter [15] have used averaged correlating factor of 2.6 for ϕ_t/ϕ_s (corresponding to 39% of solids circulating out of the riser) to improve the prediction accuracy of the riser solids holdup [15]. Such a correlating factor (i.e. 39%) or similar has been used by some researchers to predict the solids holdup [10,16]. However, considering that the gas-solid two-phase flow characteristics of the riser strongly influenced by the riser dimensions (i.e. different annular areas), using single correlating factor may lead to large errors in prediction of solids holdup, especially when the system sizes are vastly different to those examined by the abovementioned studies.

A summary of the existing correlations for predicting the solids holdup in the upper section of CFB risers are summarised in Table 1. In general, the solids holdup in the pneumatic conveying flow regime is a function of gas velocity, solids flux, and riser dimensions, and is not only dependent on the particle properties including particle density and size [2,6,10,15–21]. Moreover, the majority of correlations presented in Table 1 are developed around the expression of Kunii and Levenspiel [11] with some including the particles dimensionless numbers such as *Re* and *Ar*. Gao et al. [21], on the other hand, used flow and particles dimensionless quantities to develop their correlation.

Overall the existing correlations have exhibited limited accuracy and/or application range. For example, Bai and Kato [16] developed a correlation for the partially-developed flow in the riser, where the average solids holdup at the dilute section of the riser were relatively high ($\phi \geq 0.025$) compared with that of a fully developed dilute pneumatic conveying flow regime with $\phi < 0.01$ [1,15,17,22,23]. The correlation by Bai and Kato [16] therefore, may lead to overestimation of the riser solids holdup. Huang et al. [20] and Issangya et al. [19] considered the combined effects of operating conditions and particle properties on the solids holdup at the upper section of the riser. However, the effect of riser dimensions was not directly considered in their correlation, which in turn is believed to be the source of inaccuracy in prediction of solids holdup when applied to systems with different sizes. Gao et al. [21] introduced the flow and particles dimensionless quantities (e.g. particle Reynolds number, normalised SCR and particles terminal velocity to riser gas superficial velocity ratio) in the development of their correlation. The correlation, however, was developed only based on their data and hence has very limited application range. Moreover, Qi et al. [10] developed an empirical correlation to predict the solids holdup applicable over a broader range of particle Reynolds number (i.e. $Re_{dp} = 5.7–311.2$). Nevertheless, the accuracy of the correlation when applied to systems with largely different dimensions may be lower due to using an averaged correlating factor, overlooking the direct effect of the reduced solids flux.

It is also worth mentioning that the existing correlations were mainly developed for circulating fluidized beds with a single fluidized

Nomenclature

Symbols

E_i	calculated error (−)
G_s	actual solid circulation rate (kg/m^2 s)
G_{ideal}	ideal solid circulation rate if the entire solid at the upper section of the riser circulated out of the riser (kg/m^2 s)
D	diameter of the riser (m)
L	riser height (m)
u_t	particle terminal velocity (m/s)
$u_{g,}$	superficial gas velocity (m/s)
$u_{g,riser}$	riser superficial gas velocity (m/s)
d_p	particle diameter (μm)
n	exponent depend on the ratio of (G_s/G_{ideal})
Re_{dp}	particles riser Reynolds number ($Re_{dp} = (d_p u_g \rho_g)/\mu g$)
$V_{s(t)}$	total solids volume at the top of the riser (m^3)
x_{s1}	mass fraction of particles species 1
x_{s2}	mass fraction of particles species 2
x'_{s1}	volume fraction of particles species 1
x'_{s2}	volume fraction of particles species 2

Greek letter

ϕ_t	solids volume fraction (i.e. solids holdup) at the upper section of the riser (−)
ϕ_T	average solids volume fraction (i.e. solids holdup) along the total riser height (−)
ϕ_S	solids volume fraction (i.e. solids holdup) that circulated out of the riser (−)
ρ_f	fluid density (kg/m^3)
ρ_p	particle density (kg/m^3)
Δp_T	riser total pressure drop (kPa)
Δh_T	riser total height (m)
μ_g	gas viscosity (Pa s)

Abbreviations

CFB	circulating fluidised bed
CFM	cold flow model
CLC	chemical looping combustion
GB	glass beads
PE	polyethylene
SCR	solid circulation rate
SE	standard error

Table 1
Performance evaluation of present and existing correlations (References cited: [10,11,16,18–21]).

Author(s)	Correlation	Proposed applicability
Qi et al. [10]	$\phi = 12.75(\frac{G_s}{\rho_p(u_g-u_t)})^{1.25}(\frac{u_g}{\sqrt{gD}})^{-0.6}Ar^{-0.05}$	$Re_{dp} = 5.7–311.2$
Pugsely et al. [18]	$\phi = \frac{2G_s}{\rho_p u_g+2G_s}$	$Re_{dp} = 19.5–30$
Issangya et al. [19]	$\phi = 5.06(\frac{G_s}{\rho_p(u_g-u_t)})^{1.19}Ar^{-0.05}$	–
Bai and Kato [16]	$\phi = 4.04(\frac{G_s}{\rho_p(u_g-u_t)})^{1.214}$ for $G_s < G_s^*$ $\phi = \frac{G_s}{\rho_p(u_g-u_t)}[1+0.208(\frac{\rho_p u_g}{G_s})^{0.5}(\frac{\rho_p-\rho_g}{\rho_g})^{-0.082}]$ for $G_s \geq G_s^*$	$Re_{dp} = 5.7–109$
Huang et al. [20]	$\phi = 33.684(\frac{G_s}{\rho_p(u_g-u_t)})(\frac{u_g}{\sqrt{gd_p}})^{-0.6}+0.00184$	–
Gao [21]	$\phi = 1-1.006(\frac{G_s}{\rho_g u_g})^{0.0162}(\frac{u_t}{u_g})^{-0.0503}(\frac{D}{d_p})^{-0.0259}(\frac{d_p\rho_g u_g}{\mu_g})^{-0.02527}$	–

Re_{dp} is the particle Reynolds number in the riser and calculated by $(d_p u_g \rho_g)/\mu_g$.