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Predicting the solid circulation rate in chemical looping combustion systems using pressure drop measurements

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ABSTRACT

In chemical looping combustion systems, accurate measurement of the solid circulation rate (SCR) is crucial for optimising the system performance. Conventionally, the SCR is predicted using the riser total pressure drop leading to an overestimation of up to 70%. In this work, a model has been proposed for the SCR prediction using the pressure drop at the top section of the riser. The height of this top section was determined by the riser gas–solid flow characteristics, namely, the axial solid holdup profile and lateral solid flux profile. A kinematic model was developed to predict the axial solid holdup profile and the reduced solid flux model developed by Rhodes et al. (1992) was employed to predict the mass fraction of upwards flowing solids. The prediction results of the proposed model were validated against the experimental data obtained in this work and those reported in the literature, where the prediction accuracy of SCR was significantly improved (by up to 60%) with a deviation of around 15%.

1. Introduction

Chemical looping combustion (CLC) is a combustion technology that transfers O_2 from air to fuel via oxygen carrier particles in a dual circulating fluidised bed system [1,2]. As the method prevents the direct contact between the air and the fuel, CO_2 enriched flue gas stream can be produced and captured at possibly the lowest energy penalty.

The performance of CLC systems largely relies on the solid circulation throughout the system components as the solid circulation rate (SCR) governs the metal oxide particles transportation and energy transfer [3]. The SCR, in turn, depends on several parameters, including total solid inventory (TSI), fluidisation velocity, particle properties, and composition of the particle species (in binary systems of particles) [4,5]. An accurate measurement of the solid circulation rate (SCR) in a CLC system is essential for maintaining and controlling the solid residence time, heat flux, and chemical conversion rate (i.e. Redox rate) of oxygen carrier particles [6,7].

To determine the SCR, a number of invasive and non-invasive measurement techniques are reported in the literature, including (i) direct measurement of the descending solid mass in the downcomer after particles exit the riser and flow into the loop seal [5,8,9] where the aeration of the loop seal was stopped during steady state operation and the time was recorded until a specified accumulation of the bed height is reached; (ii) using fibre optic probes in the riser where the particle velocity is quantified by calculating the distance between the detective fibres and the time lag to receive the reflected light signals [10,11]; (iii) using fibreglass spirals [12]; and (iv) using pressure transducers placed along the height of the riser to measure the riser solid holdup. The first three methods require regular maintenance and calibration and therefore are very expensive. In contrary, the method using the pressure drop measurements has been proven to be more desirable due to its simplicity and low cost. However, the pressure drop measurement method often leads to significant overestimation of the SCR value [13], e.g., the total riser pressure drop from Ludlow et al. [12] and Guio-Perez et al. [14] largely overestimated the actual value of SCR by 75% and 60%, respectively. That is mainly because the SCR was estimated assuming the concentration of the solids flowing out of the riser was the same as that in the riser. This assumption is only valid for the ideal case, where the solids are flowing upwards uniformly. However, in a real system, only a fraction of the solids are conveyed out of the riser. Markström et al. [13] experimentally demonstrated that the solid mass circulated in their CLC system was approximately 22% of the total solid mass in the riser [13,15], which could translate into an overestimation of about 78% if SCR was calculated using the pressure drop along the height of the riser.

Another contributing factor for the observed overestimation of the SCR could be that the locations of pressure ports are not suitable for the given operating conditions. Typically the ports are located at the top and the bottom of the riser or just above the downcomer. Therefore,

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Nomenclature

Symbols

a	Coefficient (−)
A_{riser}	Cross-sectional area of the riser (m^2)
A_r	Cross-sectional area at the radial directions (m^2)
b	Coefficient (−)
g	Gravitational acceleration (m/s^2)
G_{actual}	Actual solid circulation rate (kg/m^2s)
G_r	Local solids flux at radial position (kg/m^2s)
G_{ideal}	Solid circulation rate from Δp_T (kg/s)
$\dot{m}_{\text{up}}$	Solid mass rate moving upwards (kg/s)
$\dot{m}_{\text{down}}$	Solid mass rate moving downwards (kg/s)
$\dot{m}_t$	Total solid mass rate $\lvert\dot{m}_{\text{up}}\rvert+\lvert\dot{m}_{\text{down}}\rvert$ (kg/s)
k	Constant (−)
R	Radius of the riser (m)
r	Radial distance from the riser axis (m)
r_0	Radial distance of the boundary between the up-flow and the down-flow regions (m)
u_{mf}	The minimum fluidisation velocity (m/s)
u_t	Particle terminal velocity (m/s)
u_g	Interstitial riser gas velocity (m/s)
$u_{\underline{s}}$	Slip velocity in the riser (m/s)
u_{sf}	Superficial gas velocity (m/s)
$u_{sf,t}$	Superficial gas velocity at the top of the riser (m/s)
u_p	Particle velocity (m/s)
Q_t	Solid flow at the top of the riser (m^3/s)
Q_b	Solid flow at the bottom of the riser (m^3/s)
X	Mass fraction of each species

Greek letter

ϕ	Solid volume fraction (−)
ϕ_T	Total solid volume fraction in the riser (−)
ϕ_L	Solid volume fraction at the top of the riser (−)
ε_r	Local voidage at radial position $(1-\phi_r)$ (−)
β	Constant (−)
ρ_f	Fluid density (kg/m^3)
ρ_s	Particle density (kg/m^3)
ρ	Density (kg/m^3)
Δp	Pressure drop between two points (kPa)
Δp_T	Total pressure drop between points 6 and 9 (kPa)
Δp_L	Pressure drop at Δh_L (kPa)
Δh	Height between the two pressure ports (m)
Δh_T	Total riser height (m) ($\Delta h_{6\text{-}9}$)
Δh_L	Section height (m)

Abbreviation

BM	Binary mixture
CFB	Circulating fluidised bed
CFM	Cold flow model
CLC	Chemical looping combustion
SCR	Solid circulation rate
SS	Single species
TSI	Total solid inventory

there is a possibility that the dense bed expands to the section above the downcomer into the dilute section. The dense bed expansion could occur especially when the riser and the reactor are dealing with a large solid inventory [14,16]. Moreover, when the fluidisation velocities are low or there is a gas leakage or a backflow, the solid concentration profile may become extremely non-uniform with a high concentration at the bottom. In such cases, however, only a small portion of solids could be pneumatically transported out of the riser. Under these circumstances, the pressure drop measurements would be inclusive of the dense regime overestimating the solid holdup in the dilute region, which in turn leads to an overestimation of the SCR.

The present work aims at improving the prediction of SCR values when pressure transducers are employed. Specifically, the height of the top section of the riser at which pressure drop measurements should be performed is determined and an expression for the prediction of the SCR based on the pressure measurements at that height is developed. The height of the top section is determined by taking into account the gas–solid two-phase flow characteristics of the riser, namely, the axial solid holdup profile and the lateral solid flux profile. As part of the study, therefore, a kinematic model for prediction of the riser solid holdup profile is developed. The proposed SCR expression and the kinematic model are validated using the experimental data reported in the literature including our own data on single species (SS) CLC system and binary mixture (BM) CLC system with different TSI, air reactor gas velocity, and binary mixture compositions (wt%).

2. Theory

In general, the flow profile in the dilute transport regime of the riser is characterised by a rapidly moving up dilute core surrounded by a slowly falling denser region adjacent to the wall of the riser [17]. Here, we assume that only the solid particles that are moving upwards in the riser are conveyed out of the riser. Based on this assumption, we developed our model as follows.

The solid circulation rate, G, by definition is given as,

$$G=\frac{m_s}{A_{\text{riser}}\times t} \tag{1}$$

where, m_s is the solid mass that has been transported out of the riser and then circulated throughout the system. A_{riser} is the cross-sectional area of the riser, and t is the time taken to transport the particles with a total mass of m_s.

In an ideal case where by all the solid particles are uniformly moving upwards in the riser, $m_s=m_t$, where m_t is the total solid mass in the riser. Hence, the ideal solid circulation rate is given as,

$$G_{\text{ideal}}=\frac{m_t}{A_{\text{riser}}\times t} \tag{2}$$

The total solid mass in the riser can be obtained from pressure drop measurements over the height of the riser, Δp_T,

$$m_t=\frac{\Delta p_T A_{\text{riser}}}{g} \tag{3}$$

and the time taken to transport the solid particles of mass m_t can be calculated as,

$$t=\frac{\Delta h_T}{u_g-u_t} \tag{4}$$

where u_t is the particle terminal velocity and u_g is the gas velocity and Δh_T is the height of the riser.

Therefore, G_{ideal} can be expressed as,

$$G_{\text{ideal}}=\frac{(u_g-u_t)\Delta p_T}{g\Delta h_T} \tag{5}$$

However, in practice, only a fraction of the solid particles in the riser are moving upwards [17,18]. That is, $m_{\text{up}}=xm_t$, where m_{up} is the solid mass in the riser moving upwards, and x is a constant representing the mass fraction of particles moving upwards. The constant x is a function of the gas–solid two-phase flow characteristics in the riser. Based on our earlier assumption that only particles moving upwards in the riser are