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Influence of ring-type internals on the solids residence time distribution in the fuel reactor of a dual circulating fluidized bed system for chemical looping combustion

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A B S T R A C T

The intensification of gas-solids contact in the fuel reactor of a chemical looping combustion system is enhanced with the installation of ring-type internals. This can be a key issue for achieving the necessary fuel conversion rates. Wedged rings, previously designed and tested, were found to increase the particle concentration in the counter current section of the fuel reactor and hence, to achieve a more homogeneous particles concentration along this zone. The present work investigates the effect of the mentioned internals on the residence time distribution of particles in the fuel reactor of a dual circulating fluidized bed system for chemical looping. The study was carried out in a cold flow model especially designed for the fluid-dynamic analysis of the system equipped with a recently developed residence time measurement device based on the detection of ferromagnetic tracer particles through inductance measurement. Ring internals proved the positive effect on the particles residence time, the residence time distribution is more symmetric and shows lower dispersion, the flow pattern is more plug-flow-like, these effects are intensified with the reduction of the aperture ratio of the rings. On the other hand, the upward particle transport in the counter-current zone of the fuel reactor also increases with the installation of the rings, increasing the bypass flow of solids through the fuel reactor's return loop (internal circulation). For high internal circulation rates the solids residence time distribution of the fuel reactor is dominated by the bypass effect. The findings may be used for focused design improvement of the investigated fluidized bed system.

Keywords: Residence time distribution; Gas-solids fluidization; Cold flow model; Ferromagnetic tracer; Dual circulating fluidized bed system; Counter-current reactor; Ring-type internals; Chemical looping

1. Introduction

Chemical looping combustion (CLC) is an innovative process first proposed over sixty years ago for the production of CO_2 (Lewis and Gilliland, 1954) and taken up again twenty years ago as a technology for carbon capture from combustion processes (Ishida and Jin, 1994). It performs the oxidation of fuels using metal oxides to transport oxygen from the combustion air to the fuel, which avoids the contact between these two streams. Two reaction zones can be identified with corresponding separated exhaust gas streams, CO_2 and H_2O are produced from the fuel reactor, where particles are reduced by a gaseous fuel, while N_2 and excess O_2 are released from the air reactor, where particles are oxidized by air (Fig. 1). The global heat release from CLC (mostly from the air reactor) is equal to that of direct combustion, there are no energy losses for the separation of CO_2. When operated with a sub-stoichiometric air supply, the process is called chemical looping reforming, CLR. Here,

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Nomenclature

$C(t)$	concentration function
$C(t)_{in}$	concentration function of input signal
$C(t)_{out}$	concentration function of output signal
d_P	mean particle diameter [m]
D	inner riser diameter [m]
$\mathbf{E}(t)$	normalized residence time distribution function
$\mathbf{E}(\theta)$	dimensionless normalized residence time distribution function
$\dot{m}$	mass flow [kg/s]
M	mass in the reactor [kg]
N	number of ideal stirred tanks
s^3	skewness of the residence distribution curve
t	time [s]
U	superficial gas velocity [m/s]
U_{mf}	minimum fluidization velocity [m/s]
U_t	terminal fluidization velocity [m/s]
V	volume in the reactor [m^3]
$\dot{V}$	volume flow [m^3/s]

Greek letters

β	ratio ΔP countercurrent section of the FR/ΔP total in the FR
γ	split condition or ratio current upwards/current downwards in the FR
ΔP	pressure difference [mbar]
η_G	dynamic gas viscosity [Pa s]
θ	dimensionless time (t/τ)
ρ_G	gas density [kg/m^3]
ρ_P	particle density [kg/m^3]
σ^2	variance of the residence distribution curve
τ	mean residence time [s]
τ_{PFR}	mean residence time – plug flow reactor model [s]
τ_{STR}	mean residence time – stirred tank reactor model [s]
Φ	mean particle sphericity

Abbreviations and subscripts

0	initial
AR	air reactor
CFB	circulating fluidized bed
DCFB	dual circulating fluidized bed
FR	fuel reactor
Glo	global
i	stirred tank number i
i+1	stirred tank number i+1
i−1	stirred tank number i−1
Int	internal
ILS	internal loop seal
LLS	lower loop seal
MP	mix point
PFR	plug flow reactor
RTD	residence time distribution
STR	stirred tank reactor
ULS	upper loop seal

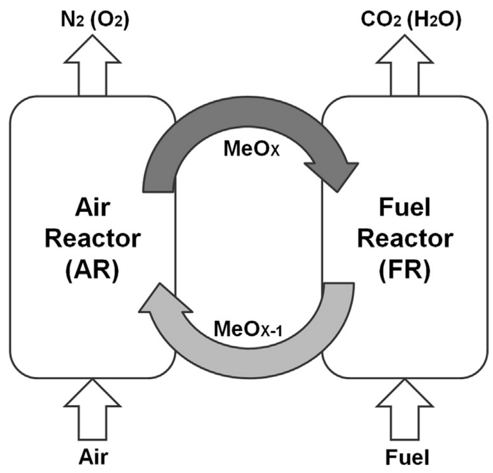

Fig. 1 – Principle of the chemical looping combustion (CLC).

synthesis gas (a mixture of CO, H_2, CO_2 and H_2O) is obtained from the fuel reactor.

CLC shows a unique potential for CO_2 capture because the gas–gas separation and the energy penalty related to such operations are inherently avoided. Reaching an optimal operation of CLC relies on two factors, the chemical and mechanical properties of the oxygen carrier and the reactor design. The investigations in past years established the reactor designs based on circulating fluidized beds as the most suitable for this process (Lyngfelt et al., 2001). One successful example is the dual circulating fluidized bed (DCFB) system, which has been proposed for robust operation of chemical looping processes (Pröll et al., 2008) and successfully implemented for chemical looping combustion (CLC) at 120 kW fuel power input (Kolbitsch et al., 2010) and CLR at 140 kW fuel power input (Pröll et al., 2010a). This design has also proven to be technically feasible at large scale in the case of gaseous fuels (Marx et al., 2012; Pröll et al., 2010b).

The DCFB system consists of two interconnected circulating fluidized beds (Fig. 2). In the, so-called, global loop, particles are fluidized in the air reactor (AR), separated in a cyclone and fed into the fuel reactor (FR) after passing through a seal (upper loop seal, ULS). The loop is completed by a seal located at the lower end of the reactors (lower loop seal, LLS); the flow of particles in this loop is called global circulation. The internal loop includes the fuel reactor (FR) and a corresponding system for internal recirculation of particles, cyclone and seal (internal loop seal, ILS); the particles flow in this section is called internal circulation rate. In the DCFB system, the fuel reactor performs in principle a counter-current flow of particles and gases and has additionally the recirculation system typical of the CFBs for returning the particles elutriated from the bed, these two characteristics have been employed in CLC of gaseous fuels to increase the gas-solids contact efficiency and contact time in this reactor in comparison with some alternative designs (Kolbitsch et al., 2009; Pröll et al., 2009a).

In consideration of the intensive use of coal in actual and future times as well as the reemergence of biomass in the energy market, the efforts are lately put on the implementation of CLC for solid fuels. The reliability of a chemical-looping combustion of solid fuels relies on three main issues, the conversion of volatile compounds formed in the upper part of the fuel reactor, the conversion of char in the fuel reactor (governed by slow gasification reactions), and the separation of fuel ash from oxygen carrier material (Pröll and Hofbauer,