Fuel Processing Technology 167 (2017) 171–182

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Research article

Control of the solids retention time by multi-staging a fluidized bed reactor

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ARTICLE INFO

Article history:
Received 7 December 2016
Received in revised form 23 May 2017
Accepted 23 June 2017
Available online 8 July 2017

Keywords:
Fluidized bed
Solids mixing
Fuel mixing
Multi-stage

ABSTRACT

Fluidized bed reactors are often operated with particles of different size and density present simultaneously (e.g. inert bed material and fuel particles in fluidized bed combustion, or catalyst particles and polymer particles in fluidized bed polymerization). This paper presents a general concept to separate a single fluidized bed reactor into two reaction zones by introducing a primary chamber in the bed where flotsam particles are fed and spend a certain initial residence time. The feasibility of the concept is experimentally proven in a fluid-dynamically down-scaled unit, both in terms of functionality (ability to maintain two separate reaction regions and to avoid backflow from the secondary to the primary region of the solids fed) and of operability (ability to control the residence time distribution of the solids fed in the primary chamber through operational parameters such as pressure and bed height). Numerical simulations show that the residence time distribution is sensitive to the degree of segregation in the primary chamber, and that the heat transfer between the two reaction regions by means of bulk solids mixing is still sufficient to sustain an endothermic process in one zone by an exothermic process in the other.

1. Introduction

Fluidized bed (FB) reactors are common in industrial processes where efficient mixing is important. The bed material, which can be either active or inert in the chemical reactions, is fluidized by gas (e.g. air or steam) so that it exhibits a fluid-like behavior. Since the bed material typically acts as a heat carrier, fluidized bed reactors are associated with very high heat-transfer rates. The convective motion in the bed also enables high and relatively uniform mass-transfer rates. Because of these favorable characteristics, fluidized bed reactors are used in many different industrial processes. One common example is that of combustion and gasification of biomasses and wastes. In such reactor configurations, a low mass fraction (typically around some percent unit) of relatively large and light fuel particles are present in a fluidized bed whose bulk consists of solids (typically a mix of ashes left after fuel conversion and, occasionally, makeup material and/or catalytic solids) of significantly smaller particle size and higher density. Another example is in fluidized bed polymerization reactors, where small catalyst particles and larger polymer particles form a polydisperse bed of solids. In the development of more advanced and diversified FB processes, and in the optimization of existing ones, a high degree of control over the mixing of the various particles is required. More specifically, one may wish to control the residence time of one type of particles in various sections of the bed, as well as the temperature, pressure and chemical environment throughout the different stages of the conversion process.

In the current work, experimental and numerical investigations are presented for a fluidized bed reactor that is divided into two zones separated by a thin wall. We show here how the overpressure can be used to efficiently purport the function of a one-way valve for the fed solids in this two-stage reactor configuration. The proposed design is intended for two-stage processes in which the residence time of a flow of particles of different size and density (in this paper denoted *fuel-like* particles) at the first stage is to be controlled. The design uses solids feeding by gravity, which at industrial scale is implemented by a valve-operated pressurized solids vessel from which solids fall into the bed. This procedure avoids troublesome screw feeding while the contact of the fuel particles with the bed solid is still ensured in the studied configuration thanks to that fuel particles need to immerse in the dense bed as they are transported to the secondary chamber. The heat transfer between the two regions is also studied in this work, as it can be a key parameter depending on the process applied. The separation of one fluidized bed into two compartments has been proposed previously as a means to allow transport of bed material whilst preventing gas mixing [1,2]. The novelty of the current work is that we here focus mainly on the transport of fuel-like particles, and not primarily on the bed material.

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http://dx.doi.org/10.1016/j.fuproc.2017.06.027
0378-3820/

Nomenclature

Latin letters

Ar	Archimedes number
B	terminal velocity correlation parameter
C_D	drag coefficient
c_p	specific heat capacity (J/kg·K)
D	lateral dispersion coefficient (m^2/s)
d	diameter (m)
e_{ss}	coefficient of restitution for particle collisions
F	force (N)
$\boldsymbol{g}$	gravitational acceleration vector (m/s^2)
$g_{0,ss}$	radial distribution function
H	height (m)
$\boldsymbol{I}$	identity matrix
I_{2D}	second invariant of the deviatoric stress tensor (1/s^2)
K	interphase momentum exchange coefficient (kg/s·m^3)
k	thermal conductivity (W/m·K)
L	length (m)
Δl	lateral displacement (m)
N	number of point particles
Nu	Nusselt number
ΔP	pressure drop (Pa)
p	pressure (Pa)
Pr	Prandtl number
R^2	coefficient of determination
Re	Reynolds number
t	time (s)
t_{50}	average residence time (s)
Δt	time step (s)
U_0, Um	fluidization velocity (m/s)
$\boldsymbol{u}$	velocity vector (m/s)
u	velocity (m/s)
u_r,s	terminal velocity for the solid phase (m/s)
x	position (m)

Greek letters

α	volume fraction
$\alpha_{s,max}$	maximum packing limit of the solid phase
λ	bulk viscosity (Pa·s)
ε	voidage
Θ	granular temperature (m^2/s^2)
μ	shear viscosity (Pa·s)
ρ	density (kg/m^3)
$\boldsymbol{\tau}$	stress-strain tensor (Pa)
τ_p	particle response time (s)
ϕ	angle of internal friction
ϕ_i	pseudo-fluid property

Subscripts

B	buoyancy
bed	bed (for the secondary chamber)
col.	collisional
D	drag
eff	effective
fr	frictional
g	gas
i	summation index
kin	kinetic
p	particle
pf	pseudo-fluid
pri	primary chamber
s	solids
sec	secondary chamber

The design is particularly well-tailored to biomass combustion and gasification processes, but it is also applicable to fluidized bed polymerization and processes in which surface treatment techniques (e.g. deposition, grafting, oxidation/reduction) are applied in series, such as when pre-treatment in an atmosphere different from that of the main reactor is needed and one wants to avoid handling of pre-treated particles outside of the reactor. Although polymerization processes are admittedly very complex, the ability to control the sequential change of reactor environment experienced by the particles is a first step to enable automated and flexible continuous processing, and the current work is concerned only with this step.

Taking biomass combustion as an example, a reactor with two communicating chambers, as the one proposed here, can be used to let devolatilization and char conversion take place in separate environments. Such a design would allow the devolatilization chamber to be pressurized, which would enable a solution where the collected volatiles are either passed through a catalyst section, the char conversion bed or mixed with the gases leaving the char conversion chamber. The retention time in the first chamber would have to be controlled by varying the chamber overpressure. If the design would exhibit sufficient heat transfer between the two chambers, by means of bulk solids mixing, the heat released during char conversion could be enough to heat also the drying and devolatilization section. With this setup, no actual transfer of char particles would be necessary and no inadvertent combustion of volatiles would take place.

It is the purpose of this work to investigate, with experiments and numerical simulations, whether such a multi-stage design with controllable retention time is conceivable.

2. Reactor design

This paper presents a novel method to divide a fluidized bed reactor into multiple reaction zones without significant modification of the original FB. This is done by inserting a primary chamber into an existing FB, so that the reactor is separated into two zones which communicate only via the slit under the walls delimiting the primary chamber. The particle mixing in such a configuration is studied (following the rules for fluid-dynamical scaling) and the utilization of this concept is proposed to address a number of current industrial challenges related to the efficient use of fluidized bed reactors (e.g. large-scale conversion of biomass and particle surface pre-treatment processes).

For the reactor design proposed in the present work to be successful, a number of important requirements have to be fulfilled. Firstly, the design should represent a one-way valve function for the particles fed, disabling backflow from the secondary to the primary chamber. Secondly, the design must allow accurate control of the retention time of particles in the primary chamber. Thirdly, the design should ensure no mixing between the gas phase environments in the two chambers (especially the off-gases produced in the reactions). Finally, the heat transfer between the two regions should not be reduced too much compared to the original, unaltered FB design. For example, heat produced in exothermic reactions in one chamber should still be able to drive endothermic reactions in the other.

While the proposed reactor design has many areas of application, for the purpose of assuring a clear and lucid presentation of the main ideas contained herein the rest of this paper will focus on the field of biomass conversion, which has the pedagogical advantage that it is connected to a wide range of possible reactor designs. With a biomass conversion process in a multi-staged reactor, biomass would be fed into the primary chamber, to be heated up by the hot bed material and with moisture and volatile matter being released in gaseous form. The produced char may then be transferred to the secondary reaction zone for further reaction. The volatile-rich gas in the primary chamber can be handled in various ways depending on the specific process at hand: it can be injected into the dense bed of the secondary chamber if contact with catalytic bed solids is desired, it can be mixed with the off-gases from the