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Numerical and experimental analysis of particle residence times in a continuously operated dual-chamber fluidized bed

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ABSTRACT

Fluidized beds that consist of multiple chambers are used in various processes including granulation, drying or coating. As overly short or long particle residence times inside the vessel are undesirable, it is of high interest to measure and detect the influences of variations of the operational parameters on the particle residence times so that they can be adjusted accordingly to gain narrow particle residence time distributions. For this purpose, an ultra-high frequency (UHF) radio frequency identification system (RFID) has been developed, that is able to detect multiple particles without a direct line-of-sight at different positions inside the vessel. Furthermore, coupled discrete element method (DEM)/computational fluid dynamics (CFD) simulations have been carried out to study a continuously operated laboratory scale dual-chamber fluidized bed. To examine the influences of operational and particle parameters 10 different variations have been evaluated both numerically and experimentally. Results show good agreement between simulation and experiment for most cases. The highest change of the residence times could be achieved by changing the particle mass inflow and the fluidization velocity. The results for non-spherical particles showed some deviations in the longer residence times, as certain particle/wall effects were not fully recreated in the simulation. Nonetheless, it was proven that coupled DEM-CFD simulations can be a useful tool in the prediction of residence time which can greatly help to optimize continuously operated fluidized processes.

1. Introduction

Fluidized beds are a commonly encountered technology in solids processing to perform processes like drying, cooling or mixing. These systems are mostly batch operated so that the throughput is limited by the vessel size, process time and down times. If a fluidized bed consists of multiple chambers, complex multi-stage processes can be performed in a single system in continuous operation, so that at a comparable vessel size the downtime can be reduced considerably and a higher throughput achieved. The particle movement through the system and especially above or below weirs that separate the different chambers from each other has therefore been of interest [1–3]. Dependent on the particle motion is the particle residence time, which is an important parameter for the operation of multi-chamber fluidized beds. Particles that enter the vessel at the same time will not necessarily stay equally long inside the system. The particle residence time can be expressed through a distribution function. For most processes, narrow distribution functions are preferred, as overly long or short residence inside the vessel can lead to undesirable product properties. Therefore, the prediction and manipulation of the residence time are of key importance in this kind of systems. As multi-chamber fluidized beds are very complex systems with a high number of influencing factors, no widely applicable model that is able to predict the residence time is available to date. Therefore, a variety of measurement systems was developed to determine particle residence times experimentally. Optical approaches like changing the color/size of certain particles and tracking those or particle tracking velocimetry (PTV) can only track particles in two dimensions and are also difficult to implement for very dense particle flows [4–6]. The fast response particle technique is based on phosphorescent particles that are activated by a light impulse and then detected by a photomultiplier. Harris, Davidson and Thorpe [7, 8] used this technique to measure particle residence times in a circulating fluidized bed. This technique can give very good results for sparse particle flow but is limited for dense flows as the photomultiplier needs to have a line-of-sight with the particles. Magnetic particle tracking (MPT) is a non-invasive measurement technique, where a single particle is equipped with a magnet which is then tracked in space. This gives very precise data, as even particle rotations and trajectories are tracked, and is suitable for dense particle flows. On the downside, it is limited to observing one particle at a time and can result in density changes of the tracer particle [9–11]. Another non-intrusive measurement technique that is potentially capable of determining residence

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Nomenclature

A	area of center of mass	[−]
$A_\perp$	cross-sectional area perpendicular to the flow	[m^2]
c_D	drag coefficient	[−]
d	particle diameter	[m]
e^n	coefficient of restitution	[−]
F	force vector	[N]
$\vec{f}_{int}$	volumetric particle/fluid interaction momentum source	[N/m^3]
g	gravitational acceleration	[m/s^2]
$\hat{I}$	inertia tensor	[kg·m^2]
k	spring stiffness	[N/m]
M	external moment	[Nm]
m	mass	[kg]
n	normal vector	[−]
p	pressure	[N/m^2]
Re	particle Reynolds number $Re=\frac{\varepsilon_f \rho_f d_e \lvert \vec{u}_f - \vec{v}_i \rvert}{\eta_f}$	[−]
T	temperature	[K]
t	tangential unit vector	[−]
u	superficial gas velocity	[m/s]
$\vec{u}$	physical velocity vector	[m/s]
$\bar{v}$	fluid cell averaged particle velocity	[m/s]
$\vec{v}^{\,n}_{rel}$	normal velocity	[m/s]
V	volume	[m^3]
W	angular velocity	[rad/s]
x	center of mass	[−]
$\vec{x}$	position vector	[m]

Greek symbols

$\bar{\beta}$	fluid cell average particle/fluid friction coefficient	[kg/(m^3·s)]
γ^n	damping coefficient	[kg/s]
δ	overlap during contact	[m]
ε	porosity	[−]
η	dynamic viscosity	[kg/(m·s)]
Λ	rotation matrix	[−]
μ_c	friction coefficient	[−]
μ_g	gas viscosity	[kg/(m·s)]
ξ	relative tangential displacement	[m]
ρ	density	[kg/m^3]
τ	viscous stress tensor	[N/m^2]
ϕ	sphericity $\phi = (36\pi \cdot V_p{}^2/A_p{}^3)^{\frac{1}{3}}$	[−]
$\phi_\perp$	crosswise sphericity	[−]
χ	correction factor	[−]

Subscripts

A	ambient
f	fluid
g	gas
i	index
j	componentwise x, y, z
p	particle
pp	particle/particle
pw	particle/wall
s	solid
1	Chamber 1/Outlet 1
2	Chamber 2/Outlet 2
3	Outlet 3

Superscripts

c	contact
d	drag
n	normal
out	outlet
pf	particle/fluid
t	tangential
∇p	pressure gradient

times in multi-chamber fluidized beds is positron emission particle tracking (PEPT). Similar to the MPT, in most cases, it is limited to one tracer particle. PEPT systems are mostly not easy to apply as they need special tracer materials [12–14]. An alternative way of measuring particle residence times is through radio-frequency identification (RFID). RFID uses electromagnetic fields to detect RFID-tags in the proximity of antennas, where each tag has a unique id which makes it possible to track the particle when it passes multiple antennas. The advantages include very low prices and that no direct line-of-sight between antenna and tag needs to be established for a successful detection. However, the exact position cannot be determined, as only the fact that a particle entered the reading range of an antenna is detected. The reading range is influenced by the wavelength of the electromagnetic field, the antenna design, and antenna power output and can go up to several meters. Such high reading ranges are unsuitable for determining particle residence times, as they could be higher than the length of the entire system. Through controlling the reading range, RFID-systems have been