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Solids flux measurements via alternate techniques in a gas-fluidized bed

Sina Tebianian [a], Kristian Dubrawski [a], Naoko Ellis [a], Ray A. Cocco [b], Roy Hays [b], S.B. Reddy Karri [b], Thomas W. Leadbeater [c], David J. Parker [c], Jamal Chaouki [d], Rouzbeh Jafari [d], Pablo Garcia-Trinanes [e], Jonathan P.K. Seville [e], John R. Grace [a,*]

[a] Department of Chemical and Biological Engineering, University of British Columbia, Vancouver V6T 1Z3, Canada
[b] Particulate Solid Research, Inc., Chicago, IL 60632, United States
[c] Positron Imaging Centre, University of Birmingham, Birmingham B15 2TT, United Kingdom
[d] Département de génie chimique, Ecole Polytechnique, Montréal, QC H3T 1J4, Canada
[e] Department of Chemical and Process Engineering, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom

HIGHLIGHTS

- A travelling fluidized bed ensured identical operating conditions at several sites.
- Solids flux was obtained by novel analyses of invasive and non-invasive methods.
- The results are directly compared by quantitative and qualitative analysis.
- The reasons underlying observed discrepancies among the results are discussed.

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ABSTRACT

A transportable fluidization column, operating under identical conditions at three different locations, was employed to compare three experimental solids flux measurement techniques for hydrodynamic characterization of gas-fluidized beds. This paper compares measurements of solids mass and momentum flux obtained by radioactive particle tracking at the Ecole Polytechnique, positron emission particle tracking at University of Birmingham, and borescopic high speed particle image velocimetry at PSRI, carried out with FCC particles of mean diameter 107 µm. These techniques provided broadly similar time-average solids flux profiles, but there were significant quantitative differences. Analysis of the results, focusing on the fundamentals of each measurement technique, provides valuable insights into the reasons for the discrepancies. The results also add to a unique hydrodynamic database for validation of CFD and other models.

1. Introduction

Major advantages of gas-fluidized bed reactors, such as efficient bed-to-surface heat transfer and temperature uniformity, derive from the motion of the particles, largely induced by interactions between voids and the dense phase [1]. Hence reactor performance depends significantly on their hydrodynamics.

Among the important properties that dictate the characteristics of a gas-fluidized bed, local solids flux plays a significant role. For example:

- Heat exchange between immersed surfaces and a fluidized bed, operating in any flow regime, depends on the frequency of particles reaching the surfaces and their velocity [2].
- The solids circulation rate is a key parameter in determining the performance of circulating fluidized beds [3].
- The mass flux of solids entrained from the bed is extremely important in determining the loss of solids not captured by cyclones.

These factors highlight the importance of developing measurement techniques that accurately determine the instantaneous solids mass and momentum fluxes, e.g. based on simultaneous measurement of local instantaneous solids velocity and concentration [4–6]. Suction probes represent a very simple technique for measuring the average solids mass flux in the upper dilute region

* Corresponding author.
E-mail addresses: sinatebian@gmail.com (S. Tebianian), jgrace@chbe.ubc.ca (J.R. Grace).

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Nomenclature

A_p	borescope area covered by particles, pixel^2
A_{tot}	total area of borescope image, pixel^2
d_{sauter}	Sauter mean particle diameter, μm
F_s	solids momentum flux, kg/ms^2
G	net solids mass flux obtained by PEPT and RPT, kg/m^{2}s
G_s	solids mass flux, kg/m^{2}s
$f_\uparrow$	upwards momentum flux due to tracer particle, kg/ms^2
$f_\downarrow$	downwards momentum flux due to tracer particle, kg/ms^2
$F_\uparrow$	upwards momentum flux due to all particles through cell, kg/ms^2
$F_\downarrow$	downwards momentum flux due to all particles through cell, kg/ms^2
F_{sc}	average solids momentum flux at centre of the bed, kg/s^{2}m
$g_\uparrow$	upwards mass flux due to tracer particle, kg/m^{2}s
$g_\downarrow$	downwards mass flux due to tracer particle, kg/m^{2}s
$G_\uparrow$	upwards mass flux due to all particles through cell, kg/m^{2}s
$G_\downarrow$	downwards mass flux due to all particles through cell, kg/m^{2}s
G_{sc}	average solids mass flux at centre of the bed, kg/m^{2}s
J	total number of cells, -
m_p	particle mass, kg
M_p	total mass of all particles in bed, kg
$n_\uparrow$	number of times tracer particle passes reference level upwards, -
$n_\downarrow$	number of times tracer particle passes reference level downwards, -
S	cross-sectional area of cell, m^2
S_{tot}	total cross-sectional area of column, m^2
t_{tot}	total time over which particle tracking measurements are taken, s
U_c	superficial gas velocity at transition to turbulent fluidization flow regime, m/s
U_g	superficial gas velocity, m/s
v_p	local instantaneous particle velocity, m/s
$v_\uparrow$	vertical component of tracer upward velocity, m/s
$v_\downarrow$	vertical component of tracer downward velocity, m/s
ε	voidage, –
ρ_p	particle density, kg/m^3
Ψ_p	solid area fraction, –

of circulating fluidized beds that could be used in industrial units. However, when operated in a non-*iso*-kinetic mode, the influence of the suction velocity on the solids collection rate in different positions of the system of interest needs to be investigated [7].

Kim et al. [8] used a momentum probe featuring two sensing ports at the tips of two stainless-steel tubes connected to a differential pressure transducer to characterize the flow behaviour of high-density circulating fluidized beds. Particle impact on the sensors was recorded as a time-varying pressure signal, which was then related to the solids momentum flux.

Although research groups around the world have developed a variety of sophisticated invasive and non-invasive techniques to measure hydrodynamic parameters of gas-fluidized beds such as solids flux [7,9], a number of issues need to be considered:

- Consider, for instance, two solids flux measurement techniques deployed by research groups, X and Y. Group X has applied and tested its technique on an experimental fluidization facility (consisting of a column, auxiliary components, instrumentation and particles) differing in multiple aspects from the facilities utilized by group Y. It is impossible to quantitatively compare the results obtained by their different measurement techniques, since there are multiple differences in equipment (geometry, scale, material of construction, etc.), particle properties (size distribution, density, shape, roughness, moisture content, etc.), gas properties (e.g. humidity) and/or operating conditions (temperature, pressure, flow rate), as well as unique features of each analytical measurement technique. As a result, there is no standard for assessing the limits and merits of each measurement technique, nor for quantifying systematic errors.
- While non-invasive techniques are often applied in academic research, invasive probes are the only potential candidates for performing many types of measurement in industrial units. However, the degree of probe interference with the local hydrodynamics of fluidized beds needs to be assessed by direct comparison with results obtained by other techniques under identical operation [10,11].

This work extends the study on a novel transportable ("travelling") fluidized bed (TFB), designed and built to provide identical operation in different physical settings, thereby allowing direct comparison of alternate experimental measurement techniques [1,12].

Three different solids mass and momentum flux measurement techniques – radioactive particle tracking (RPT), a non-invasive technique available at the Ecole Polytechnique de Montréal, positron emission particle tracking (PEPT), a non-invasive technique developed at the University of Birmingham, and borescopic high-speed particle image velocimetry (PIV), an invasive measurement technique deployed by Particulate Solid Research Inc. (PSRI) of Chicago – are compared under identical operating conditions. Furthermore, a novel approach is suggested to derive solids flux from non-invasive particle tracking techniques. The measurement techniques compared in this study represent available techniques for measuring solids flux in fluidized beds since: 1) both invasive and non-invasive methods are tested, and 2) the invasive technique considered determines the solids flux by simultaneous measurement of voidage and solids velocity, similar to other probing techniques such as optical fiber probes.

The solids flux profiles obtained by these three techniques, together with data reported in our previous studies [1,12], lead to valuable insights into the ability and accuracy of each technique and, at least in part, explain observed discrepancies. Considering different features of each measurement technique discussed in this paper, the hydrodynamic database, uniquely useful for testing the validity of CFD codes and other models, is also extended in this paper.

2. Experimental equipment and methods

The experimental apparatus consists of a novel transportable fluidization column (Fig. 1), its support structure, basic instrumentation and auxiliary components, all of which traveled with Fluid Cracking Catalyst (FCC) (d_{sauter} = 107 μm, ρ_p = 1560 kg/m^3) particles to different research laboratories for experimentation using different sophisticated measurement techniques. To provide unbiased comparisons, the measurements were performed using the same procedures as the host laboratory would normally follow for the prescribed operating conditions, and the post-processing was completed only after collecting the raw data.