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Scale-up and on-line monitoring of gas-solid systems using advanced and non-invasive measurement techniques

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Abstract

Industry relieson gas-solid systems for numerous processes. Flow dynamics play an important role in achieving the desired results. The present study proposes, validates and demonstrates a novel mechanistic scale-up approach based on maintaining similar radial profile or cross sectional distribution of gas holdup in two different gas-solid systems in order to achieve hydrodynamics similarity using advanced measurement techniques. This new methodology for scale-up and design has been implemented on gas-solid spouted bed which has been used for drying, granulation and coating. The development can be extrapolated to other gas-solid systems encountered in phosphate processes.

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Keywords: Optical probe, Gamma ray computed tomography, Gamma ray densitometry, Radioactive particle tracking and Computational fluid dynamics.

1. Introduction

Phosphate and the related processes have wide applications particularly in fertilization of soils and in various chemical productions (potassium phosphate, calcium hydrogen phosphate and di-ammonium hydrogen phosphate, etc.). These processes involve gas-solid systems for drying of the raw materials followed by granulation and chemical formation to obtain the desired products. In addition coating of the particles has also been applied. Drying is very important to the process as effective moisture removal defines the process efficiency and the subsequent unit operations. Therefore, phosphate processes have been researched over the years to improve the processes efficiency and productivity.

Gas-solid systems have been the characteristic of phosphate processes. In order to properly and effectively scale-up, design and perform drying, granulation and coating, study of the related gas-solid systems is necessary. The flow dynamics and solids movement and gas-solid interaction need to be quantified and understood. Due to the opacity of these systems and the conditions involved, advanced and non-invasive measurement techniques are needed. Furthermore, non-invasive on-line monitoring technique is essential to ensure proper scale-up and operation of these systems.

In our laboratory, these techniques have been developed and demonstrated their applications in advancing scale-up, design and operation of various multiphase flow systems in general and gas-solid systems in particular, which can be of great benefit to phosphate processes and for drying, granulation and coating of phosphate particles.

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Nomenclature

U	superficial gas velocity in spouted bed (m/s)
Ug	superficial gas velocity in fluidized bed (m/s)
U_{ms}	minimum spouting velocity (m/s)
r	point of measurement (m)
R	radial distance (m)
H	axial point of measurement in spouted bed (m)
Z	axial point of measurement in fluidized bed (m)
D	height of fluidized bed column (m)
Greek symbols	
ε	volume fraction or holdup
Subscripts	
s	solids
g	gas

2. Advanced measurement techniques

Measurement techniques are necessary for quantification of multiphase systems. Non-invasive techniques are of great importance as these systems are opaque and the flow dynamics in them are unaltered as compared to invasive techniques. The techniques that have been developed and used in our laboratory are described below:

- Gamma Ray Computed Tomography (CT): The CT unit is designed to quantitatively determine the time averaged cross-sectional and radial profile of holdup distribution of the phases in multiphase systems. It has been designed to use a sealed point gamma ray source 137Cs (~200 mCi or less) with an array of NaI scintillation detectors.
- Gamma Ray Densitometry (GRD): Gamma ray densitometry (GRD) is a non-invasive radioisotope based technique used in providing information about radial profiles of solids or gas holdup (volume fraction), flow patterns or regimes and on-line monitoring for various needs including ensuring proper scale-up and performance of multiphase systems that also include gas-solid systems (drying, granulation and coating). GRD consists of a sealed source (Cesium 137 of 250 mCi) in a source holder and a NaI scintillation detector in front of the source.
- Radioactive Particle Tracking (RPT): This technique is currently being used for gas-solids systems and hence, the data and findings will be reported in future manuscripts. It is based on following the motion of a radioactive particle (also known as radioactive tracer) that mimics the solid particles in 3-D domain using an array of scintillation detectors [1]. This tracer will be dynamically similar to the tracked phase. Such a study will provide valuable information on solids flow in 3-D, solids velocity and its components, turbulent parameters overall residence time distribution, local residence time distribution, stagnant zones, solids occurrence, Lagrangian trajectory and other related solids flow dynamic parameters.
- Computational Fluid Dynamics (CFD): The two most commonly used methods for modelling gas–solid two-phase flow systems are the discrete element method (DEM) and the two fluid model method (TFM). In the DEM approach, the gas phase is described by a locally averaged Navier–Stokes equation, the motion of individual particles is traced, and interphase forces couples the two phases. For the TFM approach, the different phases are mathematically treated as interpenetrating continua, and the conservation equation for each of the two phases is derived to obtain a set of equations that have similar structure for each phase. Two–fluid model (TFM) has been considered in the present study as an enabling tool to facilitate the developed scale-up methodology and also for the modelling of complicated gas–solid flow. Detailed CFD simulation procedures can be found in [2].

In addition to the above-mentioned techniques, sophisticated techniques that provide complement results to the above techniques have been developed and implemented in our laboratory. Such techniques are optical probes that measure simultaneously solids holdup, velocity and their time series fluctuations. Optical probes work on the principle of back reflection of light. The details of optical probe measurement and analysis can be found in [3,4]. These techniques have been utilized to develop novel scale-up methods for gas-solid and solids moving systems. To demonstrate such development two gas-solid systems such as gas-solid spouted bed and gas-solid fluidized bed have been used. These systems have been effectively used for drying, granulation and coating. The development can be extrapolated to other gas-solid and solids moving systems encountered in phosphate processes.

3. Gas-solid spouted bed and gas-solid fluidized bed

Spouted beds are two-phase gas-solid systems where the gas phase is injected as a jet through a small opening at the bottom of the bed to spout the particles that are charged in the column above. Under proper conditions, the gas phase penetrates the bed of particles as a jet, creating a central spout zone, a fountain above the spout, and an annulus moving downward surrounding the spout. Particles entrained in the gas spout move upward and form a fountain of particles above the bed surface that disengage from the gases and fall back to the bed surface, thus, inducing bed circulation. Hence, three distinct regions are created in the spouted bed namely: spout (which is dominated by the gas phase and characterizes by carrying the solid particles upward), fountain (which is also dominated by the gas phase where the solid particles that are carried from the spout form fountain at the top surface of the bed and then fall back again to the bed surface) and the annulus (which is dominated by solids phase and is characterized by the slow downward movement of solids). Due to their efficiency in contacting gases and coarser particles, spouted beds have been successfully applied to a wide variety of processes, such as coating, granulation, drying, coal gasification, catalytic reactions, etc. Two different size spouted beds of 0.076 m and 0.152 m diameter have been used in our laboratory to study the flow dynamics and the new methodology for scale-up. The conical base angel of 60 degrees was maintained for both the spouted beds.

Fluidized bed is formed when a quantity of solid particles placed under appropriate conditions to cause the gas-solid mixture to behave as a fluid. This is usually achieved by the introduction of gas through the solids medium. This results in the medium then having many properties and characteristics of normal fluids; such as the ability to free-flow under gravity, or to be pumped using fluid type technologies. The resulting phenomenon is called fluidization. Fluidized beds are used for several purposes, such as fluidized bed reactors (types of chemical reactors), fluid catalytic cracking, fluidized bed combustion, heat or mass transfer or interface modification, such as applying a coating, granulation and drying. In the present study two different size of 0.14 m and 0.44m diameters fluidized beds were used. The gas phase used in both the gas-solid systems was compressed air and glass beads of density 2450 Kg/m^3 as the solids phase.

4. Novel scale-up approach

The principle of similarity is often used in obtaining experimental data to represent large-scale and industrial conditions complex flow phenomena. The basic concept is that if two flow fields are geometrically similar and are operated with identical values of all important independent non-dimensional parameters, then the dependent non-dimensional variables must also be identical at corresponding locations [5]. It was demonstrated experimentally [6], that there is non-similarity in local hydrodynamics (solids holdup, solids velocity etc.) when all dimensionless parameters are matched in two different size beds. The dimensionless groups used for example are, $\frac{\beta d_p}{\rho_s U}, \frac{g d_p}{U^2}, \frac{\rho_f}{\rho_s}, \frac{H}{d_p}, \frac{D_c}{d_p}$ (Tables 1 and 2).However, with the variation (difference in radial profiles) shown in the local parameters confirms that global parameters (overall holdup and pressure drop, etc.) should not be used primarily to assess scale-up methodology. Table 1 & 2, shows the values of different non-dimensional parameters used in the matching conditions for non-dimensional parameters for spouted beds and fluidized beds, respectively. The assessment of the parameters suggests that more dimensionless groups are needed to explain the complete hydrodynamics of the spouted bed and fluidized bed systems. Therefore, the scale-up methodology of dimensional analysis should be modified to establish a reliable scale-up methodology, not only considering the similarity in global hydrodynamics, but also considering the similarity in local hydrodynamics. Two different size beds (spouted bed and fluidized bed) were considered for the studies, one as reference case and the other as similarity matching case.

The novel new mechanistic approach is based on matching the gas (void) holdup (or solids holdup where gas holdup [ε_g] = 1-solids holdup [ε_s]) radial profile or cross sectional distribution in two different systems (in size or in conditions) to ensure hydrodynamics similarity. This is because in gas-solid systems, the gas phase dictates the hydrodynamics of the system. If such similarity is attained, the systems should be performing desirably and similar to each other. However, in this case the global dimensionless groups are not necessary to be matched or to be close to each other's (see Tables 3 and 4). This is because as mentioned above that more dimensionless groups as compared to what have been reported in literature need to be matched in order to maintain the hydrodynamics similarity, which is a challenging task. Therefore, such proposed mechanistic approach lumps all these by matching the radial profile or cross-sectional distribution of gas holdup; a parameter that can be measured and monitored on line in lab, pilot and plant scales units. This new scale up approach has been demonstrated and approved in spouted beds and fluidized beds by using CT, GRD, Optical probes and CFD. RPT experimentation is currently in progress and hence the results of this technique will be reported in future publications.

Two conditions were identified in both spouted beds and fluidized beds to provide matching radial profiles of solids or gas holdup. Tables 3 and 4 show the newly identified conditions in spouted beds and fluidized beds, respectively. Solids velocity profiles were also compared in the two different size beds. The gas holdup and velocity profile for spouted beds using optical probe and CFD have been shown in Figures 1 and 2. Since solids velocity is bound to be different in different size spouted beds, the velocity profiles were divided by minimum spouting velocity to have a common ground for comparison. Two conditions were validated using CT technique. The results obtained using CT technique has been shown in Figure 3. The details of CT measurement and data analysis procedure can be found in [7]. The solids holdup and solids velocity profile for fluidized beds measured using optical probe and CFD is shown in Figures 4 and 5. The results represent the new conditions identified, which provide matching radial profiles of the estimated parameter.

Table 1. Conditions for matching dimensionless groups used in Spouted beds

Condition	Reference Case (0.152 m)	Matching non-dimensionless groups (0.076 m)
D_c (m)	0.152	0.076
D_i (mm)	19.1	9.5
L (m)	1.14	1.14
H (m)	0.323	0.16
T (K)	298	298
P (kPa)	101	312
Particles	Glass	Steel
d_p (mm)	2.18	1.09
ρ_s (kg/m^3)	2450	7400
ρ_f (kg/m^3)	1.21	3.71
μ (*10^5)(Pa s)	1.81	1.81
U (m/s)	1.08	0.75
ϕ_s	1	1
H/D_c	2.1	2.1
D_c/D_i	8	8
D_c/d_p	69.9	69.9
ρ_s/ρ_f	1994	1995
$\rho_f d_p U/\mu$	157	168
U^2/gd_p	54.5	52.6
$\rho_s d_p U/(\mu*10^{-3})$	313	334
U^2/gD_c	0.78	0.75

Table 2. Conditions for matching dimensionless groups used in Fluidized beds

Condition/ Cases	Case 1	Case 2
Dc (m)	0.44	0.14
L (m)	4.877	4.775
H (m)	0.88	0.28
T (K)	298	298
P (Kpa)	101	101
dp (μ m)	210	70
ρs (kg/(m^3))	2500	2500
ρf (kg/(m^3))	1.21	1.21
μ (kg·s m–2)	1.81E-05	1.81E-05
U (m/s)	0.36	0.2
ϕ_s	0.95	0.95
Dc/dp	2095.24	2000
H/Dc	2	2
ρs/ρf	2066.12	2066.12
U/Umf	3.43	3.33
Fr=(U^2)/g*H	0.015	0.0145
Fr=(U^2)/g*Dc	0.03	0.029
Um/((g*Dc)^0.5)	2.31	2.29
Res=ρs*dp*U/μ(*10-3)	10.44	1.93
Ref=ρf*dp*U/μ	5.05	0.94

Table 3. Conditions for matching radial profiles of solids/gas holdup in Spouted beds

Case	Reference Case Case A	Conditions For Similar $(\varepsilon_g)_r$
D_c (m)	0.152	0.076
D_i (m)	0.019	0.0095
L (m)	1.14	1.14
H (m)	0.323	0.16
T (K)	298	298
P (kPa)	101	364
Particles	Glass Beads	Steel
d_p (m)	0.00218	0.00109
ρ_p (kg/m^3)	2450	7400
U (m/s)	1.08	0.64
H/D_c	2.1	2.1
D_c/D_i	8	8
D_c/d_p	69.9	69.9
ρ_p/ρ_f	1994	1995
ε_{mf}	0.41	0.42
$\rho_f d_p U/\mu$	157	297
U^2/gd_p	54.5	38.3
$\rho_p d_p U/\mu$	3.13	1.39
U^2/gD_c	0.78	0.549

Table 4. Conditions for matching radial profiles of solids/gas holdup in Fluidized beds

Condition/Cases	Case 1(Base)	Case 2A (Similar)
Dc (m)	0.44	0.14
L (m)	4.877	4.775
H (m)	0.88	0.28
T (K)	298	298
P (Kpa)	101	101
dp (μ m)	210	70
ρs (kg/(m^3))	2500	2500
ρf (kg/(m^3))	1.21	1.21
μ (kg·s m–2)	1.81E-05	1.81E-05
U (m/s)	0.36	0.25
Particles	glass bead	glass bead
φ	0.95	0.95
Dc/dp	2095.24	2000.00
H/Dc	2.00	2.00
ρs/ρf	2066.12	2066.12
U/Um	3.43	4.17
Fr=(U^2)/g*H	0.015	0.0227
Fr=(U^2)/g*Dc	0.03	0.0445
Um/((g*Dc)^0.5)	2.31	2.29
Res=ρs*dp*U/μ(*10-3)	10.44	2.42
Ref=ρf*dp*U/μ	5.05	1.17

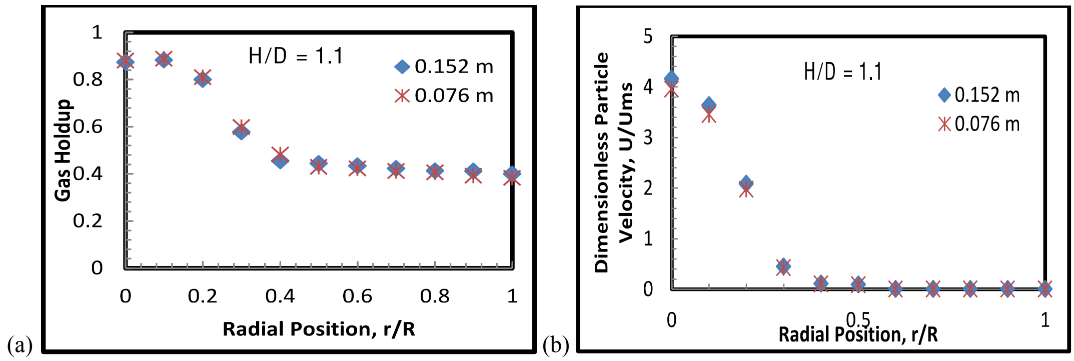


Fig. 1. Illustration of spouted bed result in two different size beds (0.076 m and 0.152 m diameter) (a) gas holdup measured by optical probe and (b) dimensionless particle velocity profile measured by optical probe

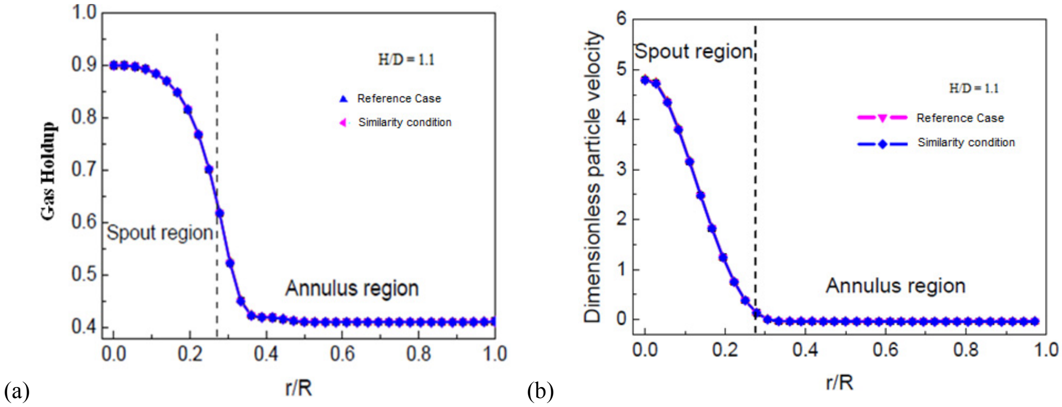


Fig. 2. Illustration of spouted bed result in two different size beds (0.076 m and 0.152 m diameter) (a) gas holdup evaluated by CFD and (b) dimensionless particle velocity profile evaluated by CFD

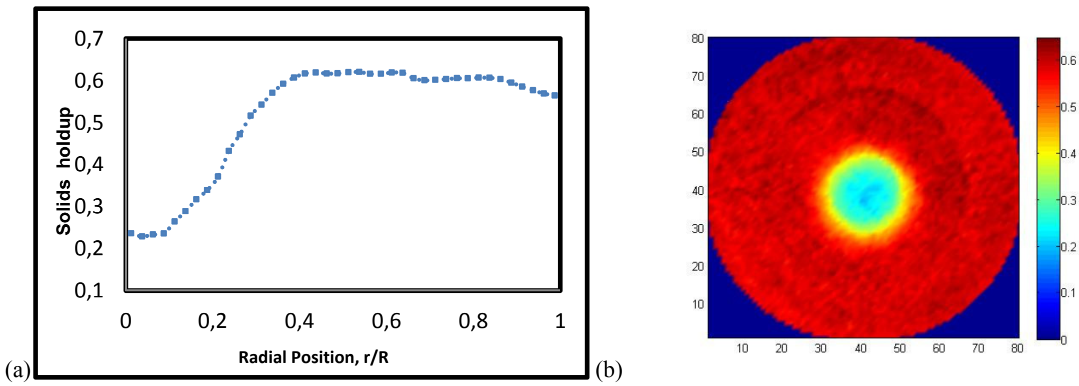


Fig. 3. Illustration of spouted bed solids holdup profile measured by CT unit in 0.152 m diameter spouted bed (a) radial profile of gas holdup and (b) solids holdup reconstruction image of spouted bed using CT

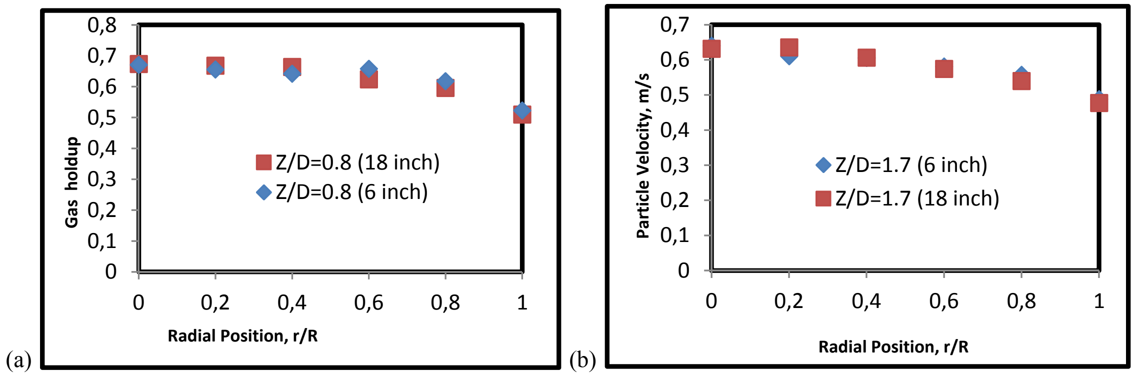


Fig. 4. Illustration of fluidized bed result (a) gas holdup measured by optical probe and (b) solids velocity profile measured by optical probe

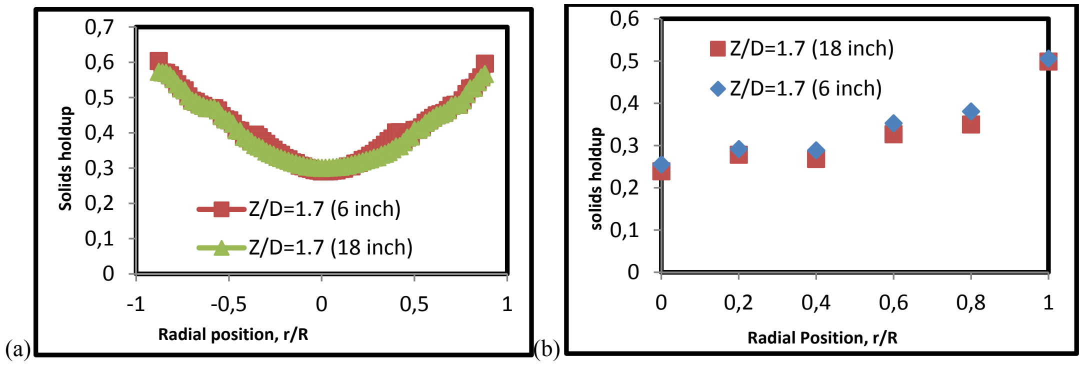


Fig. 5. Illustration of fluidized bed result (a) solids holdup profile evaluated by CFD and (b) solids holdup profile measured using optical probe

The novel scale-up approach can be validated and monitored on-line for industrial scale gas-solid and solids moving systems using Gamma ray densitometry (GRD) technique as shown in Fig. 6. A focused beam of radiation is transmitted from the source, through the column and process material, to the detector. As the density of the material in the column changes, the amount of radiation reaching the detector changes accordingly. It is generally believed that the amount of radiation that reaches the detector through the process material is reflective of its flow behavior and properties. Hence, the developed GRD system is capable of validating and monitoring on-line the gas-solid and solids moving systems. The GRD technique was applied successfully to both the spouted bed and fluidized bed systems. The sample of results for both the systems are shown in Fig 7.

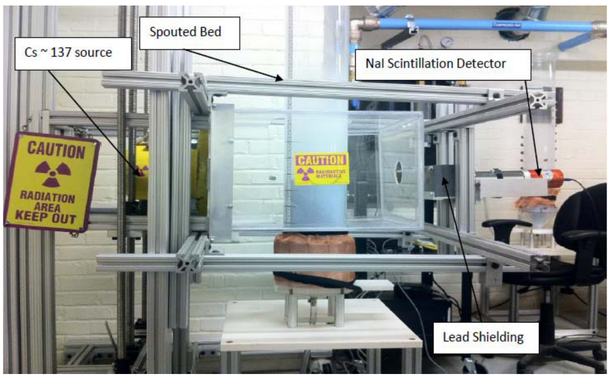
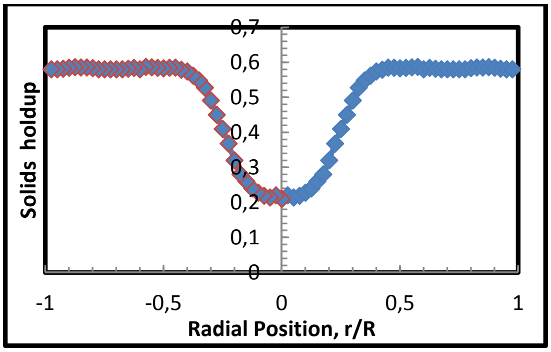


Fig. 6. Illustration of GRD technique applied onto spouted bed unit

(a) 

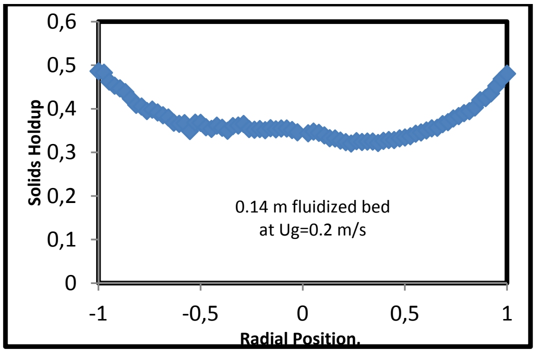
(b) 

Fig. 7. Illustration of GRD results (a) solids holdup measured in spouted bed systems and (b) solids holdup measured in fluidized bed systems

5. Concluding remarks

Both advanced experimental techniques and modeling (Computational Fluid Dynamics, CFD) have been implemented and utilized to facilitate such new scale-up and design methodology development for industrial implementation.

The new method developed with aid of advanced techniques and the on-line montioring and modeling for its implementation on gas-solid and solids moving systems such as spouted beds and fluidized beds has been successful. The development (both novel scale-up, computing methodology and on-line montoring) can be implemented on various phosphate processes with various multiphase flow systems including gas-solid, gas-liquid, liquid-solid, and gas-liquid-solid systems to advance its efficiency, economics, safety, efficient energy use.

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