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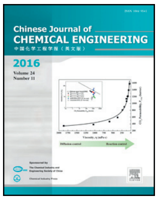

Article

Comparison between the new mechanistic and the chaos scale-up methods for gas-solid fluidized beds

Haidar Taofeeq [1,2,4], Muthanna Al-Dahhan [1,3,*]

[1] Multiphase Reactors Engineering and Applications Laboratory (mReal), Department of Chemical & Biochemical Engineering, Missouri University of Science & Technology, Rolla, MO 65409, USA
[2] Chemical Engineering Department, College of Engineering, Al-Nahrain University, Baghdad, Iraq
[3] Cihan University, Erbil, Iraq
[4] Prosthetics and Orthotics Engineering Department, College of Engineering, Al-Nahrain University, Baghdad, Iraq

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ABSTRACT

The chaotic scale-up approach by matching the Kolmogorov entropy (E_K) proposed by Schouten *et al.* (1996) was assessed in two geometrically similar gas–solid fluidized bed columns of 0.14 and 0.44 m diameter. We used four conditions of our validated new mechanistic scale-up method based on matching the radial profiles of gas holdup where the local dimensionless hydrodynamic parameters were similar as measured by advanced measurement techniques. These experimental conditions were used to evaluate the validity of the chaotic scale-up method, which were selected based on our new mechanistic scale-up methodology. Pressure gauge transducer measurements at the wall and inside the bed at various local radial locations and at three axial heights were used to estimate KE. It was found that the experimental conditions with similar or close radial profiles of the Kolmogorov entropy and with similar or close radial profiles of the gas holdup achieve the similarity in local dimensionless hydrodynamic parameters, and *vice versa*.

1. Introduction

The fluidized bed is considered one of the most important solid–gas reaction and contacting systems with a vast number of industrial applications, such as catalyst regeneration, drying, catalytic cracking, Fischer–Tropsch synthesis, and gas–solid polymerization [1,2]. Gas–solid fluidized bed reactors are characterized by many advantages compared with the other types of reactors (*e.g.*, fixed bed reactors) which include simple construction, relatively low operating and maintenance expenses, low pressure drop, approximately isothermal temperature distribution, excellent contact and good mixing between the gas and solid particles, good mass and heat transfer rates, and the ability to handle a large quantity of solid particles even with a continuous process rate [3].

Despite all these advantages, due to the complexity of flow structure and multifaceted interaction between the phases of gas–solid fluidized beds, it has been challenging to understand and quantify their hydrodynamics, design, scale-up, and performance. In addition, the gas–solid mixing behavior is poorly understood [4]. These drawbacks make it difficult to scale up gas–solid fluidized bed reactors from small-scale (laboratory- or pilot plant-scale) to industrial-scale. Rüdisüli *et al.* [2] reported some of the pitfalls that could be associated with poor scale-up, such as gas bypassing, gas channeling, partial defluidization, erosion and damage to immersed surfaces, elutriation of solid particles, reduction in the heat and mass transfer rate performance, and insufficient solid particle mixing.

Many experimental and numerical studies related to scale-up of gas–solid fluidized beds have been reported in the open literature [5–8]. As a result, various scaling methods have been proposed to maintain hydrodynamic similarity in scaling up of the gas–solid fluidizing beds [6–8]. These scale-up methods for geometrically similar gas–solid fluidized beds can be characterized as follows: (1) matching key dimensionless groups [3,9–13], (2) matching chaotic behavior by estimating Kolmogorov entropy (E_K) of the pressure signal to describe the order/disorder of the system [14–16], and (3) matching the radial or diameter profiles of the gas holdups as a mechanistic new method since the gas phase dictates the dynamics of these beds [6–8,17].

In our research group, we have assessed the scaling up method based on matching dimensionless groups using advanced measurement techniques of optical fiber probe utilization, radioactive particle tracking (RPT), gamma ray computed tomography (CT), and gamma ray densitometry (GRD). We found that the used dimensionless groups are not sufficient to maintain hydrodynamic similarity and it will become difficult to apply if the number of the dimensionless groups to be matched increases [6–8]. Al-Dahhan *et al.* [17] proposed a new mechanistic

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* Corresponding author at: Multiphase Reactors Engineering and Applications Laboratory (mReal), Department of Chemical & Biochemical Engineering, Missouri University of Science & Technology, Rolla, MO 65409, USA.
E-mail address: aldahhanm@mst.edu. (M. Al-Dahhan).

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methodology for scaling up gas–solid fluidized beds to achieve hydrodynamic similarity among geometrically similar beds. This method is based on matching the radial profiles of the gas phase holdup at a height within the bed that could represent the hydrodynamics of the bed. Advanced measurement techniques have been used to validate this method by measuring local detailed hydrodynamics using optical fiber probe, gamma ray computed tomography (CT), radioactive particle tracking (RPT), and gamma ray densitometry (GRD) techniques [6–8]. However, the method that is based on matching Kolmogorov entropy (E_K) that was proposed by Schouten *et al.* [14] of the pressure signal measured at the wall has not been evaluated by measuring the detailed local hydrodynamic parameters using the above-mentioned techniques. Schouten *et al.* [14] proposed matching Kolmogorov entropy (E_K) estimated from the pressure drop signal measured at the wall to scale-up and maintain hydrodynamic similarity of gas–solid fluidized beds. In this case, KE represents the degree of freedom of the system or in other words the degree of the order/disorder behavior of the system. The basic concept of this chaos analysis based method is that the rate of information loss should be kept similar when scaling up a fluidized bed from a small-scale to the large-scale, to ensure the hydrodynamic similarity between the two scaled beds. The advantage of this method as stated by Schouten *et al.* [14] is that the KE is explicitly linked to the bed diameter and hence the same solid particles can be used in both scales of the fluidized beds. Thus, the problem of finding appropriate solid particles is averted as in the case of matching dimensionless groups. In addition, the dimensionless entropy group number ($E_K.d_p/u$) is directly proportional to the Froude number (u_g^2/gd_p) and the ratio between the static bed height and the bed diameter. van den Bleek and Schouten [15,16] claimed that when the dimensionless entropy group number is matched in the two scaled fluidized beds, the matching of dimensionless scaling groups in terms of the Froude number and H/D_c ratio are enough to have the cases matching.

Accordingly, the focus of this work is to assess the scale-up of a gas–solid fluidized bed based on the chaos analysis based methodology proposed by Schouten *et al.* [14], by applying their methodology using pressure signal on the matching cases using our new mechanistic scale-up methodology, which is based on matching the radial profiles of the gas holdups between two fluidized beds. As well, the similarity detailed hydrodynamic parameters have been measured and confirmed using the above mentioned advanced measurement techniques. In this case, at these conditions we will assess if the estimated KE from the measured pressure signal at the wall and inside the bed at various axial and radial locations are matched or not.

2. Assessment of the Chaotic Method for Scale-up of Fluidized Bed

The chaotic based scale-up methodology was assessed using the experimental conditions that we used for validating our new mechanistic scale-up methodology, that is based on matching the radial profiles of the gas holdup between two scales of gas–solid fluidized beds that are geometrically similar. Therefore, the experimental conditions used by Zaid [6], Efhaima [7], and Efhaima and Al-Dahhan [8] were used in the present study, as illustrated in Table 1. In this table, there are conditions of Case B with respect to the conditions of the reference case (Case A) that provide similar gas holdup radial profiles as we confirmed and measured by optical fiber probe and gamma ray computed tomography (CT) measurements in these two beds. The local hydrodynamic parameters such as dimensionless solid velocity, gas/solid holdups, and dimensionless turbulent parameters (stresses and turbulent kinetic energy) have been measured using radioactive particle tracking, gamma ray computed tomography and optical fiber probe techniques. We found that these hydrodynamic parameters are similar or close to each other when the radial profiles of the gas holdup are close to each other. The question then will be whether the Kolmogorov entropy (E_K) of the pressure signal measured at the wall or inside the bed be similar or close to each other or not in these beds identical to Cases A and B. This has been assessed here by adopting the conditions of Case A and the conditions of Case B for similar ($\varepsilon_{g,r}$). Since we have already approved the similarity of these mentioned local parameters that have been reported in Zaid [6], Al-Dahhan *et al.* [17], Efhaima [7], and Efhaima and Al-Dahhan [8], we are not going to report these results rather that we state that if KEs are similar or not when these local hydrodynamic parameters are similar and *vice versa*. The same approach will be applied to the cases where the hydrodynamic parameters are not similar which are for the cases of Case C and Case D with respect to the reference Case A.

Table 1
Conditions that provide similar gas holdup radial profiles giving similarity in local hydrodynamics and non-similar gas holdup radial profiles giving non-similarity in local hydrodynamics

Condition	Reference case (Case A)	Condition for similar ($\varepsilon_{g,r}$) (Case B)	Condition for non-similar ($\varepsilon_{g,r}$) (Case C)	Condition for non-similar ($\varepsilon_{g,r}$) (Case D)
D_c/m	0.44	0.14	0.14	0.14
Particle type	Glass beads			
L/m	4.877	4.775	4.775	4.775
H/m	0.88	0.28	0.28	0.28
T/K	298	298	298	298
P/kPa	101	101	101	101
d_p/μm	210	70	70	210
$\rho_s/\mathrm{kg\cdot m^{-3}}$	2500	2500	2500	2500
$\rho_f/\mathrm{kg\cdot m^{-3}}$	1.21	1.21	1.21	1.21
$\mu/\mathrm{kg\cdot s\cdot m^{-2}}$	1.81×10^{-5}	$1.81\mathrm{E} \times 10^{-5}$	1.81×10^{-5}	1.81×10^{-5}
$U_{mf}/\mathrm{m\cdot s^{-1}}$	0.105	0.06	0.06	0.12
$U_g/\mathrm{m\cdot s^{-1}}$	0.36	0.25	0.2	0.2
Φ/sphericity	0.95	0.95	0.95	0.95

In this approach, Case A was selected as a reference condition, while Case B was identified (matching conditions) to have similar or close radial profiles of the gas holdup. Cases C and D were selected as mismatching conditions because they have different radial profiles of radial gas holdup compared with the reference condition (Case A). It is worth mentioning that the new scale-up methodology was validated using both invasive and noninvasive techniques mentioned above. We confirmed that Cases A and B have the same radial profiles of dimensionless particle velocity in the form of (V_p/u_{mf}), where u_{mf} is the minimum fluidization velocity. Additionally, the radial profiles of the dimensionless turbulent parameters with respect to the minimum fluidization velocities (*e.g.*, dimensionless shear stresses, dimensionless turbulent kinetic energy, and dimensionless eddy diffusivity) were matched for Cases A and B [6–8,17].

3. Experimental Setup

The experimental setup consisted of two fluidized bed columns of 0.14 m and 0.44 m inside diameters, with similar geometries. Both columns were constructed from Plexiglas®, and the plenums were made of aluminum. The columns and plenums were placed on the top of a stainless steel base. An industrial-scale compressor was used to supply compressed air to the columns at pressures up to 1.38 MPa. Omega flow meters (Omega Inc., model FL-6715A) controlled the gas flow rate entering the columns. Schematic diagrams of the two fluidized bed columns are shown in Figs. 1 and 2.

The 0.14 m inside diameter column was 1.84 m high and connected at its top with an upper section that had a larger diameter of 0.42 m and 0.84 m height to disengage the solid particles from the flowing gas by reducing the superficial gas velocity and hence the particle velocity. The gas phase was introduced through a sparger tube inside the plenum section and then through a distributor plate affixed between the column and plenum sections. The gas distributor plate was manufactured of a porous polyethylene sheet and had a

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