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Detailed parametric design methodology for hydrodynamics of liquid–solid circulating fluidized bed using design of experiments

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ABSTRACT

A design-of-experiments methodology is used to develop a statistical model for the prediction of the hydrodynamics of a liquid–solid circulating fluidized bed. To illustrate the multilevel factorial design approach, a step by step methodology is taken to study the effects of the interactions among the independent factors considered on the performance variables. A multilevel full factorial design with three levels of the two factors and five levels of the third factor has been studied. Various statistical models such as the linear, two-factor interaction, quadratic, and cubic models are tested. The model has been developed to predict responses, viz., average solids holdup and solids circulation rate. The validity of the developed regression model is verified using the analysis of variance. Furthermore, the model developed was compared with an experimental dataset to assess its adequacy and reliability. This detailed statistical design methodology for non-linear systems considered here provides a very important tool for design and optimization in a cost-effective approach.

Introduction

Fluidization is encountered in many process industries wherever fixed or packed beds are confined. The circulating fluidized bed (CFB) is a configuration where particles are entrained with considerable flux within a tall column called a 'riser'. At the top, they are separated efficiently from the carrying fluid, usually external to the reactor, and returned to the bottom of the riser, through another connecting reactor called the 'downcomer', forming a closed-loop system for the particles. The CFBs have more advantages over packed beds which include high gas throughput, limited/no back-mixing, long and controllable residence time of particles, temperature uniformity, effective contacting, operational flexibility, flexibility in handling particles of widely differing in properties such as densities, sizes, and shapes, and overall profitability, etc. (Yang, 2003). The gas–solid CFB reactors are preferred for many applications such as combustion, environmental remedies, and catalytic cracking and so on (Berruti, Chaouki, Godfroy, Pugsley, & Patience, 1995).

Although the gas–solid circulating fluidized technique has been implemented industrially, liquid–solid CFBs (LSCFBs) are still being researched for commercial applications. Andalib, Nakhla, and Zhu (2012) developed an open integrated anaerobic fluidized bed with a CFB bioreactor for biological nutrient removal from the high strength wastewater. Some of the studies conducted with LSCFBs for different applications in laboratories or pilot-scale applications are biological nutrient removal from leachate, cesium removal from nuclear wastes, biological nutrient removal, and continuous enzymatic polymerization of phenol (Choudhury, Zhu, Nakhla, Patel, & Islam, 2009; Eldyasti, Choudhury, Nakhla, & Zhu, 2012; Feng, Jing, Wu, Chen, & Song, 2003; Trivedi, Bassi, & Zhu, 2006).

For simultaneous reaction and regeneration or for simultaneous adsorption and desorption purposes, solids holdup and solids circulation are the important hydrodynamic variables that have a significant effect on CFB performance. Previously published experimental data show that average solids holdup and solids circulation rate are significantly influenced by the interaction among the factors, viz., primary liquid velocity, auxiliary liquid velocity, and solids inventory in the downcomer (Atta, Razzak, Nigam, & Zhu, 2009; Shilapuram, Krishnaiah, & Sai, 2009; Vidyasagar, Krishnaiah, & Sai, 2008, 2011). The various models available to date for the prediction of hydrodynamics (solids holdup and solids circulation rate) are broadly categorized into three types. The first employs the method of empirical correlation development. The literature shows that previously developed correlations were either in terms of individual factors that affect the hydrodynamics or in terms

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of dimensionless numbers (Basava Rao, Sailu, & Sandilya, 2007; Vidyasagar et al., 2011; Zheng & Zhu, 2000). Although the various developed empirical correlations are based on the experimental data, they are not able to capture the interaction effects among the variables. The second method used for hydrodynamic predictions employs fundamental first principles for pressure, mass, and momentum balance of the phases involved (solid and liquid) using computational fluid dynamic techniques (Cheng & Zhu, 2005; Dadashi, Zhang, & Zhu, 2015; Dadashi, Zhu, & Zhang, 2014; Razzak, Agarwal, Zhu, & Zhang, 2008; Roy & Dudukovic, 2001; Roy, Sai, & Jayanti, 2014). In this method, the continuity equation and momentum balance for liquid and solid phases are solved to obtain velocity vectors, holdup distributions, and solids circulation rates (in terms of the solids velocity). Momentum balance and the continuity equation for the phases involve the total liquid velocity. However, the distinguished characteristic of a LSCFB is that, by regulating the auxiliary liquid velocity, solids holdup and solids circulation rate (in terms of solids velocity) in the riser are varied. In other words, for the same total liquid velocity entering into the riser (sum of the primary and auxiliary liquid velocity) different combinations of primary and auxiliary liquid velocities are possible. Each combination results in establishing a different set of average solids holdup and solids circulation rate in the riser. That is, the total liquid velocity and ratio of primary-to-auxiliary liquid velocity decides the average solids holdup and solids circulation rate. Nevertheless, the limitation with this second method is that only the total liquid velocity is considered in obtaining the average solids holdup and solids circulation rate by solving simultaneously the continuity equation and momentum balance for all the phases. Hence this method does not distinguish this unique feature of a LSCFB. In other words, one cannot employ the continuity equation and momentum balance for the phase for the primary liquid alone and the auxiliary liquid alone and solve them to find the individual contributions in the estimation of average solids holdup and solids circulation rate. Furthermore, interaction effects among the factors cannot be directly obtained by this method. The third method available is an extension of the core–annulus flow model which is applicable for gas–solid CFBs, specifically for determining the radial hydrodynamic behavior of LSCFBs (Liang & Zhu, 1997). However, predictions in LSCFB by this method are poor and does not account for the coupling interaction among factors.

To conclude, on the modeling front, with the exception of our recent study, no other unique model is available in finding the effects of the interaction on the overall hydrodynamic behavior (Palkar & Shilapuram, 2015). In practice, the LSCFB is used in many applications such as for simultaneous reaction and regeneration of deactivated catalyst, as well as for adsorption and desorption of solid particles (Dadashi et al., 2014; Lau et al., 2013; Mazumder, Zhu, Bassi, & Ray, 2009a, 2009b; Mazumder, Zhu, & Ray, 2010). In all instances, the desired conversion (for reaction) or purity (for separation), which is determined by the solids holdup and solids circulation rate, is of primary interest compared with the quantity processed (or throughput) in that scenario. Moreover, not only is the individual effect of the primary liquid velocity, auxiliary liquid velocity, and solids inventory in the downcomer important, but also the interaction among these factors plays an important role in establishing desired settings. A useful model then will be one relating these available factors, along with their contributions of individual, square, and interaction effects. Hence, the objective is to obtain a statistical-based regression model using the 'design-of-experiments' (DOE) methodology. In addition, multiphase flows in particular involve high turbulence, internals (examples such as the stainless steel tubes through which the primary liquid enters, and distributor plates through which an auxiliary liquid enters), and complicated geometry with each part of a unit operating under different hydrodynamic regimes (for example, the riser of a LSCFB in pneumatic conveying, liquid–solid separation under gravity settling, the return pipe in pneumatic conveying, and the downcomer and return leg in a slow-moving packed bed). These flows are quite complex (Vidyasagar et al., 2008; Shilapuram & Sai, 2012). Hence, a unique model representing the LSCFB from fundamental principles is quite difficult. Nonetheless, LSCFBs are gaining potential interest among various process industries; therefore, one must have a model affording good predictions for accurate design and control of the LSCFB. Hence, statistical-based regression model using the DOE methodology serves this purpose.

The experimental design DOE is one of the important tools for improving the product realization process. This technique is mainly useful for the design and development of new manufacturing processes, and process management. The use of the experimental design technique in the early stage of the process development results in (1) reduction in development time, (2) improved process yields, and (3) reduced overall cost. This gives an optimum set of independent variables to minimize or maximize the dependent variables. In addition, this technique is useful whenever it is not experimentally possible to visualize the interaction effects and its dependencies. In this regard, the regression model developed is helpful to determine these effects in an efficient way in developing an efficient process (Montgomery, 1997).

To date, the DOE technique has not been used very extensively in the field of process engineering. This technique is gaining interest in various process applications wherever either many factors affects the response or one does not have proper fundamental principles for the analysis of the system under consideration. Various studies have introduced this concept in many fields of research very recently (Abbas & Baker, 2011; Al-Hassani, Abbas, & Wan Daud, 2014; Dora, Mohanty, & Roy, 2013; Jena, Sahoo, Roy, & Meikap, 2009; Mahalik, Mohanty, Biswal, Roy, & Sahu, 2015; Palkar & Shilapuram, 2015; Samimi, Zakeri, Maleki, & Mohebbi-Kalhori, 2015). Abbas and Baker (2011) studied the impact of operating parameters, i.e., catalyst weight, decomposition temperature, and methane partial pressure on the rate of methane decomposition using the factorial design methodology. A statistical analysis for a gas–liquid–solid system with the help of factorial design to estimate the gas holdup and liquid holdup was studied by Jena et al. (2009). An attempt using factorial design was also made to observe hydrodynamic characteristics of a three-phase fluidization of a homogeneous ternary mixture of particles in studying the effect of various operating parameters such as superficial liquid velocity, gas velocity, initial static bed height, average particle size, and column diameter (Dora et al., 2013). A full factorial design was performed by Al-Hassani et al. (2014) to build a statistical relationship for various parameters like the temperature of the reaction, reaction relative time and types of the catalyst used. The statistical modeling and optimization of a multistage gas–solid fluidized bed reactor was performed by Mahalik et al. (2015) to control hazardous pollutants in the flue gas. The DOE technique was also used for the analysis and model predictions of the effect of various process parameters on the crushing strength of catalyst support (Samimi et al., 2015).

Shilapuram et al. (2009) dealt with different experimental methods to obtain hydrodynamic responses of a LSCFB. Results clearly showed that the range of a stable operating regime (operating regime window), average solids holdup, and solids circulation rate were significantly different for the different methods of operation for the same settings of factors (primary and auxiliary liquid velocity, solids inventory in the downcomer, and viscosity of liquid media). In our previous study, a full factorial design of the experimental methodology was adapted to model the hydrodynamics of the LSCFB.

Therefore, in the present study, an attempt has been made to adapt the multi-level factorial design methodology for modeling the chosen LSCFB system is adapted and to find a generalized

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