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Hydrodynamics and particle mixing/segregation measurements in an industrial gas phase olefin polymerization reactor using image processing technique and CFD-PBM model

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ABSTRACT

Particle size distribution (PSD) has a significant impact on the performance of fluidized bed reactors due to uneven distribution in the segregation and mixing phenomena. This paper develops a new method of digital image processing that investigates the hydrodynamics of an industrial gas phase olefin polymerization reactor and studies the fluidization structure of a wide range of particle size distribution in an industrial gas phase polymerization reactor by means of a CFD-PBM coupled model, where the direct quadrature method of moments (DQMOM) was implemented to solve the population balance model. It was shown that the applied parameter assumptions and closure laws were appropriately chosen to satisfactorily predict the available operational data in terms of pressure drop and bed height. The transient CFD-PBM/DQMOM coupled model and image analysis technique are then implemented extensively to analyze bubble fluidization structure and segregation phenomena at different velocities. The particle segregation indicates that the small bubbles present in the bed are unable to induce vigorous mixing at low superficial gas velocity while particle mixing improves at a velocity above the minimum fluidization velocity. Further, the predicted results show higher axial segregation phenomena when compared to the radial direction.

1. Introduction

Fluidized bed reactors are widely used in industrial applications such as polymerization, granulation, drying, coating and chemical industries because of low investment and operating costs as well as the favorable heat/mass transfer that results in an efficient gas–solid mixing [1–17]. This physiochemical phenomenon is based on the idea of suspending a bed of small particles in a fluid-like state by the passage of a gas via the bed. In this case, gas velocities higher than the minimum fluidization velocity are required to maintain the bed at fluidization condition in the form of bubbles. The bubble formations as well as their created fluidization structures have crucial influence on

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gas and solid mixing, heat and mass transfer, and reactant conservation. Although numerous investigations have been carried out regarding the fluidized bed structure and bed hydrodynamics, but there is lack of detailed knowledge about the flow structure in freely bubbling fluidized bed reactor. The issue of reactor scale-up is also a primary concern in commercializing the fluidization process [11,18–24].

However, some techniques such as capacitances probes [25], optical probes [26], X-ray imaging [27], pressure transducers [28], particle image velocimetry [29], and magnetic resonance imaging [30,31] have been used towards the investigation of fluidized beds. Recently, considerable attention has been paid to the implementation of computational fluid dynamics (CFD) to simulate of the flow structure in the gas phase fluidized bed reactors (FBRs) because of better access to high-performance computer technology and computational power [32–38]. In a practical polydisperse fluidized bed reactor, particles consist of a broad particle size distribution that change continuously due to growth, breakage, and agglomeration as well as particle–particle and fluid–particle interactions [3,4,39,40]. In these kinds of reactors, the particle segregation was observed where smaller particles migrate to the top of the bed while lager particles migrate to the bottom of the bed [41–43]. Therefore, providing a precise understanding of mixing and segregation and the fluidization structure is crucial to optimize the design, operation, and scale-up of polydisperse gas fluidized bed reactors. The population balance equation (PBE) for particle size distribution needs to be solved along with continuity, momentum, and energy equations in order to describe the particle size distribution (PSD) in multiphase flow.

One efficient method to analyze the impact of PSD on the performance of FBRs is by coupling the population balance model (PBM) into the CFD framework (CFD-PBM coupled model) [4,18,39]. Recently, more details of the coupled model were reviewed by Akbari et al. [44–47]. Silva et al. [48] utilized a CFD-PBM coupled model to investigate the quadrature method of moments (QMOM) and direct quadrature method of moments (DQMOM) in terms of efficiency and accuracy. In addition, Upadhyay and Ezekoye [49] presented that the proper choice of moments of the initial number density function may be a significant factor in obtaining more accurate solutions from QMOM or DQMOM. The QMOM and DQMOM solutions offer similar accuracy. But DQMOM is the most efficient method and is recommended for coupling population balance solutions to CFD simulations. Segregation phenomena in polydisperse fluidized beds have been extensively investigated by Fan et al. [50] and Fan and Fox [51]. They used an Eulerian–Eulerian model and DQMOM to describe particle segregation in a lab-scale FBR. The results obtained from the model were in agreement with the experimental results. Their results showed that segregation occurred at a superficial gas velocity lower than the minimum fluidization velocity of large particles. During segregation, small particles moved to the upper portions of the bed while larger particles migrated to the bottom of the bed and formed the de-fluidized layer. In addition, the segregation rates were low at a high superficial gas velocity.

Furthermore, it is not possible to specify a universal CFD framework for all possible applications due to computational constraints. However, it can be modified based on the operating conditions, bed configuration, and scale as well as the accuracy associated with their numerical implementation. Therefore, new techniques such as image analysis are needed for verification and validation of CFD modeling to become a standard tool to design and scale up industrial scale reactors.

The most recent works in the development of modern techniques for hydrodynamic study of gas-fluidized beds focus on the use of tomographic methods to present cross-sectional and three-dimensional images of the multi-phase flow behavior [52,53]. The main part of the study focuses on radiation absorption techniques such as X-ray, g-ray, positron emission tomography and electrical capacitance techniques. However, significant drawbacks of these methods are the weak spatial resolution and long scan times. Moreover, the limited size of the interrogation area, relative high capital investment and radiation hazards do not favor broad application of these methods [54].

Olaof et al. [55] experimentally studied fluidization behavior in a dense polydisperse gas-fluidized bed with two and three discrete particle sizes using a digital image analysis technique to study segregation phenomena. Their results showed that segregation occurred at the minimum fluidization velocity of an individual component, whereas the ternary mixtures were found to be well-mixed at a velocity lower than the minimum fluidization velocity of larger particles. Shen et al. [56] developed digital image analysis to extend the qualitative and quantitative analysis of freely bubbling fluidized bed to simulate the size, velocity, and axial and radial distribution of the bubble. In addition, bed dynamics and segregation rates were investigated by Goldschmidt et al. [54]. They developed an image analysis technique in terms of bed expansion and segregation dynamics in two-dimensional gas-fluidized beds.

To the best of our knowledge, this is the first time that an image processing algorithm is developed and combined with a CFD-PBM coupled model to characterize the hydrodynamics of an industrial gas phase fluidized bed reactor and predict bubble diameter, number of bubbles, axial and radial segregation phenomena under conditions pertinent to the industrial scale polymerization reactor. Moreover, the accuracy of the presented image processing technique and CFD-PBM coupled model was extensively tested. The simulation results were also compared with industrial operational data in terms of pressure drop and bed height. Therefore, the model can be used as a reliable tool for analyzing and improving the design and operation of the industrial gas phase polymerization FBRs.

2. Extracting bubble characteristics using an image processing method

Image processing is the study of any algorithm that takes an image as input and returns an image as output. It is the use of computer algorithms to perform image processing on digital images [57,58]. An image is an array, or a matrix, of square pixels (picture elements) arranged in columns and rows. The types of images are as follows: binary,