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A novel hydrodynamic model for conical spouted beds based on streamtube modeling approach

Arezou Niksiar, Morteza Sohrabi *

Chemical Engineering Department, Amirkabir University of Technology, Tehran 15875-4413, Iran

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ABSTRACT

The streamtube modeling technique adopted with a new approach and a hydrodynamic model is presented for conical spouted beds. None of the required empirical equations in the well-known streamtube model are needed to predict hydrodynamic parameters. The hydrodynamic parameters for three zones including spout, annulus, and fountain are determined based on the mass and momentum conservation equations. The locus of the streamlines is predicted together with the hydrodynamic parameters of the bed. Only a single empirical equation, which is the bed voidage at the minimum fluidization condition, is needed to solve the model. The model uses a one-dimensional formulization, nevertheless, the method is capable of predicting the radial distribution of air and solid velocities inside the spouted bed. The interparticle interactions of the solids are taken into account based on the granular kinetic theory. The simulated particle velocity profile in annulus shows reasonable agreement with the experimental results. The model is also successful in calculating fountain height.

1. Introduction

Spouted beds are being used in a number of physical and chemical processes. The advantages of spouted beds, including excellent hydrodynamic qualities and efficient heat and mass transfer between the phases, make the latter an appropriate alternative for performing fluid–solid processes [1].

Spouted bed technology is highly dependent upon empirical correlations for design and modeling purposes [2]. A number of empirical correlations are essentially presented for cylindrical spouted beds with flat or conical base. Nevertheless, it has been shown that the correlations proposed in the literature for the calculation of the hydrodynamics of spouted beds of cylindrical geometry are not suitable for evaluating the hydrodynamics of the operation in conical contactors [2,3]. A literature survey reveals that the empirical equations for the determination of useful parameters for hydrodynamic design of spouted beds with conical geometry are very scarce. Recently, in a comprehensive analysis, a number of correlations available in the literature for determining spouted bed's hydrodynamic parameters have been evaluated in detail. Such a study reveals that some correlations may impose errors as high as 700% when determining a design parameter [2].

Spouted beds have applications in a number of important processes including drying [4,5], pyrolysis [6,7], gasification [8,9], oxidation [10, 11], and desulfurization [12]. Certain mathematical models have been proposed for various processes implemented in spouted beds (drying [13–16], gasification [17,18], oxidation [19], and desulfurization [20, 21]). In this area, many computational fluid dynamics (CFD) models with different degrees of detail have been presented to predict flow patterns in spouted beds [22–25]. Recently, Salikov et al. [26] investigated the influence of the gas flow rate on spouted bed dynamics and spouting stability by means of 3D CFD-DEM (discrete element modeling) simulations. Deb and Tafti [27] coupled DEM with CFD to simulate a flat-bottomed rectangular spouted bed with two-dimensional jets.

Jiang et al. [28] adopted the three-dimensionally coupled CFD technology and Eulerian two-fluid model (TFM) to model the complex gas–solid flow in a pressurized conical–cylindrical spouted bed. Ren et al. [29] carried out numerical simulations based on the 3D DEM for studying the mixing behavior of monocomponent and binary particle systems in a spouted bed.

Despite a huge number of CFD models, Olazar et al. [30] succeeded in the prediction of reasonably accurate flow patterns of solid and air inside the spouted bed, applying a simple one-dimensional model. The great advantage of their simple model is the need for only two empirical equations: one for obtaining minimum spouting velocity and the second for determination of the pressure gradient throughout the bed [30]. Nevertheless, this one-dimensional model is unable to predict the radial distribution of velocities inside the bed.

As a reliable hydrodynamic modeling approach, the streamtube modeling of Piccinini et al. [31] is extended and used by researchers for the mathematical analysis of some processes [14,16,19,21]. This modeling approach generally requires a number of empirical correlations as supplementary equations such as axial velocities of gas and solid, bed voidage, spout diameter, minimum spouting velocity, minimum fluidizing velocity, maximum spoutable height, and fountain height. Nevertheless, according to the above discussion, the existing

* Corresponding author. Tel.: +98 21 64543155; fax: +98 21 66405847.
E-mail address: sohrabi@aut.ac.ir (M. Sohrabi).

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correlations are subjected to some large errors and their use should be restricted.

In this study, as an extension of the Olazar et al. [30] hydrodynamic model, an Eulerian–Eulerian two-fluid model is developed to predict the flow behavior of conical spouted beds. Despite the model of Olazar et al. [30], the present model is capable of predicting the radial distribution of gas and particle velocity in the annulus zone. In the present study, for the first time, the concept of streamtube modeling approach is adopted without the need for a bulk of empirical equations to determine the hydrodynamic parameters. On the other hand, the hydrodynamic parameters are predicted based on the mass and momentum conservation equations. Gidapows' drag model and Lun's granular kinetic theory are applied to describe the interfacial forces and the solid stresses, respectively.

2. Mathematical model

Fig. 1 illustrates schematic representation of three zones in the spouted bed consisting of the spout, annulus, and fountain. The particles, upon leaving the spout, drop down to the annulus region. It is assumed that air simply flows out of the bed. In the fountain, gas and particles move upward co-currently.

In this study, the spout region is modeled with the plug flow assumption. The concept of streamtube modeling from Lim and Mathur [32] is applied in order to model the annular region. The equations describing mass and momentum are given below.

2.1. Governing conservation equations

2.1.1. Spout zone

Along the spout region, the gas and particles flow co-currently from the bottom to the top, while the particles enter the spout from the annulus region. Therefore, the voidage fraction of the spout, ε_s is changed from bottom to top. Gas flows upward with uniform velocity in the radial direction, u_s, passes the spout and enters the annulus region by velocity U_r. Fig. 2 shows a control volume of the spout region selected to develop the model's equations. The diameter of this element is assumed to be constant and equal to the inlet diameter of the bed ($d_s = D_i$).

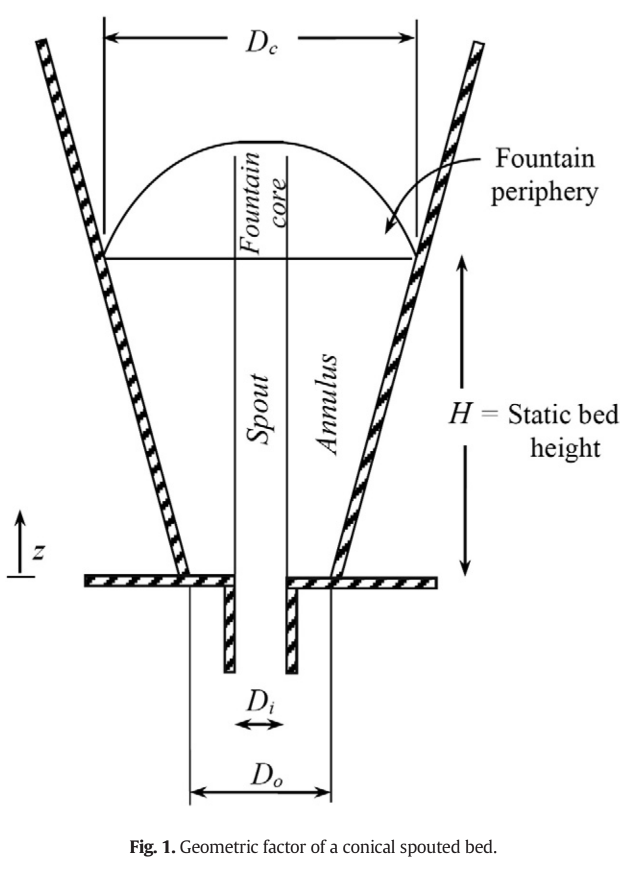

Fig. 1. Geometric factor of a conical spouted bed.

In the spout region, the mass conservation equations for air and particulate phases are:

$$\frac{d(u_s\varepsilon_s)}{dz} = \frac{-4U_r}{d_s} \tag{1}$$

$$\frac{d[v_s(1-\varepsilon_s]}{dz} = \frac{4V_r}{d_s} \tag{2}$$

where U_r and V_r are radial air and solid velocities at the interphase between spout and annulus, respectively.

The momentum balance equation for air in the spout is represented as follows [33]:

$$-\rho_g\frac{d\left(\varepsilon_s u_s^2\right)}{dz} - \frac{4\rho_g u_s}{d_s}U_r - \beta_s(u_s-v_s) - \varepsilon_s\frac{dp}{dz} = 0 \tag{3}$$

By substituting the air continuity from Eq. (1) into Eq. (3), it yields:

$$-\rho_g\varepsilon_s u_s\frac{du_s}{dz} - \beta_s(u_s-v_s) - \varepsilon_s\frac{dp}{dz} = 0 \tag{4}$$

The momentum balance for particulate phase accounting for convective momentum transfer, momentum transferred by particles entering from the annulus zone, the gravitational force, the buoyancy force, the fluid–particle interaction force, and the pressure of solid yields [33]:

$$-\rho_p\frac{d\left[v_s^2(1-\varepsilon_s)\right]}{dz} + \frac{4\rho_p v_s}{d_s}V_r - \rho_p(1-\varepsilon_s)g + \rho_g(1-\varepsilon_s)g + \beta_s(u_s-v_s) - (1-\varepsilon_s)\frac{dp}{dz} = 0 \tag{5}$$

By substituting the solid continuity from Eq. (2) into the above equation, the following relation is obtained [33]:

$$-v_s(1-\varepsilon_s)\rho_p\frac{dv_s}{dz} - (1-\varepsilon_s)\left(\rho_p-\rho_g\right)g + \beta_s(u_s-v_s) - (1-\varepsilon_s)\frac{dp}{dz} = 0 \tag{6}$$

2.1.2. Annular zone

The annulus zone is modeled based on the streamtube concept of Lim and Mathur [32]. In this model, the width of the annulus at the top of the bed is divided into k_{max} equal intervals. The streamlines start at the annulus–fountain interface, and end at the spout–annulus interface. Hence, the annulus is considered to consist of a series of

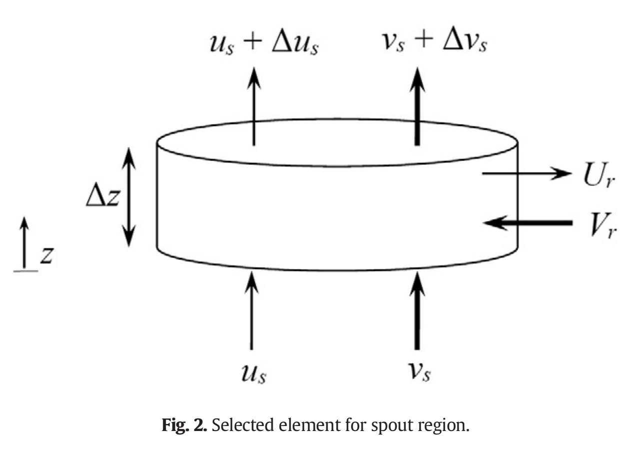

Fig. 2. Selected element for spout region.