Powder Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Sub-grid drag model for immersed vertical cylinders in fluidized beds

Vikrant Verma [a,*], Tingwen Li [a,b], Jean-François Dietiker [a,c], William A. Rogers [a]

[a] National Energy Technology Laboratory, Morgantown, WV 26505, USA
[b] AECOM, Morgantown, WV 26505, USA
[c] West Virginia University Research Corporation, Morgantown, WV 26506, USA

ARTICLE INFO

Article history:
Received 29 April 2016
Received in revised form 22 October 2016
Accepted 15 December 2016
Available online xxxx

Keywords:
Two-fluid model
Filtered model
Fluidized bed
Cylinders
Drag force

ABSTRACT

Immersed vertical cylinders are often used as heat exchanger in gas-solid fluidized beds. Computational Fluid Dynamics (CFD) simulations are computationally expensive for large scale systems with bundles of cylinders. Therefore sub-grid models are required to facilitate simulations on a coarse grid, where internal cylinders are treated as a porous medium. The influence of cylinders on the gas-solid flow tends to enhance segregation and affect the gas-solid drag. A correction to gas-solid drag must be modeled using a suitable sub-grid constitutive relationship. In the past, Sarkar et al. [1] have developed a sub-grid drag model for horizontal cylinder arrays based on 2D simulations. However, the effect of a vertical cylinder arrangement was not considered due to computational complexities. In this study, highly resolved 3D simulations with vertical cylinders were performed in small periodic domains. These simulations were filtered to construct a sub-grid drag model which can then be implemented in coarse-grid simulations. Gas-solid drag was filtered for different solids fractions and a significant reduction in drag was identified when compared with simulation without cylinders and simulation with horizontal cylinders. Slip velocities significantly increase when vertical cylinders are present. Vertical suspension drag due to vertical cylinders is insignificant however substantial horizontal suspension drag is observed which is consistent to the finding by Sarkar et al. [1] for horizontal cylinders.

1. Introduction

Vertical cylinder tubes are often integrated in industrial gas-solid fluidized beds. The presence of these in-bed tubes has several advantages, including preventing slugging in the bed where bubble size can reach the bed diameter. Almstedt [2] and Jin et al. [3] suggested that in-bed tube geometries offer a fairly well-defined bubble path up through the bed, as the bubbles grow to a limited size in free passage between the tubes. If there are many such free bubble paths in a wide bed, the bed as a whole will not show a slugging behavior. In many industrial fluidized beds, submerged tubes (i.e. heating or cooling tubes) are used to enhance heat and mass transfer. In addition to acting as a heat exchanger, these submerged tubes also alter the hydrodynamics significantly. It is well known that presence of these tubes affects bubble growth significantly, such as preventing them from coalescing and forcing large bubbles to split [3,4]. Bubble splitting results in redistribution of gas into emulsion phase and a homogenous distribution of bubbles across the reactors [5,6]. Hence it affects particle clustering and changes macroscopic flow patterns [1].

Study of vertical tubes in large scale fluidized beds remains a challenge. This is due to lack of accurate measurement techniques since measurements for gas and solid phases are inherently affected by vertical tubes. Spatial measurements are investigated on the basis of time-averaged statistics. Rudisuli et al. [6,7] have investigated bubble characteristics using pressure fluctuation measurements and an optical probe technique. However accurate information describing solids motion still remains a challenge for researchers. CFD modeling has helped to investigate hydrodynamics in great detail and has revealed microscopic information on gas and solid motion [8]. However, CFD simulations are computationally expensive for large scale systems and the presence of cylinder bundles introduces additional complexity. Although it is reasonably accurate to study a two-dimensional cross section of the bed when horizontal tubes are present, numerical simulations with vertical tubes must be performed with three-dimensional geometries [1]. The grid used in CFD simulations needs to be fine enough (with grid cells on the order of a few particle diameters) to resolve flow phenomenon with the smallest length-scales [9]. To obtain good quantitative predictions, billions of computational cells are required to resolve the flow around cylinders in industrial scale reactors. Even with advancement of computational resources, simulations are unable to study industrial scale reactors. Therefore, to achieve real length and time scale simulations for industrial fluidized beds, coarse grained model is preferred such as filtered two-fluid model or sub-grid model [9,10]. Having the ability to perform such simulations could help to design and optimize the industrial scale reactors. The multiphase flow group at Princeton

* Corresponding author.
E-mail addresses: dr.v.vikrant@gmail.com, Fnu.Vikrant@contr.netl.doe.gov (V. Verma).

http://dx.doi.org/10.1016/j.powtec.2016.12.044
0032-5910/© 2017 Elsevier B.V. All rights reserved.

University has developed filtered models to approximate the unresolved physics and geometry using constitutive relations [14–16]. They have shown the capability of the model to predict hydrodynamics behavior in terms of particle bed height, pressure drop across the bed, and porosity distribution using filtered model. The filtered model employs constitutive relations obtained from highly resolved simulations to model a complex system where flow is significantly affected. The influence of cylinders on the gas-solid flow tends to enhance particle segregation and affects the gas-solid drag. A correction to gas-solid drag must be modeled via a suitable sub-grid constitutive relationship. In the past, Sarkar et al. [1] have developed a sub-grid drag model for horizontal cylinder arrays based on 2D simulations. In another study [11] they showed a verification of their sub-grid model for horizontal cylinders; by comparing results obtained from highly resolved simulation. However, the effect of a vertical cylinder arrangement was not considered due to computational complexities. In this work we show a correction to gas-solid drag for use as a sub-grid model for arrays of vertical cylinders. We follow the same filtering method as used for horizontal tubes in Sarkar et al. [1]. Readers are referred to Sarkar et al. [1] for details on the method. Only information relevant to the present filtering method is discussed in this article.

2. Two-fluid model simulations

Simulations were performed using MFIX two fluid model (TFM) [12]. Details on theory and numerical techniques used in MFIX can be found at https://mfix.netl.doe.gov [12,13]. Conservative TFM model equations used in MFIX are given in Table 1. Highly resolved TFM simulations were performed for a 3D periodic domain in a Cartesian grid structure. Periodic domain forms a cubic lattice with one full cylinder at the center and quarter-cylinder at each corner as shown in Fig. 1. We made this choice of cylinder diameter and spacing based on an industrial design of 1 MW carbon capture pilot plant that was design with similar cylinder arrangements. Developed sub-grid drag model from this study is eventually applied to study this 1 MW carbon capture pilot plant under Carbon Capture Simulation Initiative (CCSI) project. For comparison purposes, simulations were performed for a 3D periodic domain without cylinders. Studies were performed for various solids fraction of 0.2, 0.3, 0.4 and 0.5, which are typical for most fluidized bed operations. Details on particle properties and computational parameters are given in Tables 2 and 3. Gas-particle flow is driven by enforcing a vertical pressure drop (ΔP), expressed in terms of static bed weight ($(\phi_g\rho_g + \phi_s\rho_s)\vec{g}$). The second order discretization Superbee scheme, and Wen and Yu [17] gas-solid drag model was used. Simulations were performed to achieve steady state filtered gas and solids velocities, which typically took 20–25 s of simulated time.

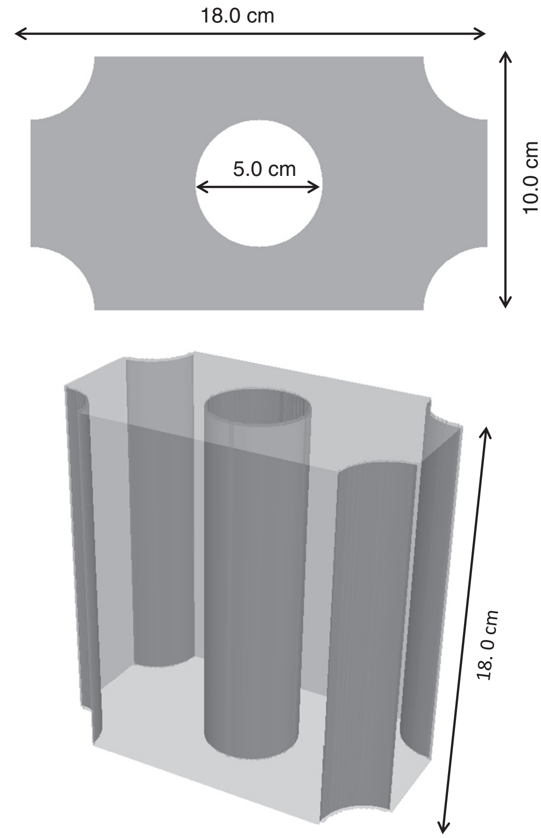

Fig. 1. Periodic domain with vertical tubes, (top) top view of domain (bottom) full 3D domain.

3. Filtered two-fluid model equations for vertical cylinder drag

Microscopic quantities for gas and solids phase obtained from MFIX-TFM simulations were filtered out using constitutive relationships as

Table 1
Summary of TFM governing equations.

Continuity equation: (T1-1)

$$\frac{\partial(\phi_g\rho_g)}{\partial t} + \nabla\cdot(\phi_g\rho_g\vec{v}_g) = 0$$
$$\frac{\partial(\phi_s\rho_s)}{\partial t} + \nabla\cdot(\phi_s\rho_s\vec{v}_s) = 0$$

Momentum equation: (T1-2)

$$\frac{\partial(\phi_g\rho_g\vec{v}_g)}{\partial t} + \nabla\cdot(\phi_g\rho_g\vec{v}_g\vec{v}_g) = -\phi_g\nabla p_g - \nabla\cdot(\phi_g\bar{\bar{\tau}}_g) - \beta_{g\cdot s}(\vec{v}_g - \vec{v}_s) + \phi_g\rho_g\vec{g}$$
$$\frac{\partial(\phi_s\rho_s\vec{v}_s)}{\partial t} + \nabla\cdot(\phi_s\rho_s\vec{v}_s\vec{v}_s) = -\phi_s\nabla p_g - \nabla p_s - \nabla\cdot(\phi_s\bar{\bar{\tau}}_s) + \beta_{g\cdot s}(\vec{v}_g - \vec{v}_s) + \phi_s\rho_s\vec{g}$$

Granular energy conservation (algebraic formulation): (T1-3)

$$\theta_s = \left[\frac{-K_1\phi_s tr(D_s) + \sqrt{[K_1 tr(D_s)\phi_s]^2 + 4K_4\phi_s[K_2 tr^2(D_s) + 2K3(D_s:D_s)]}}{2\phi_s K_4}\right]^2$$

Where $D_s = \frac{1}{2}[\nabla\vec{v}_s + (\nabla\vec{v}_s)^T]$,

$K_1 = 2(1+e_{pp})\rho_s g_0, K_2 = \frac{4d_p(1+e_{pp})\rho_s\phi_s g_0}{3\sqrt{\pi}} - \frac{2}{3}K_3,$

$K_3 = \frac{d_p\rho_s}{2}\left\{\frac{\sqrt{\pi}}{3(3-e_{pp})}[0.5(1+3e_{pp}) + 0.4(1+3e_{pp})(3e_{pp}-1)\phi_s g_0] + \frac{8\phi_s g_0(1+e_{pp})}{5\sqrt{\pi}}\right\},$

$K_4 = \frac{12(1-e_{pp}^2)\rho_s g_0}{d_p\sqrt{\pi}}$

Wen and Yu, 1996 drag correlation:

$$\beta_{g\cdot s,micro} = \frac{3}{4}C_D\frac{\rho_g(1-\phi_s)\phi_s|v_g - v_s|}{d_p}(1-\phi_s)^{-2.65}$$
$$C_D = \begin{cases}\frac{24}{Re_p}(1+0.15Re_p^{0.687}), Re_p<1000\\ 0.44, Re_p \geq 1000\end{cases}$$
$$Re_p = \frac{(1-\phi_s)\rho_g d_p|v_g - v_s|}{\mu_g}$$

Please cite this article as: V. Verma, et al., Sub-grid drag model for immersed vertical cylinders in fluidized beds, Powder Technol. (2017), http://dx.doi.org/10.1016/j.powtec.2016.12.044