CFD STUDY OF A FLUIDIZED BED DRYER

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Abstract. *In this work, we investigate numerically the drying of the soybean meal in a fluidized bed. Our modeling is implemented using the open-source code MFIX. For the code, the gas and solid phases are treated as inter-penetrating continua in an Eulerian/Eulerian framework. The numerical results are compared with a set of bed hydrodynamics and drying data for the soybean meal from our fluid bed experimental rig. Following, the outcome of the one main parameters from the physical model was explored: drag relationship between the two phases. The results obtained by the different drag relationships were compared with the fluidization curves from the experimental data. The degree of accordance points to the better hydrodynamic setting to be used. Finally, a comparison of numerical results from the drying phenomena with experimental measurements led to the conclusion about the proper setting of the drag relationship in the hidrodynamic model..*

***Keywords**: fluidized bed, drying, computational fluid dynamics, MFIX*

1. INTRODUCTION

The fundamental goal during soybean meal production is a quality product with a minimum cost. The drying process contributes to final moisture approaches to the desired levels. Fluidized bed drying involves simultaneous heat, mass and momentum transfer process, giving a highly non-linear set of governing equations. Also numerous parameters affect drying processes, many of them material dependent. In spirit of their large application, understanding of the complex multi-phase flows involved in fluidized beds using computer simulations can became a good approach to the design, optimization, and control of industrial-scale fluidized bed driers. Availability of more sophisticated computer models is expected to result in greatly increased performance and reduced costs associated with fluidized bed driers implementation and operation. In this work is explored the effect of different parameters from hidrodynamics on the drying results predicted by a CFD code for a laboratory gas fluidized bed dryer.

CFD studies have become popular in the field of fluidized systems during the last two decades. Using the van der Hoef et al.(2008) classification, those studies can be classified in Eulerian-Eulerian or Eulerian-Lagrangian. Without being exhaustive, in the category Eulerian-Eulerian, we can highlight works such as Syamlal and O´Brien (1989), Tsuo and Gidaspow(1990), Gidaspow et al.(1990, 1992, 1996, 2004), Bokkers et al.(2004), Pannala et al. (2007), Li and Kuipers(2007). On the Eulerian-Lagrangian approach also progress has been made (Tsuji et al.(1993), Rhodes et al.(2001) , Goldschmidt et al.(2003), Tsuji(2007) , Wang, et. al. (2008), Link et al.(2009)). Coupling the hydrodynamics with heat transfer was also studied (Syamlal and Gidaspow(1985); Kuipers et al.(1992); Wang et al. (1997), Patil et al. (2006), Zhou, et al. (2009) and, increasing the degree of complexity, an additional coupling with reaction kinetics (Syamlal and O´Brien(2003) , Shi et al.(2006), Zhang et al.(2009), Chalermsinsuwan et al.(2009), and Cadoret et al.(2009)).

On the other side, mathematical modelling and numerical simulation of fluidized bed dryers is not recent. The reader is refered to the review by Wang et al.(2007) for one account on mathematical modelling.

By its turn, exploring the hydrodynamics coupled with thermodynamics of drying using the Eulerian-Eulerian or Eulerian-Lagrangian approach is recent. A few works can be highlighted. As in Wang et al. (2008), the predicted drying results using CFD showed some tendencies for temperature and solids moisture. Due to computationally intensive time demand the CFD results were limited to shorter periods of time or focusing the hydrodynamics (Zhonghua and Mujumdar(2007), Wang et al.(2008), Sobieski(2008)). In this sense the results are valuable for exploring hydrodynamics and can benefit from previous works where purely the hydrodynamics were studied.

In this work is explored the effect of different parameters from drying kinetics on the drying results predicted by solving a full set of Eulerian-Eulerian equations using a CFD code. The numerical setup and some comparison are based on a laboratory scale gas fluidized bed dryer.

2. MATHEMATICAL MODEL

The mathematical model is based on the assumption that the phases can be mathematically described as interpenetrating continua; the point variables are averaged over a region that is large compared with the particle spacing but much smaller than the flow domain (see Anderson, 1967). A short summary of the equations solved by the numerical code in this study are presented next. Refer to Benyahia et al. (2006) and Syamlal et al. (1993) for more detailment.

The continuity equations for the fluid and solid phase are given by :

$$\frac{\partial}{\partial t}\left(\varepsilon_f\rho_f\right) + \nabla\bullet\left(\varepsilon_f\rho_f\,\vec{v}_f\right) = \sum_{n=1}^{N_f} R_{fn} \tag{2}$$

$$\frac{\partial}{\partial t}\left(\varepsilon_s\rho_s\right) + \nabla\bullet\left(\varepsilon_s\rho_s\,\vec{v}_s\right) = \sum_{n=1}^{N_s} R_{sn} \tag{3}$$

In the previous equations ε_f, ε_s, ρ_f, ρ_s, $\vec{v}_f$ and $\vec{v}_s$ are the volumetric fraction, density and velocity field for the fluid and solids phases. The right side term in the continuity equations accounts for interphase mass transfer because of chemical reactions or physical processes, such as evaporation. The subscript n corresponds to the n chemical specie.

The momentum equations for the fluid and solid phases are given by:

$$\frac{\partial}{\partial t}\left(\varepsilon_f\rho_f\vec{v}_f\right) + \nabla\bullet\left(\varepsilon_f\rho_f\vec{v}_f\vec{v}_f\right) = \nabla\bullet\overline{\overline{S}}_f + \varepsilon_f\rho_f\vec{g} - \vec{I}_{fs} \tag{4}$$

$$\frac{\partial}{\partial t}\left(\varepsilon_s\rho_s\vec{v}_s\right) + \nabla\bullet\left(\varepsilon_s\rho_s\vec{v}_s\vec{v}_s\right) = \nabla\bullet\overline{\overline{S}}_s + \varepsilon_s\rho_s\vec{g} + \vec{I}_{fs} \tag{5}$$

$\overline{\overline{S}}_f$ $\overline{\overline{S}}_s$ are the stress tensors for the fluid and solid phase. It is assumed newtonian behavior for the fluid and solid phases. Moreover, the solid phase behavior is divided between a plastic regime (also named as slow shearing frictional regime) and a viscous regime (also named as rapidly shearing regime). The constitutive relations for the plastic regime are related to the soil mechanics theory On the other hand, the viscous regime behavior is ruled by kinetic theory related parameters.

$\vec{I}_{fs}$ is the momentum interaction term between the solid and fluid phases. In his formulation there is a term proportional to velocities differences between phases: the drag coefficient β. There is a number of correlation the drag coefficient. The first of the correlations for the drag coefficient is based on Wen and Yu (1966) work. The Gidaspow drag coefficient is a combination between the Wen Yu correlation and the correlation from Ergun (1952). The correlation proposed by Syamlal and O'Brien (1993) carries the advantage of being adjustable for different minimum fluidization conditions. The drag correlation from Hill, Koch and Ladd (2001a, b) work is based on Lattice-Boltzmann simulations. The blended drag correlation originally proposed by Lathowers and Bellan (2000) allows controlling the transition from the Wen and Yu, and Ergun based correlations.

Equation (5) is a transport equation for the granular energy Θ. Its solution provides a way of determine the pressure and viscosity for the solid phase during the viscous regime. The terms κ_s γ and ϕ_{gs} are the granular energy conductivity, dissipation and production, respectively.

$$\frac{3}{2}\left[\frac{\partial}{\partial t}\varepsilon_s\rho_s\Theta + \nabla\bullet\rho_s\vec{v}_s\Theta\right] = \overline{\overline{S}}_s : \nabla\vec{v}_s - \nabla\bullet\left(\kappa_s\nabla\Theta\right) - \gamma + \phi_{gs} \tag{6}$$

The energy equations in terms of temperatures T_f and T_s for the fluid and solid phases are given in Eqs. (7) and (8). The specific heat and conductive flux for the fluid and solid phase are denoted by C_{pf}, C_{ps}, $\vec{q}_f$ and $\vec{q}_s$, respectively. The second term in the right hand side of Eqs. (7) and (8) accounts for the thermal energy transfer between the phases. The last terms in Eqs (7) and (8) accounts for the enthalpy variation due to chemical or phase change reactions. For the energy equation the following assumptions were made : no viscous dissipation, no pressure work, no radiation exchange effects.

$$\varepsilon_f\,\rho_f\,C_{pf}\left[\frac{\partial T_f}{\partial t} + \left(\vec{v}_f\bullet\nabla\right)T_f\right] = -\nabla\bullet\vec{q}_f + \gamma_{fs}\left(T_s - T_f\right) - \Delta H_f \tag{7}$$

$$\varepsilon_s\rho_s C_{ps}\left[\frac{\partial T_s}{\partial t} + \left(\vec{v}_s\bullet\nabla\right)T_s\right] = -\nabla\bullet\vec{q}_s - \gamma_{fs}\left(T_s - T_f\right) - \Delta H_s \tag{8}$$

The species transport equations in terms of mass fractions X_{fn} and X_{sn} for the chemical species in the fluid and solid phases are given by Eqs. (9) and (10): In these equations the diffusive effects were neglected. The terms R_{fn} and R_{sn}

represents the fluid and solids species production due to a chemical or phase change reaction. For our case of study, we considered the solid phase containing two species : liquid water and dry soybean meal. The fluid phase is considered composed of two species : gaseous water and dry air. The water evaporation from solids to air is modeled according to Eq. (11), where C is given from Luz et al (2009) according to Eq. (12), and the superscript eq corresponds to the saturation values.

$$\frac{\partial}{\partial t}\left(\varepsilon_f\ \rho_f\ X_{fn}\right)+\nabla\bullet\left(\varepsilon_f\ \rho_f\ \vec{v}_f\ X_{fn}\right)=R_{fn} \tag{9}$$

$$\frac{\partial}{\partial t}\left(\varepsilon_s\ \rho_s\ X_{sn}\right)+\nabla\bullet\left(\varepsilon_s \rho_s \vec{v}_s\ X_{sn}\right)=R_{sn} \tag{10}$$

$$R_{s-liquid-water} = C\ \left(X_{\text{s-liquid-water}} - X^{eq}_{\text{s-liquid-water}}\right) \tag{11}$$

$$C=\left(-0.0047T_{air}+0.7668\right)X^2_{s-liquid-water}+\left(0.0022T_{air}-0.2515\right)X_{s-liquid-water}+0.0027\exp\left(71.8130/T_{air}\right) \tag{19}$$

where T_{air} is the inlet air temperature.

3. NUMERICAL METHOD

MFIX (Multiphase Flow with Interphase eXchanges) is an open source CFD code developed at the National Energy Technology Laboratory (NETL-USA) for describing the hydrodynamics, heat transfer and chemical reactions in fluid-solids systems. It has been used for describing bubbling and circulating fluidized beds, spouted beds and gasifiers. MFIX calculations give transient data on the three-dimensional distribution of pressure, velocity, temperature, and species mass fractions. Furthermore, the code has a bult-in database for calculating the heat capacity and enthalpy variations given in eqs. (7) and (8).

The hydrodynamic model is solved using the finite volume approach with discretization on a staggered grid. A second order accurate discretization scheme was used and superbee scheme was adopted for discretization of the convective fluxes at cell faces for all equations in this work. With the governing equations discretized, a sequential iterative solver is used to calculate the field variables at each time step. The main numerical algorithm is an extension of SIMPLE (see Patankar (1980) ot Anderson (1995)). Modifications to this algorithm in MFIX include a partial elimination algorithm to reduce the strong coupling between the two phases due to the interphase transfer terms. Also, MFIX makes use of a solids volume fraction correction step instead of a solids pressure correction step which is thought to assist convergence in loosely packed regions. Finally, an adaptive time step is used to minimize computation time. See Syamlal (1998) for more details.

The CFD setup is based on the experimental fluidized bed rig available at the Chemical Engineering Department of the Maringá State University (see Costa et al. 2009). Figure. 1 sumarizes the fluidized bed geometry. Table 1 sumarizes the set of physical properties, boundary and initial conditions used in the drying simulations. The numerical runs were based on an axisymmetrical cylindrical coordinate system. The grid employed after mesh refinement studies was 20 (radial) × 80 (axial).

Table 1. Baseline drying simulation parameters and material properties

Solids density, ρ_s (kg/m^3)	1240.0
Gas density, ρ_g (kg/m^3)	1.189
Mean particle diameter, d_p (cm)	0.1958
Minimum fluidization velocity, U_{mf} (m/s)	0.66
Minimum fluidization voidage, ε	0.346
Gas superficial velocity, v_{air} (m/s)	2.06
Static bed height (cm)	7.5
Air inlet temperature (C)	50
Air inlet humidity	0.004
Solids initial moisture	0.2101
Solids initial temperature (C)	25

In this work, the parameters for controlling the numerical solution (e.g., under-relaxation, sweep direction, linear equation solvers, number of iterations, residual tolerances) were kept as their default code values. For setting up the mathematical model we also kept the default code values. The computer used in the numerical simulations was a PC with OpenSuse linux and Intel Quad Core processor.

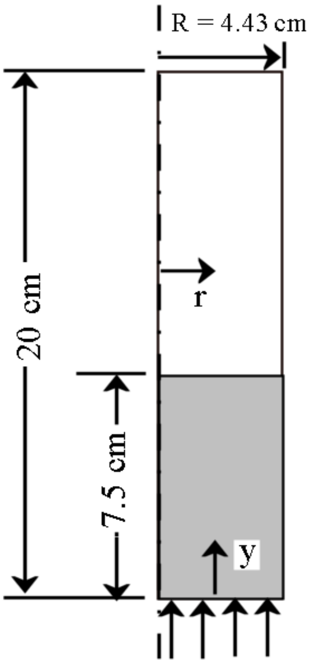
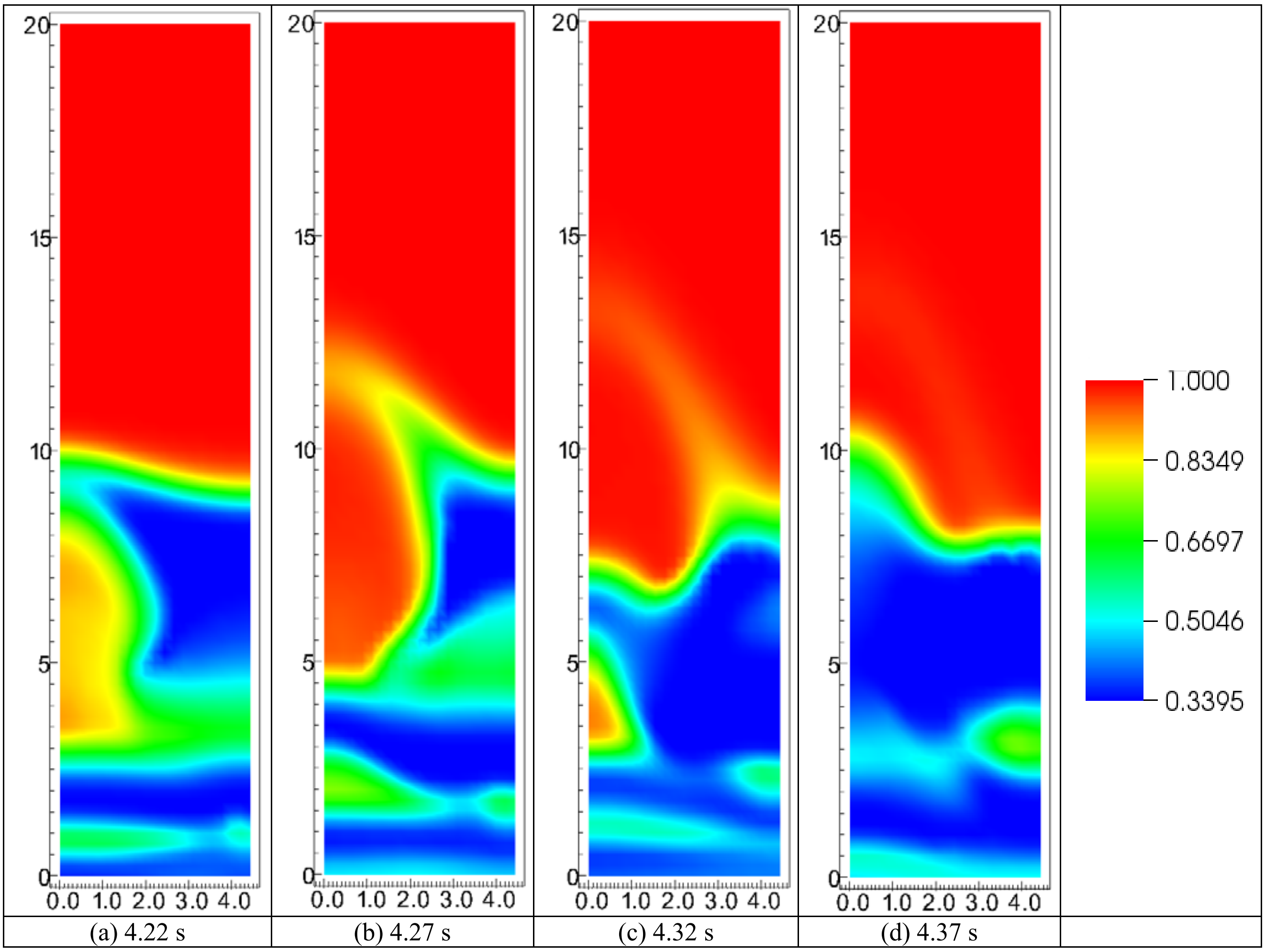


Figure 1. Bed geometry for CFD simulations.

4. RESULTS AND DISCUSSION



(a) 4.22 s
(b) 4.27 s
(c) 4.32 s
(d) 4.37 s

Figure 2. Instantaneous voidage fields at different times

Figure 2 is a sampling plot showing the instantaneous gas volumetric fraction fields for different times. It clearly shows the passage of high voidage regions (bubbles) in the dense bed.

Pressure drop curves were experimentally obtained for particles with different diameters. The minimum fluidization velocity was achieved from the descendant velocity path. The experimentally measured pressure drops were compared with the numerical values calculated using the drag correlations according to Wen and Yu, Gidaspow, Syamlal and O´Brien, and Hill, Koch and Ladd. The points depict the pressure drop experimental values for increasing and decreasing flow velocity, whereas the lines show the numerical values using different drag correlations. The experimental uncertainties were ± 4.5 % for velocity and ± 4.9 Pa for pressure. For analysis, we considered two regions, the defluidized state, with velocities below the minimum fluidization velocity and greater pressure drop variation, and the fluidized state with higher velocities and smaller pressure drop variation. These figure analyses shows that in the defluidized state Syamlal-Obrien under predicts the pressure drop for the smaller diameters, whereas for the intermediate particle diameter the results locate between the increasing and decreasing values. Furthermore, for the defluidized state, for the highest diameter the results predicted using the Syamlal-Obrien correlation are over the experimental. By his turn, for the fluidized state the Syamlal-Obrien correlation is in good agreement with the experimental data, for all particle diameters. The defluidized and fluidized state results using the Gidaspow and Koch-Hill are over predicted in all velocities. By his turn, the last correlations show the results are not so much affected by the particle diameter. Finally, for Wen and Yu greater values are obtained in the defluidized state. All the correlations give good agreement in the fluidized region.

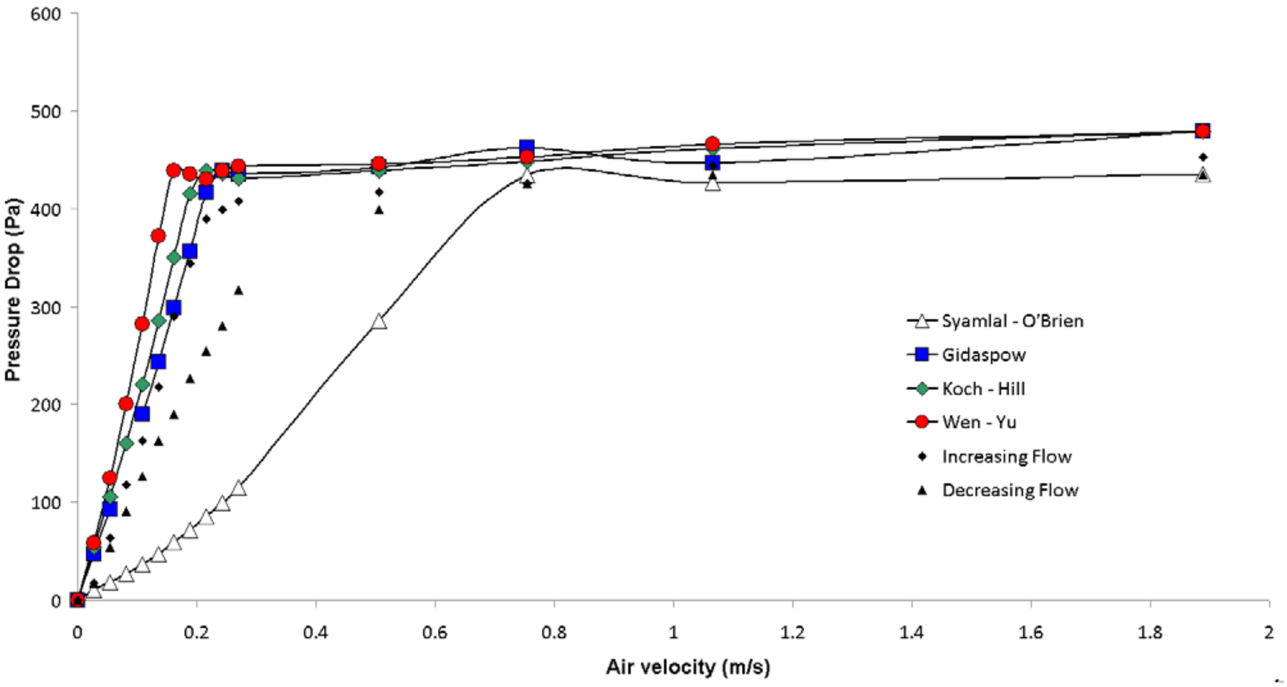


Figure 3 Pressure drop versus air velocity. $d_p = 0.0993$ cm, $U_{mf} = 0.48$ m/s

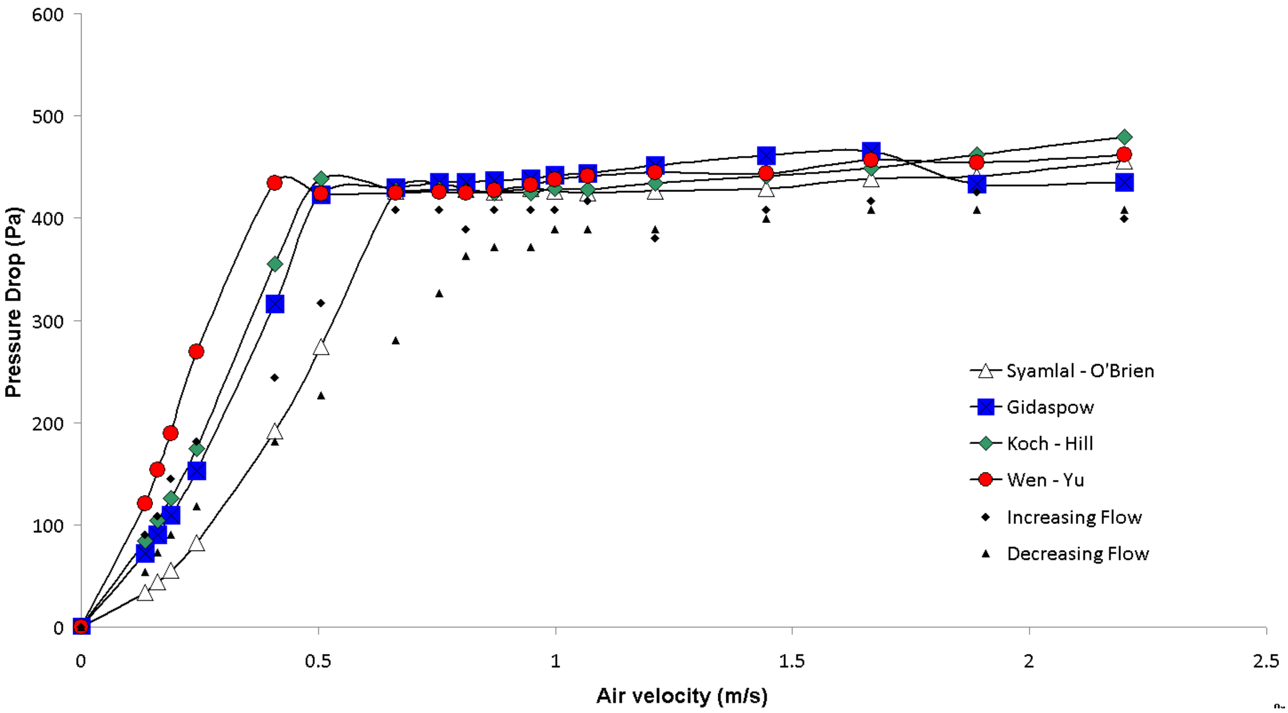


Figure 4 Pressure drop versus air velocity. Comparison $d_p = 0.1958$ cm, $U_{mf} = 0.66$ m/s

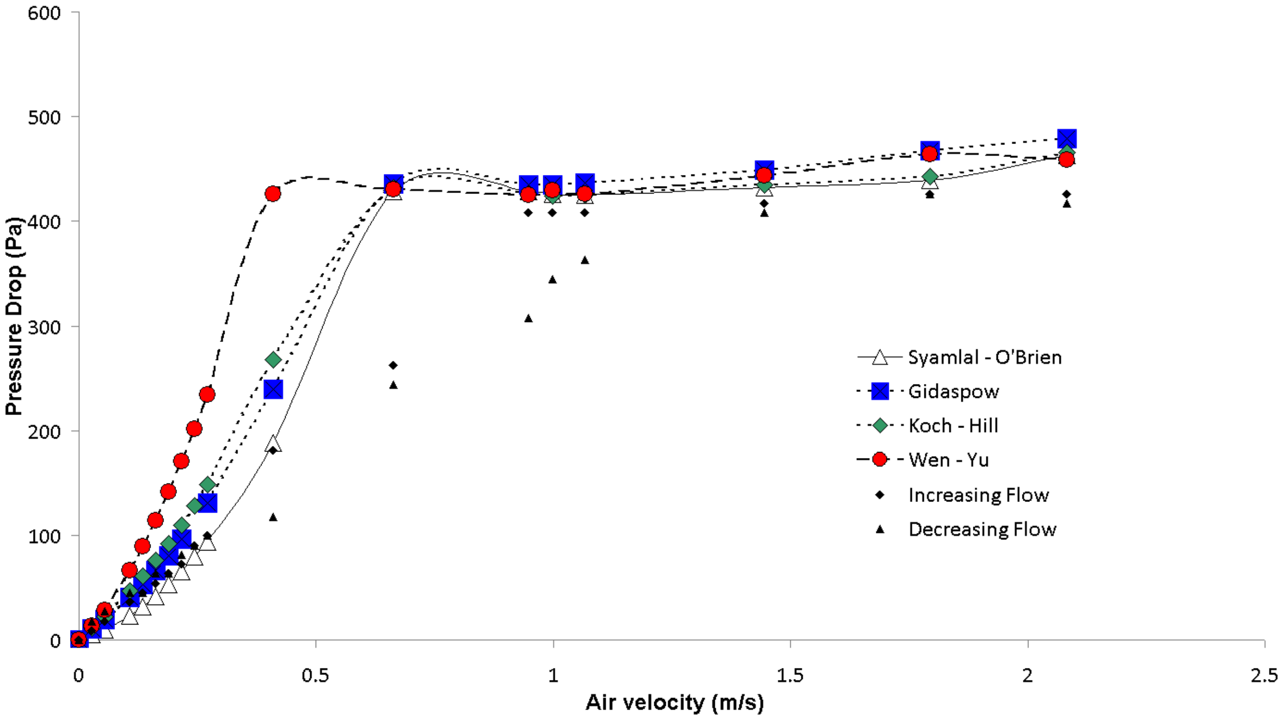


Figure 5 Pressure drop versus air velocity. $d_p = 0.2362$ cm, $U_{mf} = 1.2$ m/s

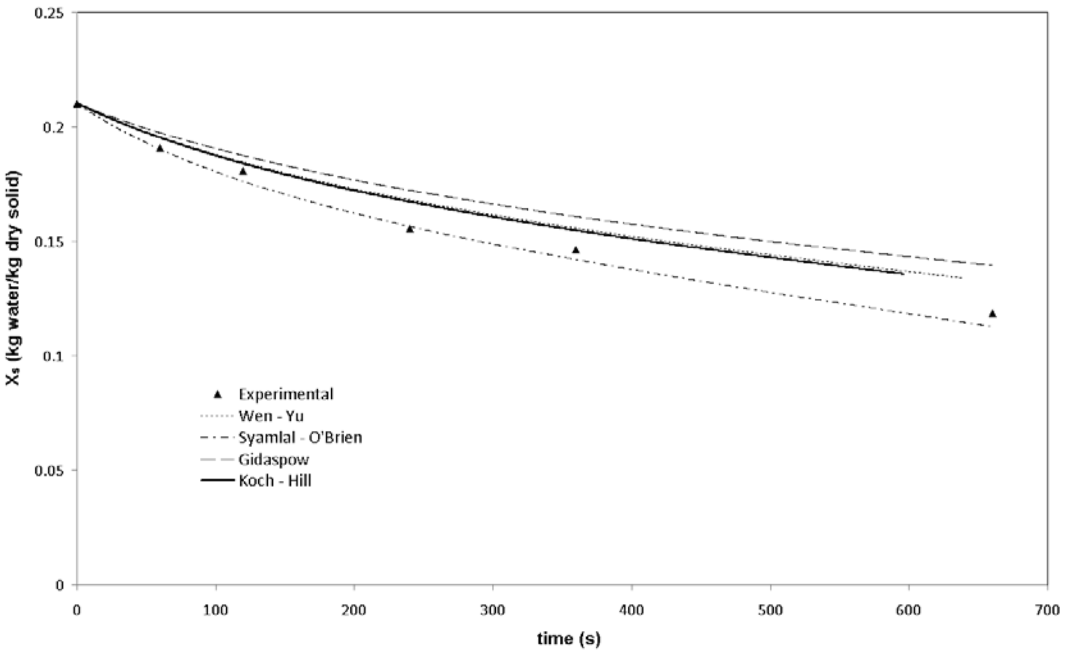


Figure 6 Effect of different drag correlations on the drying results.

Figure 6 shows a comparison for the solids moisture content, for the baseline case. All the results for drying will be given in terms of an averaged liquid water mass fraction for the dense part of the fluidized bed. The experimental uncertainty is ± 0.0001 kg water/kg solid. As can be seen the results obtained using the Syamlal and Obrien drag correlation are closer to the experimentally measured. As Syamlal and Obrien drag correlation is the only that can be adjusted for the experimental minimum fluidization velocity, their results were used for comparison with experimental data for longer simulation times. This is shown in Figure 7. Analysis shows the good agreement persists up to 3500 s simulation time.

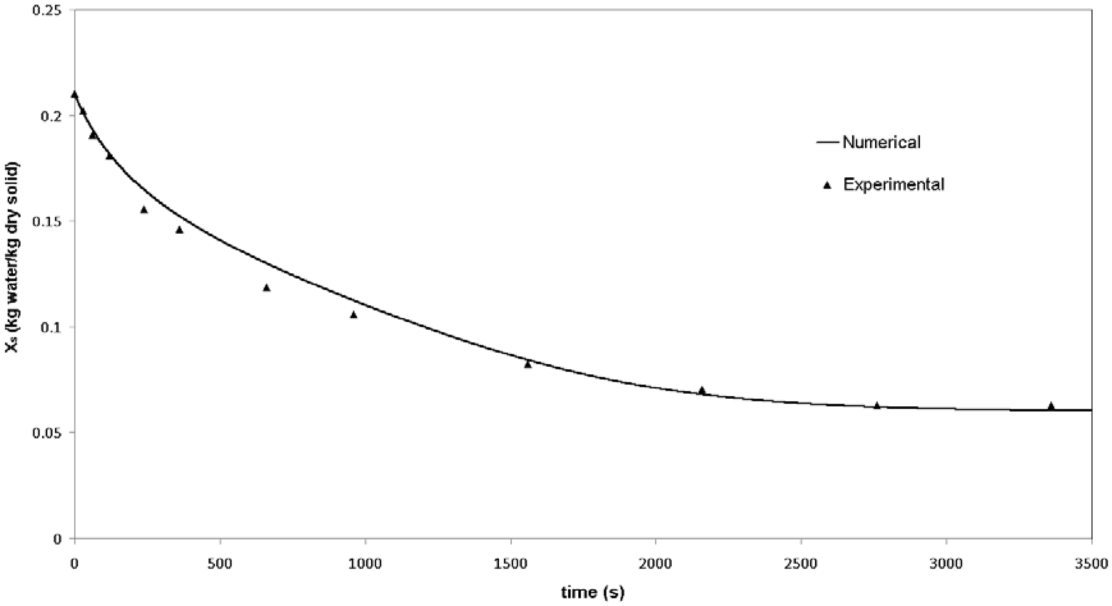


Figure 7 Solids moisture versus time numerical X experimental

5. CONCLUSIONS

This work demonstrates that the available mathematical model and numerical code can be used to predict the hydrodynamics and drying kinetics for drying of soybean meal in a fluidized bed. Particularly, the results points to sensitivity of the results of the bed hidrodynamics to the drag correlations. Finally, comparison with experimental data available from our experimental rig show the potentials for use of CFD in simulation of fluidized bed drying.

6. ACKNOWLEDGEMENTS

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