CFD SIMULATION OF PARTICLE MIXING IN A FLUIDIZED BED

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ABSTRACT

This project is to do the research of CFD simulation of particle mixing in a fluidized bed. Nowadays, fluidized bed is widely used in different kinds of industry, such as power plant, petroleum industry and food processing industry. The objectives of this project are to study the mixing and segregation phenomena in a fluidized bed and to design distributors with low pressure drop operation. Fluidized beds suspend solid fuels on upward-blowing jets of air during the combustion process. The main characteristics of fluidized bed are pressure drop, fluid velocities, bubble size and bed height. Computational fluid dynamics (CFD) simulation is the method to study this project. Firstly, Ergun 6.2 software is used to study particle mixing and segregation phenomena. Secondly, 3D geometry of fluidized bed is drawn by using Solidworks 2012. Flow simulation program is used to study pressure drop in the fluidized bed 3D drawing. Minimum fluidized velocity and operation point is found by using Ergun 6.2 software. Pressure drop is found by using Flow Simulation program. Compare with other researcher's results these simulation results are accepted.

ABSTRAK

Projek ini adalah untuk melakukan penyelidikan CFD simulasi zarah mencampurkan dalam relau fluidized. Kini, relau fluidized digunakan secara meluas dalam pelbagai industri, seperti loji kuasa, industri petroleum dan industri pemprosesan makanan. Objektif projek ini adalah untuk mengkaji pengasingan pergaulan dan fenomena dalam relau fluidized dan merekabentuk pengedar dengan operasi kejatuhan tekanan yang rendah. Relau fluidized menggantung bahan api pepejal di atas-bertiup jet udara semasa proses pembakaran. Ciri-ciri utama relau fluidized adalah kejatuhan tekanan, halaju cecair, saiz gelembung dan ketinggian katil. Dinamik bendalir pengiraan (CFD) simulasi adalah kaedah untuk mengkaji projek ini. Pertama, Ergun 6.2 perisian digunakan untuk mengkaji zarah pergaulan dan fenomena pengasingan. Kedua, geometri 3D relau fluidized diambil dengan menggunakan Solidworks 2012. Program simulasi aliran digunakan untuk mengkaji kejatuhan tekanan di dalam relau lukisan 3D fluidized. Halaju dibendalirkan minimum dan titik operasi didapati dengan menggunakan Ergun 6.2 perisian. Kejatuhan tekanan yang didapati dengan menggunakan program Simulasi Aliran. Bandingkan dengan hasil penyelidik lain keputusan ini simulasi diterima.

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LIST OF SYMBOLS

U_{mf}	min fluidized velocity
U_b	bubble rise velocity
μ	fluid viscosity
ρ_g	density of gas
ρ_p	density of particles
Ar	Archimedes number
d_p	diameter of particle
D_b	bubble diameter
ε_b	bubble void fraction
H	height of the bed
z	vertical length of bubble
s^0	entropy of fluid
C_d	coefficient of discharge

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND STUDIES

Currently, environment pollution is one of the most serious issues in the world such as ozone layer depletion, acid rains and greenhouse effect (Proimos, 2011). From the study, industrial combustion plays the main role to contribute the polluted gases to atmosphere.

Research suggested that fluidized bed is a good device to reduce the toxic gases emission in industry. In general, fluidized bed is a coal burning furnace in which the air is passed through the hot and turbulent bed of sand or ash. It behaves like a fluid, and the coal will burned efficiently at lower temperatures to reduce nitrogen oxides emission. If limestone is added to the bed along with the coal, the emission of sulfur dioxide to the atmosphere can be further reduced significantly (Oxford World Encyclopedia 1998).

Fluidized bed is applicable in different areas. Back to 1922, the first industrial application of fluidization in the coal gasification reactor was made by Fritz Winkler. In 1940s, the fluidized solid process was successfully commercialized on a massive scale in the petroleum industry to crack the heavy hydrocarbons to fuel oil and metallurgical processing (roasting arsenopyrite). In the 1960s, VAW-Lippewerk in Lünen, Germany implemented the first industrial bed for the combustion of coal and later for the calcinations of aluminium hydroxide. However, the explosion of research, application and commercialization of fluidized bed process in other industry only started since 1980s (Wang, 2003).

Nowadays, fluidized beds are also widely used in different kinds of industry. First of all, fluidized bed is important equipment in power plant which is used for a coal gasification process. In petroleum industry, fluidized bed is used for catalytic cracking process which effects intimate contact between the catalyst and hot vapors in the cracking of heavy hydrocarbons to fuel oil. In metallurgical industry, fluidized bed is used for roasting arsenopyrite and calcinations of aluminum hydroxide. In food processing industry, fluidized bed is used to accelerate freezing (http://www.almoprocess.com/).

1.2 PROBLEM STATEMENT

The researches on fluidized bed have already been going for one hundred years since the early of 20th century (Wang, 2003). Until now, the fluidized bed is still not used widely. Because the operation cost and installation cost are very high.

Eliminate the drawback CFD simulation of fluidized bed is required. CFD simulation can increase the operation efficiency and reduce the installation and operation cost. The simulation results of pressure drop can achieve low operation cost. And particle mixing and segregation result can lead good combustion efficiency to reduce pollution gases. This research is to prepare the high combustion efficiency, low emission, and low operation cost fluidized bed for industrial use by using CFD simulation.

1.3 OBJECTIVES

The objectives for this project are as follows

i. To study and predict the mixing and segregation phenomena in a fluidized bed system.

ii. To design distributors with low pressure drop operation.

1.4 SCOPES

The scopes for this project are as follows

a. Study internal CFD simulation
b. Study Ergun fluidized bed model
c. 3D engineering drawing of fluidized bed and distributors model will be used
d. Run Ergun simulation and air flow simulation
e. Data analysis and compare
f. Final report preparation

CHAPTER 2

LITERATURE REVIEW

2.1 BASIC FLUIDIZED BED SYSTEM

Fluidized beds suspend solid fuels on upward-blowing jets of air during the combustion process. The result is a turbulent mixing of gas and solids. The tumbling action, much like a bubbling fluid, provides more effective chemical reactions and heat transfer (Grace John R., Leckner Bo, Zhu Jesse, Cheng Yi 2008).

2.2 DISTRIBUTOR

Distributor is a plate which is located at the bottom of the fluidized bed. The fluid flows upward through the bed. It contains numerous holes, and makes the solid particles to be suspended.

2.2.1 Function of Distributor

The major function of the distributor is to distribute the fluidizing gas across the base of the bed so that it is maintained in the fluidized condition over the whole of its cross-section. The distributor also plays a major part in determining the size of the bubbles in the bed which are the major cause of particle circulation (Qureshi and Creasy 1978).

2.3 THE MAIN CHARACTERISTICS OF FLUIDIZED BED

The ideal fluidization bed showed similar to the nature of the liquid. The fluid density is smaller than the average density of the bed may be suspended in the bed surface; maintain the level of bed surface; bed obey hydrostatic relationship, i.e. height difference *L* of the two cross section of the differential pressure.

$$\Delta p = \rho g L \tag{2.1}$$

Particles having with a liquid like fluidity can be ejected from the orifice of the wall.

The above properties make the phenomenon of the particulate material in the fluidized bed can be like a fluid continuous feeding and discharging the bed has a unique advantage to a wide range of applications, and due to the uniform particle sufficiently mixed bed temperature, concentration.

In the two-phase movement of fluid and particles within the bed, due to the differential flow rate, fluid density of the particles, the particle size and the different sizes of the bed, can exhibit different fluidized state, but mainly divided into the fluidization state and aggregative fluidized state (Grace John R., Leckner Bo, Zhu Jesse, Cheng Yi 2008).

2.4 PRESSURE DROP

The air through the distributor pressure should be different. It is relatively undisturbed by the bed pressure fluctuations above it.

Treated as a combination of a sudden contraction followed by a sudden enlargement, a simple drilled orifice in a distribution plate would be expected to have an overall pressure drop given by

$$\Delta H_d = 0.5\left(\frac{u^2}{2g}\right) + \left(\frac{u_0^2}{2g}\right) \tag{2.2}$$

In consistent units, or

$$\frac{2g\Delta H_d}{u_0^2} = 1.5 \; velocity\ heads \tag{2.3}$$

However, unless the plate is very thick compare with the orifice diameter $(\text{i.e.} \frac{d}{t} \ll 1)$, the expansion loss will be influenced by flow patterns resulting from the sudden contraction of the flow on entry to the orifice (A.E.QURESHI & D.E.CREASY 1978).

$$\frac{2g\Delta H_d}{u_0^2} = 1/C_d^2 \quad (2.4)$$

C_d is coefficient of discharge.

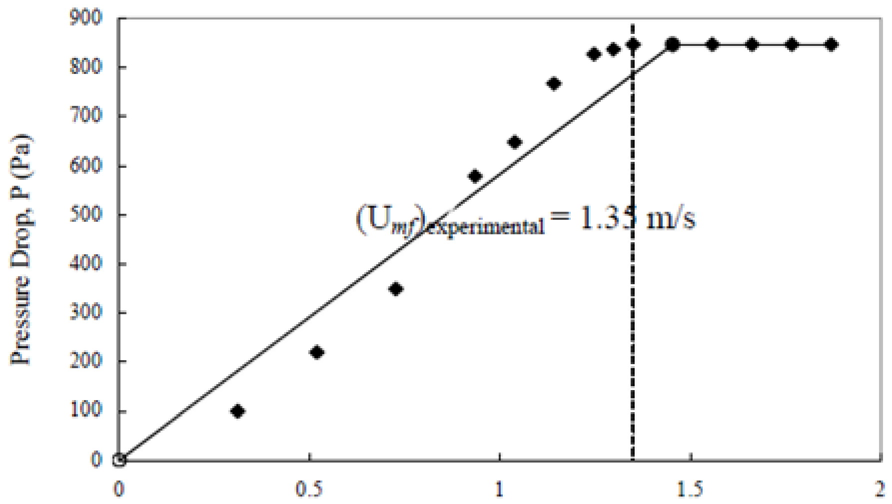
C_d is a weak function of the distributor free area $\emptyset$ and $\frac{d}{t}$ taking a rough correlation as

$$C_d=0.82(d/t)^{-0.13} \quad (2.5)$$

Substitution in the above equation yields

$$\frac{2g\Delta H_d}{u_0^2} = 1.49(\frac{d}{t})^{0.26} \quad (2.6)$$

Figure 2.1 presents the results obtained for pressure drop across the bed as the superficial gas velocity was increased. At relatively low superficial gas velocity, the pressure drop across the bed was approximately proportional to the superficial gas velocity. However, the pressure drop values were constant at above the minimum fluidization velocity, U_{mf}. The consistency in pressure drop showed that the fluidizing gas stream had fully supported the weight of the whole bed in the dense phase. Thus U_{mf} reached when the drag force of the up-wards fluidizing air equals to the bed weight. In this case, U_{mf} was determined as 1.35 ms^{-1} (S.M. Tasirin, S.K. Kamarudin and A.M.A. Hweage 2008).



Superficial Gas Velocity, U(m/s)

Figure 2.1: Pressure drop versus superficial gas velocity (at increasing gas flow rate) for initially mixed/segregated mixtures (S.M. Tasirin, S.K. Kamarudin and A.M.A. Hweage 2008).

Many researchers now use the kinetic theory of granular materials as part of their efforts in simulating multiphase systems. It is used in both the dilute-phase modeling of circulating fluidized beds and the dense phase modeling of bubbling fluidized beds. The granular kinetic theory is also found in multiphase modeling within the commercial simulation software FLUENT, with Benyahia using an early version of FLUENT in their simulations of dilute-phase riser flow. Arastoopour were the first to consider polydisperse systems and successfully computed pressure drop effects in dilute riser flow (Scott Cooper, Charles J. Coronella 2004).

At the simulation study, a 2D CFD model was used to describe the gas–solid two-phase flow in fluidized bed polymerization reactors. The effects of some important input parameters on the flow field were investigated. The model was validated by comparing the pressure drop and the minimum fluidization velocity data with those calculated according to the classical equation. The effects of distributor shape, solid particle size, operation gas velocity and the feed manner on the flow behavior in the reactor. The results show that the final fluidizations are almost the same at the plane and triangle distributors. In addition, with the increase of the solid particle diameter, the bubble number decreases and the bubble size increases, resulting in a small bed expansion ratio. Both the bubble number and the bed expansion ratio increase with the increase of the gas inlet velocity. There exists a tempestuous wiggle from side to side in the bed at the continuous feed manner, which cannot be found at the batch feed manner. Further studies on the CFD model for the gas–solid two-phase flow in FBR are in progress in our group (Xi-Zhong Chen, De-Pan Shi, Xi Gao, Zheng-Hong Luo 2010).

Relate to this project the straight cylindrical or columnar fluidized beds are the majority of the gas-solid fluidization studies. There is another kind of fluidized beds, which have inclined walls. These are called tapered fluidized beds.

Tapered fluidized beds can be run swimmingly without any unstableness, which can be run with less pressure fluctuations. Tapered fluidized beds are very useful for fluidization of materials with a wide particle size distribution, as well as for exothermic reactions and also for extensive particle mixing.

In the present work, an Eulerian–Eulerian multi-fluid model, which considers the conservation of mass and momentum for the solid and gas phases, has been adopted. The kinetic theory of granular flow, which considers the conservation of solid fluctuation energy, has been used for closure.

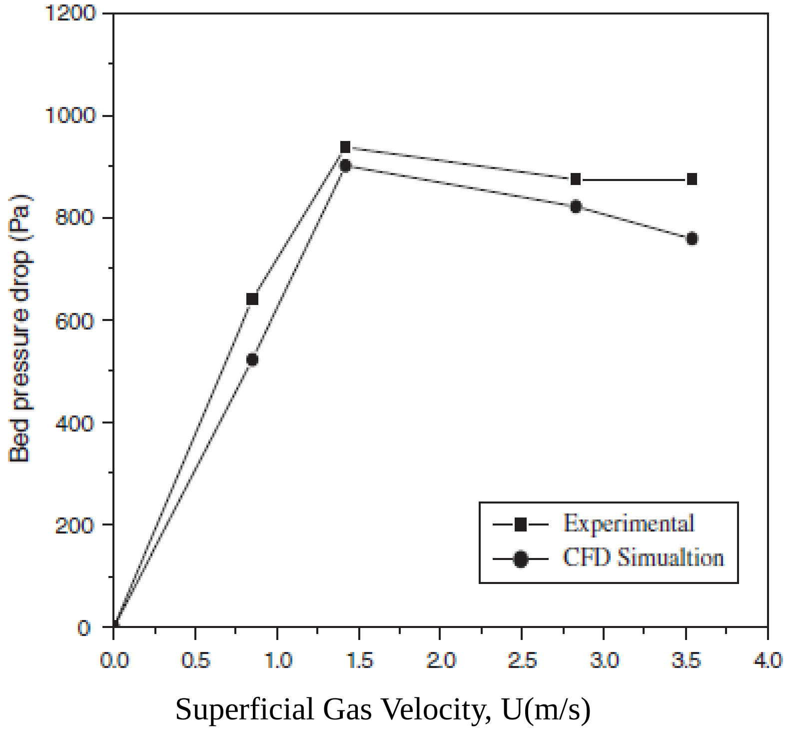


Figure 2.2: Comparison Plot of Experimental Bed Pressure Drop with CFD Simulation using Gidaspow drag model (particle = glass bead, diameter = 2 mm, Initial static bed height = 6.5 cm) (D.C. Sau & K.C. Biswal 2010).

The floating gas-solids fluidized bed has been applied as a binary fluidized bed and it was shown that its appearance may vary from well-mixed to completely separate. Visual observation showed that intermediate mixing regimes could exist, as well as the extreme situations of complete separation and good mixing of particles. These observations were supported by the interpretation of measured pressure-drop profiles due to the presence of particles: different degrees of mixing were reported, varying from completely separated to intermediately and well-mixed (G. Kwant W. Prins W.P.M. van Swaaij 1994).

Another type of distributor is tuyer type air distributor. A Tuyer type air distributor plate was selected, consisting of a plate with vertical nozzles with lateral perforations through which passes the air that is distributed uniformly into the reactor. This alternative was selected due to its convenience for use with high temperatures and its advantage of reducing the backflow of bed material toward the plenum. Table 2.1

shows the necessary parameters for the air distribution plate design considered for the most homogenous material of the bed and sand.

Table 2.1: Particle separator dimensional and operational characteristics

Parameter	Value
Cyclone diameter (mm)	190.5
Cyclone gas exit diameter (mm)	95.25
Cyclone body cylindrical height (mm)	285.75
Cyclone total height (mm)	762
Cyclone solids exit diameter (mm)	71.4
Separation efficiency (%)	99.7
Pressure drop (kPa)	0.46

Source: Ramirez, Martinez and Petro (2007)

From the mass flow of the product gas in the gasification process (mass balance), and its density, the gas volumetric flow at the cyclone inlet for the operating conditions of the gasifier was calculated (approximately 750 ℃ and 101,325 kPa). Table 7 shows the dimensions of the designed cyclone, along with its efficiency and pressure drop.

Table 2.2: Calculated parameters for the distribution plate

Parameter	Value
Pressure drop in the bed (kPa)	6.05
Tuyer orifice diameter (mm)	2.38
Pressure drop in the distributing (kPa)	1.1
Tuyer internal diameter (mm)	7.94
Air velocity for the orifice (m/s)	36
Total number of tuyers	24
Tuyer height (mm)	4

Source: Ramirez, Martinez and Petro (2007)

Table 2.3: Design parameters for the air distribution plate

Parameter	Value
Fluidization velocity (m/s)	0.7
Min. fluidization velocity (m/s)	0.07
Max. fluidization velocity (m/s)	0.47
Particle density (kg/m^3)	2650
Mean particle size (μ m)	385
Bed porosity	0.46
Bed zone diameter (m)	0.3
Number of tuyer lateral orifices	4

Source: Ramirez, Martinez and Petro (2007)

Using the model of calculation proposed in literature (Basu, 1984) the results presented in Table 4 were obtained (J. J. Ramirez, J. D. Martinez, S. L Petro 2007).

2.5 FLUID VELOCITIES

There are many kinds of velocity have been studied in journals. First is fluidized velocity of the particles. Second is bubble rise velocity. Third is fluid flow velocity. Forth is superficial gas velocity. The objects of the velocity which have been studied are particles, fluid and bubbles.

From one journal, they study proved that, Lacey index, M capable to determine the performance of particle mixing and recommend the bubbling fluidized as a good alternative for solid mixing. Finally the optimum parameters for solid mixing in this study was determined the bed depth of 17 cm with the gas velocity 1.38 Umf that give highest Lacey mixing index. This study also proved that the superficial velocity of air higher that Umf, capable to reduce the effect of bed height to the mixing process (S.M. Tasirin, S.K. Kamarudin and A.M.A. Hweage 2008).

2.6 PARTICLES MIXING AND SEGREGATION PHENOMENA

Various models have been proposed to describe structural phenomena such as segregation, mixing, and layer compositions in binary particle systems (Di Felice, 1993; Gibilaro et al., 1985; Juma and Richardson, 1979, 1983; Dutta et al., 1988; Kennedy and Bretton, 1966; Asif and Petersen, 1993). Experimental and empirical results for the pressure and concentration profiles that exist in binary systems have been used to make predictions of the solids concentration in segregated systems. Kennedy and Bretton (1966) and A-Dibouni and Garside (1979) predicted binary segregation using a model that matched the diffusive and convective fluxes of each component. Other phenomena such as layer inversion have also been studied (Moritomi et al., 1982; Van Duijn and Rietema, 1982; Epstein and LeClair, 1985; Matsuura and Akehata, 1985; Gibilaro et al., 1986; Syamlal and O'Brien, 1988; Di Felice et al., 1988; Jean and Fan, 1986; Patwardhan and Tien, 1985). Correspondence concerning this article should be addressed to M. A. Burnr. Current address of K. D. Seibert: Merck and Co., Inc., P.O. Box 2000, RY50D-207, Rahway, NJ 07065. An example of a structural phenomenon seen in a mixed particle liquid-fluidized bed is classification. Classification is the result of the stable fluidization of particles with nonuniform particle diameters and/or densities. The changing hydrodynamic forces on the particles cause them to segregate or “classify” with larger particles gravitating toward the bottom of the bed and smaller particles toward the top. Classified beds are currently used industrially in the isolation of adsorbing solutes (Gailliot, 1990; Draeger and Chase, 1990; Chase and Draeger, 1992; Chase, 1994; Batt, 1995). Knowledge of the fluidization characteristics, the operating parameters, and the physical properties of the particles/ bed is important in this type of application in order to maintain the stable classified structure.

2.7 BUBBLING

A multi-fluid computational fluid dynamics (CFD) model based on kinetic theory of granular flow and Eulerian–Eulerian approach for binary mixture of particles was presented. The multi-fluid model with gas phase and two particle phases of either different particle sizes or densities is used to simulate flows in bubbling gas–solid fluidized beds. The flow behavior of particle mixing or separation in bubbling fluidized beds was numerically predicted. Details of particle collision information were obtained through tracing particle motions based on Eulerian–Lagrangian approach coupled with the discrete hard-sphere model. The distributions of volume fraction, velocity and granular temperature of particles of two different sizes or densities were obtained. The discrete hard-sphere modeling results quantified the granular temperatures, particle fluctuating velocities, particle phase stresses, as well as the particle shear viscosities. The simulations using both the multi-fluid model and the discrete hard-sphere model clearly indicate particle separation phenomenon in the fluidized beds, where relatively larger or heavier particles are observed near the bed bottom than at the bed top region while relatively smaller or lighter particles were found at bed top than at the bed bottom. Better particle mixing can be obtained by increasing the fluidizing velocity (Lu Huilin, ZhaoYunhua, Jianmin Ding, Dimitri Gidaspow, LiWei 2006).

Sun and Battaglia 2006 performed simulations with and without particle rotation to study segregation phenomena in a bi-dispersed bubbling gas-fluidized bed using a multi-fluid Eulerian model. They claimed that with particle rotation in the kinetic theory model and slightly friction considered the multi-fluid model better captures the bubble dynamics and time-averaged bed behavior.

The distribution of particle mass fraction along the bed height for binary mixture with same particle densities but diameters has been experimentally studied in a bubbling fluidized bed (Huilin 2003).

These are the equations of calculate the mean bubble volume fraction.

$$U_{mf} = \frac{\mu}{\rho g d_p}\left(\sqrt{33.7^2 + 0.0408Ar} - 33.7\right) \tag{2.7}$$

$$\mathrm{Ar} = {d_p}^3 \frac{g}{\mu^2}(\rho_p - \rho_g)\rho_g \tag{2.8}$$

$$D_b(z) = 0.54\left(U - U_{mf}\right)^{0.4}(z + 4\sqrt{s}\circ)^{0.8}\mathrm{g}^{-0.2} \tag{2.9}$$

$$\mathrm{U}_b(z) = 0.71\sqrt{gD_b}+\mathrm{U}\text{-}U_{mf} \tag{2.10}$$

$$\varepsilon_b(z) = \frac{U-U_{mf}}{U_b} \tag{2.11}$$

$$\bar{\varepsilon_b} = \frac{1}{H}\int_0^H \varepsilon_b(z)dz \rightarrow \bar{\varepsilon} = 1 - (1 - \bar{\varepsilon_b})(1 - \varepsilon_{mf}) \tag{2.12}$$