Simulation Study of Flow in Fluidized Bed Reactor: Vortex Distribution

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ABSTRACT

The developments in research of the simulation study of flow in fluidized bed are briefly introduced. The problem related to the fluidized bed reactors is also reported. The characteristics of the fluidization were discussed further in detail. The distributor designs and their impacts to the flow in the fluidized bed were also studied. The distributor was designed and used in the simulation of flow of fluidized bed by using SolidWorks. The flow simulation was conducted through a series of procedure; initializing the mesh, calculating control option, inserting boundary condition, choose goals, and running the analysis. The parameter used was volumetric flow rate, using 0.00000007 m3/s, 0.00001 m3/s, 0.0001 m3/s, 0.001 m3/s, and 0.0005 m3/s. The results of each flow was obtained; the 1st run had non-existent flow, 2nd run had transition flow with minimum vortex, 3rd run had developed flow but dead zones still persists, 4th run had perfect flow but impractical, and 5th run had perfect flow with minimum dead zones. It was concluded that the flow in the 5th run is the best out of them.

Keywords: fluidization bed reactor, distributor design, flow simulation, vortex distribution.

INTRODUCTION

Fluidization is the process whereby solid particles exhibit fluid behaviour as fluid passes through them. Using this principle, fluidized bed reactors (FBR) acts as the device, in which chemical reactions take place to create the desired products. FBR is one of the commonly used commercial reactors in the chemical processing industry for the contacting of gas-solid. This is due to its excellent heat and mass transfer characteristics, nearly isothermal operation of the reactor, and easy handling of the solids behaving like liquids in the reactor [1].
The process, by which a fluid passes vertically through a collection of solid

particles, or fluidized bed, is referred to as fluidization. This process causes the particles to achieve hydrodynamic conditions similar to a fluid [2]. Relative motion between particles were allowed as fluid passes through the bed, with the drag force overcomes the gravitational force and reduces the frictional force between particles. When the velocity of the fluid flow rate reaches a certain extent, the solid particles in the bed will appear as though they are suspended and floating. Fluidization can be obtained using liquid, gas, or a liquid-gas combination, as the fluid passes through the solid material. Liquid-solid and gas-liquid-solid systems are important for several industries. The type of fluid used depends on the application of the fluidized beds.

The performance of fluidized bed reactors are greatly influenced by other parameters, including distributor design, bed materials, bed height, inflow fluid flow rate, and pressure drops. This research will focus on the effects of the distributor design on the flow of fluidized bed reactors. The distributor design of a FBR also plays a role in determining the bubble size generated during the operation of the reactor [3]. The bubble size can be reduced by designing distributor with correct pitch and hole sizes. The method to design a distributor to meet a specified bubble size, and to estimate a bubble size based on a given distributor was also presented. In another experiment using a 100mm diameter glass column with multi-orifice distributors, they concluded that bed height and bed materials affect the performance of the distributor and thus the FBR operation itself [4]. It was found that the number of operating orifice of distributor is a function of gas velocity and the ratio of pressure drops across the distributor and the bed. Reference to [5] reveals that there were several key factors that have major influence in designing a high-performance distributor. The factors mentioned are pressure drop ratio, orifice size, plus geometry and spacing. These factors strongly affect the jet penetration, dead zones, particle shifting, attrition and mixing. The fact that the performance of FBR depends on the distributor design to a large extent have been pointed out by another authors. In order to understand these effects, Computational Fluid Dynamics (CFD) analysis was used to simulate the performance of various distributor designs. Each design was analyzed on its performance based on predetermined variables, velocity and temperature [6].

The flows of fluids in the reactor were also studied computationally by various authors. The simulation of the operation of fluidized bed reactor allows the study various parameters to be executed accurately. The hydrodynamics of a two-dimensional gas–solid fluidized bed reactor were studied experimentally and computationally by using CFD simulation. The pressure drops of experimental measurements at superficial gas velocities higher than minimum fluidization velocity were relatively close to the prediction of the simulations [7]. There were also similarities of the predicted instantaneous and time-local voidage profiles between the simulation and experiment results. In a study of simulating a liquid-solid fluidized bed using granular flow extension, the results are not greatly influenced by a better geometry representation of the distributor plate [8]. The simulations also show similar trends to experimental trends by various other authors. The parameters involved are mesh, time step, convergence criteria, drag law and coefficient of restitution. In other work, it was said that the disadvantage of multiphase reactors can be overcome by restructuring fluidized beds [9]. The restructuring will help limit bubble size for better mass transfer, reduces attrition and elutriation, and prevents channelling. This is done by decoupling of mass transfer limitations using a variety of methods, including the manipulation of gas supply dynamics, the particle dynamics, and the geometry of the gas supply.

EXPERIMENTAL WORK

1.1 Designing Distributor and Model

The modelling process involves the repetition use of sketches and features in the Solid Works software. There is no definite procedure for designing as there are plenty of techniques that can be used. However, the process of modelling in this experiment can be described in general by:

1) Drawn basic sketches of the model.
2) Used extrude boss/base feature to turn sketches into solid 3D model by adding the height parameter of the sketch.
3) Used revolved boss/base feature to turn sketches into solid 3D model by using rotation of sketch at an axis.
4) Used extrude cut feature on sketches to remove solids in the solid 3D model.
5) Used plane reference geometry feature to create new planes away from the origin.

Using the process above, basic skills in the software are utilized in order to create the desired model. The diameter of the holes, positioning of orifices, and the creation of vortex flow was taken into account in creating the desired distributor design. Figures 1 and 2 show the distributor and schematic diagram of dimension used.

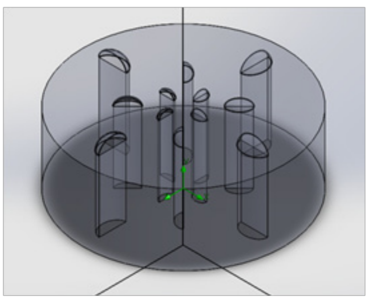

Figure 1: Image of distributor designed

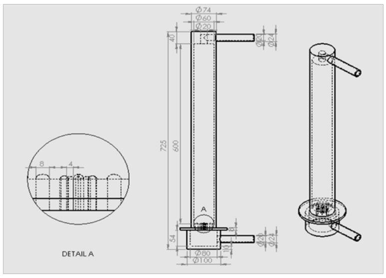

Figure 2: Schematic presentation of dimension and details of model

1.2 Flow Simulation

The operating condition was set in the simulation for temperature and pressure at 293 K and 101325 Pa respectively. The process flowchart in Figure 3 is the general procedure to starting the simulation study of fluidized bed reactors. SI units are used throughout the research for every simulation done. The lids for the model were created first. After setting up the project, the mesh and geometry was initialized and checked in the second step. For the third step, the porosity for the simulation was set to 0.5 and resistance calculation formula was set to depend on velocity. The fourth step involves the insert of boundary condition by setting inlet volume flow at the opening of model and static pressure at the exit. The volume flow rate, the variable, was set in the boundary condition using 0.00000007, 0.00001, 0.0001, 0.001 and 0.0005 m3/s for each respective simulation project. Finally the maximum volume flow rate parameter was chosen. The simulation analysis for each project was run to obtain the required data.

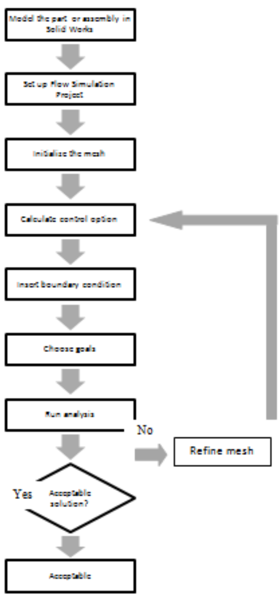

Figure 2: The flowchart of flow simulation process

RESULTS AND DISCUSSION

The main focus of this research was to observe and study the simulation of flow in a bubbling fluidized bed reactor using vortex distribution. In conjunction with that, the most suitable parameter was also to be determined. The objectives of the research were due to problems face in a fluidized reactor, especially dead zones. The volumetric flow rate of the fluid passing through the fluidized bed is one of the parameters in the simulation. The change in volumetric flow rate can significantly affect the flow in a fluidized bed. An extreme change in the parameter could lead to de-fluidization or great expansion of the dense phase [10]. It was also stated that the volumetric flow rate may also be influenced by change in variation in molar gas flow, temperature, bed pressure, distributed feed, membranes, and change of phase. Another author states that the bed density is decreased and gas-solid contacting pattern changes resulting from increase in gas flow rate [11]. The gas-solid pattern “change from dense bed to turbulent bed, then to fast-fluidized mode and ultimately to pneumatic conveying mode”. Using volumetric flow rate as the main parameter variable, results of the simulation were obtained.

2.1 First Simulation Run

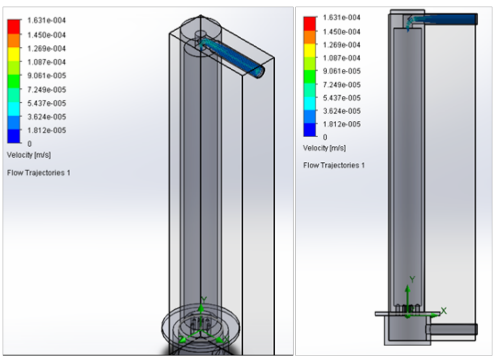

Figure 4: Isometric and side view of flow in first simulation run.

Table 1: Result of the First Run

Name	Minimum	Maximum
Pressure [Pa]	101325.00	101325.00
Temperature [K]	293.20	293.20
Density [kg/m^3]	1.20	1.20
Velocity [m/s]	0	1.631e-004
Temperature (Fluid) [K]	293.20	293.20

Using volumetric flow rate of 0.00000007 m3/s, the result of the simulation were obtained. Based on Figure 3, the flow of the fluid through the fluidized bed were almost non-existent until it reaches the top of the reactor. This may be due to very low flow velocity of the fluid. Since the simulation executed is considered turbulent, the low velocity would affect the Reynolds number defined as:

$$Re = (uDH)/v \quad (1)$$

Using the Equation 1, the values of u = 1.631x10-4, DH = 0.02, and v = 1.4838x10-5 were inputted to calculate the Reynolds number. The Re obtained was 0.22. This proves that the flow inside the fluidized bed were laminar instead of the intended turbulent flow. It also indicates that the volumetric flow rate used was not sufficient to overcome the minimum fluidization in the case if the solid particles were included in the simulation. The reason being that the drag force are not enough to overcome gravitational force of particles to expand the bed [2].

2.2 Second Simulation Run

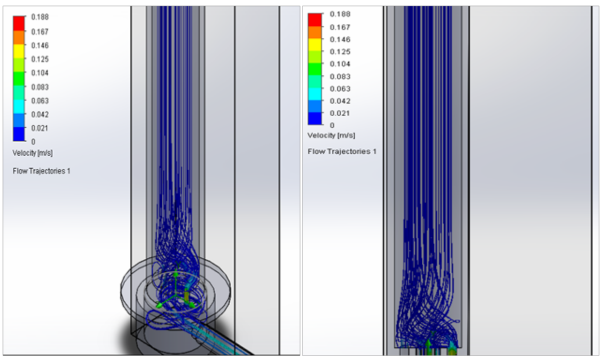

Figure 5: Isometric and side view of flow in second simulation run.

Table 2: Result of the Second Run

Name	Minimum	Maximum
Pressure [Pa]	101325.00	101325.14
Temperature [K]	293.20	293.20
Density [kg/m^3]	1.20	1.20
Velocity [m/s]	0	0.188
Temperature (Fluid) [K]	293.20	293.20

The second simulation was run using volumetric flow rate of 0.00001 m3/s. The designed distributor created a vortex flow as intended according to Figure 4. However, the Reynolds number for the flow calculated using Equation (1) above is only 253.40 which indicate the flow is transition. The flow returned from vortex to straight line in less than a quarter of the bed height.
As stated by other authors previously, there are dead zones present in the fluidized bed which affects the efficiency of the reactor. These dead zones can be seen in the second simulation run. The dead zones are affected by the spacing of the distributor holes and gas velocity, and usually forms between the gas jets [12]. Thus, it can be said that the velocity of the fluid, u = 0.188, are not high enough to counter the dead zones created.

2.3 Third Simulation Run

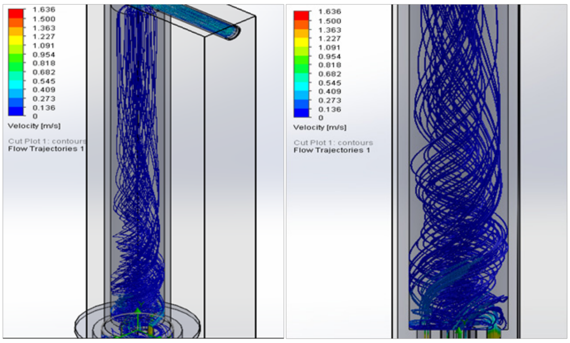

Figure 6: Isometric and side view of flow in third simulation run.

Table 3: Result of the Third Run

Name	Minimum	Maximum
Pressure [Pa]	101324.99	101328.83
Temperature [K]	293.20	293.20
Density [kg/m^3]	1.20	1.20
Velocity [m/s]	0	1.636
Temperature (Fluid) [K]	293.20	293.20

For the third simulation run, the value of volumetric flow rate was set to 0.0001 m3/s. The velocity obtained was 1.636 m/s, and the Reynolds number was also calculated as before. The Re for this simulation run is 2205.15 which is a turbulent flow. The vortex flow in the bed is more developed compared to the second simulation run and is maintained until about half the bed height as shown in Figure 6.

However, the vortex flow does not fully circulate through the bed, creating spaces in the bed that may contribute to dead zones. The presence of the dead zones at the surface of distributor is lower compared to the previous run.

2.4 Fourth Simulation Run

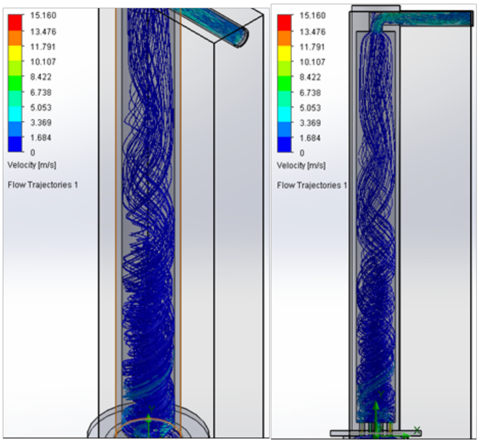

Figure 7: Isometric and side view of flow in fourth simulation run.

Table 4: Result of the Fourth Run

Name	Minimum	Maximum
Pressure [Pa]	101305.27	101593.34
Temperature [K]	293.10	293.21
Density [kg/m^3]	1.20	1.21
Velocity [m/s]	0	15.160
Temperature (Fluid) [K]	293.10	293.21

In this simulation run, 0.001 m3/s flow rate was used. This results in a significant increase of gas velocity to 15.16 m/s. Based on Figure 6, the resulting vortex flow are far greater compared to other previous runs as expected and swirl until slightly above third quarter of the bed. The motion of flow promotes rapid mixing in the bed. The Reynolds number calculated is 20434.02.
The spaces at the distributor zone are at minimum and almost non-existent, which means minimum dead zone presence. There is also a considerable pressure drop of 19.73 Pa. The fluidizing performance was reported to be higher as the pressure drop of gas distributor is higher [13]. Although this vortex flow is better, there are flaws that require consideration. The flow swirls until the third quarter, which is about the same height of the freeboard region. Freeboard region is the section between the exit gas stream and surface of dense phase region. Assuming there are solid particles in the bed, the swirling exceeding the freeboard region means

the particles will be swept out of the fluidized bed [14]. Thus, the flow generated in the fourth run is impressive in the absence of solid particles, but it is impractical to be used in real life.

2.5 Fifth Simulation Run

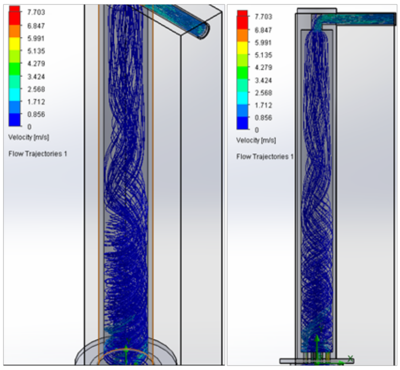

Figure 8: Isometric and side view of flow in fifth simulation run.

Table 5: Result of the Fifth Run

Name	Minimum	Maximum
Pressure [Pa]	101322.27	101395.56
Temperature [K]	293.17	293.20
Density [kg/ m^3]	1.20	1.20
Velocity [m/s]	0	7.703
Temperature (Fluid) [K]	293.17	293.20

The flow rate of 0.0005 m3/s was used for the last simulation run. For this last run, the volumetric flow rate was chosen after comparing the results of the previous run. As shown in Figure 8, the vortex flow was simulated and the swirling motion dissipates after halfway through the bed. The gas velocity was determined to be 7.703 m/s, and the Reynolds number calculated was 10382.80.

The vortex flow creates minimal spaces that could contribute to dead zones in the bed. Just as it was with the fourth run, there is also a noticeable pressure drop of 2.73 Pa. While taking the freeboard region under consideration, the height of the swirling motion is only halfway through and still in the said region. This means the flow in the fourth simulation run did not occur in the last run. The mixing of the flow can also be considered sufficient by the heavy swirl in the lower region of the bed.

CONCLUSION

Fluidized bed reactors are essential to the industry that requires uniform mixing, and excellent heat and mass transfer. However, even the most complicated reactors may experience dead zones in the bed which affects the performance of the reactor. In this research, the design of the distributor was the main scope which affects the flow distribution and efficiency. The designed distributor was used with the intent of creating a swirling motion and vortex flow in the bed. It promotes the flow in both horizontal and vertical direction, which enhances the mixing of fluids in the bed.

The best parameter and flow were to be determined in five simulation runs. In the first run using Q = 0.00000007 m3/s, the gas velocity, u, obtained is 1.631x10-4 m/s. The Reynolds number calculated is Re = 0.22 which corresponds to a laminar flow. The flow was non-existent and is not enough to overcome minimum fluidization. For the second run, Q = 0.00001 m3/s was used, u = 0.188 m/s and Re = 253.40. The flow generated is transition, and swirling motion only occurs at the very bottom part of the bed. There are also numerous spaces that could contribute to dead zones in the bed. In the third run, Q = 0.0001 m3/s was used and u = 1.636 m/s obtained to get Re = 2205.15. The vortex flow generated was more developed and stable, but is still unable to eliminate or minimize the dead zones. Then, Q = 0.001 m3/s was used in the fourth run. With u = 15.16 m/s, Re = 20434.02 was calculated. The vortex flow is more stable and rapid mixing was observed, but the swirling motion nearing the top of the bed leaves concern for solid particles being swept out of the bed if it were included. Thus, it is considered impractical for use. The last run uses Q = 0.0005 m3/s, and obtained u = 7.703 m/s and Re = 10382.80. The flow is considered as an improved version of the fourth run, with almost identical rapid mixing and stable flow. The height of the swirling motion is reduced, thus eliminating the flaw in the previous run. The dead zones also appear to be minimal. Thus, it can be concluded that the fifth run is the ideal flow for the model. The flows simulated were to create a vortex that covers the surface of distributor in order to eliminate the dead zones. The best height of the swirling motion is between halfway to third quarter of the bed so particles would not be swept out of the bed.

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