Investigation of forces acting on particles in a rolling Circulating Fluidized Bed

Zhilong WANG**, Tong ZHAO**, Kai LIU* and Masahiro TAKEI**

*Faculty of Mechanical and Precision Instrument Engineering, Xi'an University of Technology, Xi'an 710048, China
E-mail: xalg088@163.com
**Division of Artificial Systems Science, Graduate School of Engineering Chiba University, Chiba 263-8522, Japan

Abstract
This paper presents an investigation of forces acting on particles used CFD-DEM simulation method in a rolling Circulating Fluidized Bed. In the simulation, the discrete particle phase is solved by the DEM approach and each individual particle motion is described by Newton's equations of motion; the continuum fluid phase is solved by the Navier-Stokes equations at a computational cell scale. Conclusions obtained from the simulation results are shown as follows. The behavior of particle movement in the radial direction is mainly dominated by unsteady forces including pressure gradient force \( F_{PG,Y} \) and virtual mass force \( F_{VM,Y} \) in a static CFB and by the component of gravity force \( F_{g,x} \) in a rolling CFB. The rolling motion of CFB has a large influence on the axial velocity of air phase, which is caused by the instantaneous change of the relative pressure and the distribution of discrete particles. By comparing forces acting on particles, as the magnitude order of electrostatic force \( F_E \) is extremely lower than that of any other forces, \( F_E \) is not taken into consideration. Furthermore, Van der Waals force \( F_{VDW} \) as an adhesive force is also disregarded on account of the little particle number and low particle concentration at the present work.

Key words: Circulating Fluidized Bed, Forces acting on particle, rolling motion,

1. Introduction

Recently, the application of Circulating Fluidized Bed (CFB) is prevailing in the field of chemical industry, energy, and material science on account of its higher heat transfer and recovery efficiency (Mori S, 1998; Lothar Reh, 1999). Therefore, CFB is used as a process device for ship exhaust fumes. As the CFB installed on the ship is significantly influenced by its motion, it is essential to investigate the interior particle movement of the ship’s CFB.

In order to analyze the behavior of particle movement in CFB, forces acting on particles are utilized to give an insight into investigation. Numerous investigations of forces acting on particles have been carried out and are partly well documented in the following literatures. Jie Li et al analyzed the effect of competition between particle-particle and gas-particle interactions on flow patterns in dense gas-fluidized beds (Jie Li et al, 2007). They found that the gas-solid two phases flow can form agglomerate flow in case of the systems dominated by particle dissipative collision, while it can produce particular flow in case of the systems dominated by gas-solid interaction. Shuyan Wang et al investigated the influence of inter-particle van der Waals forces on the micro-particles collisions by using the direct simulation Monte Carlo (DSMC) method in a two-dimensional riser (Shuyan Wang et al, 2007). The electrostatic phenomena in gas-solids fluidized beds is investigated by Hsiaotao T. Bi (Hsiaotao T. Bi, 2006), who pointed out that it is the bipolar charging that dominate charge generation mechanism in dense gas-solids fluidized beds. M.A. Hassani et al studied the effect of electrostatic forces on bubble hydrodynamics, bed porosity, solids diffusivity and solid circulation length (M.A. Hassani et al, 2013). The influence of various forces including drag force, gravity, virtual mass force and pressure gradient force on particle movement has been investigated in a simple cabin model under accelerated ventilation circumstances in our previous paper (Zhilong WANG et al, 2014). Apart from these theoretical study, the experimental investigation of a rolling CFB have also been carried out. Murata H et al performed a series of
experiments with a three-dimensional rolling CFB model identical to the paper (Hiroyuki Murata, et al, 2012). They concluded that the total pressure drop at an inclined attitude is larger than that at the upright attitude and the gravity dominantly affects gas-solid flow in CFB under rolling motion. Nevertheless, these previous studies just qualitatively analyzed various forces acting on particle or experimentally investigated the phenomena of particle movement influenced by these forces. Therefore, in order to give an insight into particle movement, it is necessary to quantitative analyze various forces acting on particles in a rolling CFB.

Commonly, the mathematical models are classified into two categories: the continuum-continuum approach at a macroscopic level denoted by the TFM (Gidaspow, 1994), and the continuum-discrete approach at a microscopic level mainly represented by the combined method CFD-DEM (Tsui, et al., 1993; Xu B.H and Yu A. B, 1997, 2003). As the process device for CFB’s exhaust fumes is installed on the ship and affected by its rolling motion, the interior particle movement of the CFB is considerably complicated. In compared with the TFM approach, the CFD-DEM approach takes the interaction forces between particles into consideration, which can give an insight into particle movement. Hence, in this paper, CFD-DEM approach is utilized to simulate the complicated particle movement in the CFB.

In this paper, the ship motion influenced by the sea fluctuation is simplified as a sinusoidal function. Under the absolutely coordinate system, the gas-solid two phases flow in a rolling CFB is considered as a non-inertial pattern, which is considerably increased the computational time of the numerical simulation. In order to reduce the computational time, Moving Reference Frame (MRF) is utilized to transform the simulation from non-inertial coordinate system to inertial coordinate system. Eventually, the CFB is simulated by means of CFD-DEM approach and the law of particle movement in the rolling conditions is clarified. The aim of this paper is to give an insight explanation for the behavior of particle movement in a rolling CFB through the forces acting on particles.

2. Mathematic model
2.1 Continuum fluid phase

Because the initial velocity of the air $u_f=4\text{m/s}$ is not higher, the air is regarded as incompressible fluid. The continuum fluid phase is solved by a series of Navier-Stokes equations. The form of these equations are all defined in relative coordinate system since the MRF is attached to the Circulating Fluidized Bed (CFB) walls. Therefore, the mass and momentum conservation equations are described at the Moving Reference Frame (MRF) $o$-xyz in relative coordinate system are expressed as follows:

$$\frac{\partial}{\partial t}(\alpha_f \rho_f) + \nabla \cdot (\alpha_f \rho_f u_f) = 0$$

$$\frac{\partial}{\partial t}(\alpha_f \rho_f u_f) + \nabla \cdot (\alpha_f \rho_f u_f u_f) + \rho_i \alpha_f (2\omega \times u_f + \omega \times \omega \times r + \frac{du_f}{dt} \times r + \frac{dr}{dt}) = -\alpha_f \nabla p + \alpha_f \nabla \cdot \tau_f + \beta_{gp} (u_f - u_f)$$

where $\alpha_f$ is the volume fraction of the gas phase, $\rho_f$ represent the gas density, $r$ denotes the displacement vector between a cross section of the CFB and the rotation axis $z$, $\tau_f$ is the gas phase stress tensor, $u_f$ represents the relative velocity of gas phase viewed from the moving frame. $\omega$ and $\alpha$ are the angular velocity and the angular acceleration of the CFB, respectively. $\nabla p$ denotes the pressure gradient in the MRF. The drag coefficient between gas and particle is represented by $\beta_{gp}$, which is determined by Ergun's equation ($\alpha_f \leq 0.8$) (Ergun. S, 1952) or Wen and Yu's equation ($\alpha_f > 0.8$) (Wen C.Y and Yu Y. H, 1966).

2.2 Discrete particle phase

The particle as the discrete phase is solved by the equations of Newton motion. The high particle volume fraction in the CFB result in the frequent collision between particles, hence, the collision force between particles is taken into consideration. In this paper, the forces acting on particles include force gravity force $F_G$, drag force $F_D$, pressure gradient force $F_{PG}$, virtual mass force $F_{VM}$, collision forces between particles $F_C$, Van der waals force $F_{VDM}$, and electrostatic force $F_E$. In addition, the inertia forces $F_{ini}$ acting on particles caused by the swing motion of the CFB are
also considered in this equation. Therefore, the particle movement in the MRF is determined by the following equation:

\[
\frac{\pi \rho_p d_p^3}{6} \frac{du_p}{dt} = F_d + F_d + F_{cm} + F_{cg} + F_{vdw} + F_E + F_{ui}
\]  \quad (3)

\[
F_{vdw} = -\frac{H a_0 a_2}{6(a_1 + a_2)d^2}
\]  \quad (4)

\[
F_E = \frac{\mathbf{q}_i \mathbf{q}_j}{|\mathbf{r}'|} \mathbf{r}'
\]  \quad (5)

\[
F_{ui} = F_{centrifugal} + F_{coriolis} + F_{Euler} = -m\omega \times (\omega \times \mathbf{r}) - 2m\omega \times \mathbf{u}_p - m\frac{\ddot{\mathbf{r}}}{\dot{\mathbf{r}}}
\]  \quad (6)

where, \( \rho_p \) is the particle density, \( d_p \) is the particle diameter, \( u_p \) represents the particle velocity in MRF. The influences of forces \( F_d \), \( F_d \), \( F_{cm} \) and \( F_{pc} \) on particles have been detailedly discussed in our previously published paper (Zhilong WANG et al, 2014). \( F_{vdw} \) is an inherent force between particles, which has a significant influence on particles clust er and the adhesion strength between particle and wall. In Equation (4), Both \( a_1 \) and \( a_2 \) represent particles’ radius, \( H \) denotes a Hamaker constant number of spherical particle. In addition, particle charging is caused by frequent particle–particle, wall–particle collisions and gas–solid friction which are unavoidable in CFB (Bia H.T, 2005). As is shown in Eq (5), \( q_1 \) and \( q_2 \) represent two particles’ electricity. \( \mathbf{r}' \) is the displacement vector between two particles. The influences of the micro-force \( F_{vdw} \) and \( F_E \) on particle movement are analyzed, which is used to decide whether or not these forces are taken into consideration under this paper’s simulated conditions. Eq (6) shows the inertia force \( F_{ui} \) caused by the motion of the CFB. \( F_{ui} \) includes the centrifugal force \( F_{centrifugal} \), the coriolis force \( F_{coriolis} \) and the Euler force \( F_{Euler} \).

In terms of the scalar expression of \( \mathbf{r} = (0, 0, \omega)_v, v = (v_x, v_y, v_z) \) and \( \mathbf{r} = (x, y, z) \) in MRF, Eq (6) is expressed as:

\[
F_{ui, x} = \rho_p V_p (\alpha y + 2\omega v_{p_z} + \alpha^2 x)
\]  \quad (7)

\[
F_{ui, y} = -\rho_p V_p (\alpha x + 2\omega v_{p_z} - \alpha^2 y)
\]  \quad (8)

where, \( V_p \) is the particle volume, \( \omega \) denotes the instantaneous angular velocity of CFB, and \( \alpha \) represents the angular acceleration.

### 3. Simulation Conditions and Calculation Method

In order to well investigate the complex particle movement in a CFB, a three-dimensional geometry model is proposed. As is shown in Fig.1, the CFB includes riser, cyclone separator, downer, and J valve. The height of the riser \( h_r = 1024 \text{mm} \), the cross section of the riser is square with dimensions of \( a \times a = 288 \text{mm} \times 288 \text{mm} \). The diameter of the leg of the J valve is \( d = 40 \text{mm} \), and the diameter of the outlet of the cyclone separator is \( b = 170 \text{mm} \). The top plane of the cyclone separator and that of the riser are on the same plane. The distance of the riser's top plane to \( Z \) axis is \( h = 592 \text{mm} \). Meanwhile, it is the distance between the center line of the cyclone separator and that of the riser is \( c = 650 \text{mm} \). Six axial positions represent the corresponding domain with \( 10 \text{mm} \) height and \( 288 \text{mm} \times 288 \text{mm} \) cross section by the distance between the rolling axis and the different position. In addition, two coordinate system of absolute and relative is utilized. The absolute coordinate system \( O-XYZ \) is static, while the relative one \( o-xyz \) is attached to the CFB and moved with it. The origin of these two coordinate systems are coincident. In Fig.1, \( x \) axial direction is neglected on account of it perpendicular to the paper, similarly, \( y \) and \( z \) axial direction are identical.

The CFB model in Figure.1 mounted on ship is used to simulate the complex particle movement under an unsteady
circumstance. The ship motion influenced by the sea fluctuation is simplified as a sinusoidal function, which is regarded as the unsteady circumstance. The sinusoidal function is expressed as following:

\[
\theta(t) = \Theta \sin(\omega t) = \Theta \sin(2\pi t / T)
\]

where, \( \theta(t) \) is the rolling angle of the CFB, \( \Theta \) represents amplitude of the ship motion, \( T \) denotes the rolling periods, \( \omega \) is the angular velocity of the rolling motion.

Table 1 shows the simulation parameters. Initially, particles are generated from an injection file, and gravitational settling process provides the particle patching. Eventually, the total number of particles are \( n = 40000 \). In this simulation, particles are assumed to be spherical and coarse particles with the diameter \( d_p = 0.5 \text{mm} \) are used in order to reduce the computational time and to develop a mechanistic understanding. As the patched particles are deposited on the bottom of the riser, the air pass through the void between particles with an initial velocity \( u_0 = 4 \text{m/s} \) from the inlet1, and then particles reach to the top of the CFB. And then the gas-solid two phases flow is separated in the cyclone separator, particles flow down in the downer and return to the riser by J valve; while the gas discharged from the cyclone separator. In order to better send back particles to the riser, the pressure of inlet2 is set to 1000pa. The whole particles’ motion process formed a circulation. In case the gas-solid flows reached a static state where the number of particles flow in and out of a certain grid cell is equivalent, the sinusoidal function used to simulate the swing of the CFB is compiled.

![Fig.1 Schematic of Circulating Fluidized Bed mounted on ship](image1)

![Fig.2 Division and nomination of the cross section of the CFB riser](image2)

Out of Figure 1, it is seen that Inlet1 and Inlet2 as the bottom planes of the riser and J valve, which are defined as velocity inlet boundary conditions and pressure inlet boundary conditions, respectively. The outlet of cyclone separator is set to pressure outlet boundary condition. Additionally, Fig. 2 shows the division and nomination of the cross section of the CFB riser with nine parts (1-9) and three regions (region1, region2, region3).

In this present work, CFD-DEM method is used to the gas-solid two phases flow to gain insight into particles movement. On account of the complex interior flow in CFB under the unsteady circumstance and the higher Reynolds number of the gas-solid two phases flow, the standard \( k-\varepsilon \) turbulent flow model is adopted. According to the structure characteristic of the CFB, the riser is divided by structured hexahedron grids and the rest parts are discretized into unstructured tetrahedral grid, which reduce the calculation time to some considerable extent. The total grid cell number
of the CFB simulation model is about 200,000. Finite volume method (FVM) is used to discretize the continuum and momentum conservation equations of gas phase. And then the SIMPLEC algorithm based on pressure-velocity coupled is used to solve the discretization equations. Hence, the gas flow field is obtained from the simulation. Nevertheless, individual particle is solved by Newton’s second law of motion. In addition, the interaction between particles are preliminarily estimated by collision force $F_c$, Van der Waals force $F_{VDW}$, and electrostatic force $F_E$. The $F_c$ is obtained from the soft spherical model of DEM approach, while the $F_{VDW}$ and $F_E$ are evaluated by Equation.(4) and Eq.(5). Particles’ maximum amount of charge is a function of particle diameter $d_p$ and relative permittivity of the material (Hassani M A et al, 2013). All of particles are assumed to carry the equally and maximally positive charge $+2.673 \times 10^{-22}$C in order to largely reduce the complication of gas-solid flow system and obviously observe the influence of $F_E$ on it. The interaction between gas and particle is achieved by the two-way coupling method. The fluid forces acting on individual particles are react on the fluid phase from the particles, therefore, Newton’s third law of motion is satisfied (Xu B H and Yu A B, 1997).

4. Results and Discussion

4.1 Effects of the Rolling Motion of CFB on Air Axial Velocity

Initially, particles moved along the positive direction of $y$ axis are mainly dominated by the drag force $F_D$. In case particles are fluidized, a steady state of the average axial velocity of the air phase is reached. The axial velocity of air phase is shown in Figure.3 within a period of the rolling motion, which is decreased with the increase of the riser. Out from Fig.3, it is also seen that the air axial velocity have a peak at the time $t'=1.25s$ and $t'=3.75s$ on most of the cross sections except $y=-2900mm$. Therefore, the axial velocity of air phase is largely influenced by the unsteady circumstances.

Fig.4 shows the relative pressure drop of the rolling CFB riser. The relative pressure is decreased with the increase of the height of the riser. Namely, pressure drop exists in the riser of the rolling CFB. Moreover, the maximum relative pressure is reached at the time $t'=1.27s$ and $t'=3.75s$.

Consequently, the pressure drop and the tendency of the relative pressure changed with the variation of the time $t'$. are provided a good explanation for the phenomena of the Figure.3. During the process that particles are carried by air with an initial velocity $u_0=4m/s$, the air velocity is decreased with the increase of the riser. The air phase is doing work to particles, which results in the decrease of the air phase and the pressure loss in the CFB riser. Additionally, it is the higher relative pressure and the distribution of particles that caused the peak of the air phase's axial velocity at the time $t'=1.25s$ and $t'=3.75s$, when the CFB is at a static state on account of the angle velocity of the CFB $\omega=0rad/s$.

4.2 Variation of Particle Concentration under Static and Rolling Circumstances

As is shown in Figure.5, the averaged particle concentration on the six positions of the CFB riser is increased with the increase of the distance between $Z$ axis (static)/ $z$ axis (rolling) and the cross section of the CFB riser. On account of
the identical particles’ diameter, the averaged particle concentration on the each region denoted by the middle cross section is fundamentally fluctuant on a small scale with the time ranges from 1s to 3s. This results are in agreement with that published by Rhodes M J (Rhodes M J, 1997). Compared with Fig.5, Fig.6 shows the analogical distribution pattern, which is that the averaged particle concentration is decreased with the increase of the height of the riser. Obviously, the farther the distance between the z axis and the cross section of the riser, the more influence of the unsteady circumstance on the averaged particle concentration has. In case of focusing on the cross section y=2900mm, the particle concentration in this represented region is periodically fluctuated. Nevertheless, particle concentration on the plane y=750mm and y=1200mm keep a constant and low value with the change of time.

![Fig.5 The distribution of particle concentration in the riser under static circumstances](image)

As Figure.2 shows, region1 is composed of part1 to part3, region2 is made up of part4 to part6, and part7 to part9 consist of region3. Fig.7 shows the variation of the particle concentration in the three different regions (region1, region2 and region3) on the domain that represented by the cross section y=-2300mm. The averaged particle concentration of region1 is lower than that of region3 in case of the rolling time t’ ranging from 0s to 1.25s and from 3.75s to 5s, which begins after the CFB undergoes a period of time T=5s. By contrast, in case of t’ varying from 1.25s to 3.75s, the averaged particle concentration of region1 is higher than that of region3. Nevertheless, particle concentration in region2 is fluctuated with a small amplitude value. In addition, the averaged particle concentration of the three different regions are identical when t’=1.25s and t’=3.75s. Namely, the distribution of particles behavior are uniform in the radial direction in case the CFB reaches the maximum angular displacement. Therefore, the rolling motion of the CFB exercise a considerable influence on particles behavior, especially in the radial direction. As a result, particles have exchange phenomena in the radial direction and the particle concentration is varied periodically, particularly in region1 and region3.

![Fig.6 The distribution of particle concentration in the riser under unsteady circumstance](image)

![Fig.7 Time variation of the averaged particle concentration in three different regions](image)

![Fig. 8 The frequency analysis of particle concentration in different regions at the radial direction](image)
In order to investigate the relationship between the fluctuated frequency of the particle concentration in the region 1 and region 2 and the frequency of CFB’s rolling motion, Fast Fourier Transformation (FFT) as an effective approach is used to transfer the data from time-domain to frequency-domain. As is shown in Figure 8, the point of particle concentration in Fig. 6 is transformed to the frequency-domain by FFT. Obviously, the frequency of the region 1 and region 2 is 0.2Hz, which is totally consistent with the frequency of the rolling motion of the CFB. However, as particles in region 2 are rapidly moved and exchanged, it has no obvious frequency value. Additionally, in case of the higher frequency, the amplitudes of the three regions are all relatively low.

4.2 Variation of Particle Concentration under Static and Rolling Circumstances

Figure 9 illustrates the variation of forces acting on particles at the axial direction in the CFB without rolling effect. It is obvious that the resultant force \( F_{\text{resultant,Y}} \) in the axial direction is mainly dominated by the following two forces: the component of the drag force \( F_{D,Y} \) with a value fluctuated at \( 1.800 \times 10^{-6} \text{N} \), and the gravity force \( F_G \) with a constant value \(-1.605 \times 10^{-6} \text{N}\). It is shown that the magnitude order of Van der Waals force \( F_{\text{VDW}} \) and electrostatic force \( F_E \) is less than \( 10^{-6} \) and \( 10^{-27} \), respectively. The less particle numbers and the lower particle concentration are the main cause that result in the small \( F_{\text{VDW}} \) and \( F_E \) on account of the limitation of the computer. In this paper, as interparticle forces, \( F_{\text{VDW}} \) is regarded as an attractive force, while \( F_E \) is treated as a repulsive force. Therefore, the effects of \( F_{\text{VDW}} \) and \( F_E \) are partly counteract each other. Consequently, in the case of little particle numbers, the influence of the \( F_{\text{VDW}} \) and \( F_E \) on particle movement can be ignored. In practice, particles with different diameters and plenty of numbers are distributed in a real CFB model, which result in an complicated and unbalanced micro forces between particles. If particles’ diameter are equivalent, with the increase of particle number, the quits phenomena between \( F_{\text{VDW}} \) and \( F_E \) are much more obvious. In this case, the interparticle forces \( F_{\text{VDW}} \) and \( F_E \) also have little influence on particle movement. Additionally, as the magnitude of the unsteady forces composed of pressure gradient force \( F_{\text{PG,Y}} \) and virtual mass force \( F_{\text{VM,Y}} \) are much smaller than that of \( F_{D,Y} \) and \( F_G \), the unsteady forces \( F_{\text{PG,Y}} \) and \( F_{\text{VM,Y}} \) are disregarded in case of the static CFB. Therefore, the particle movement in the axial direction is mainly determined by the \( F_{\text{resultant,Y}} \). As the amplitude of \( F_{\text{resultant,Y}} \) is fluctuated, the behavior of particle movement in the gas-solid two phases flow is complicated. In case the value of \( F_{\text{resultant,Y}} \) is positive, particles have the trend to move upwards; while in case it is negative, particles tend to move downwards. Conversely, in the radial direction, \( F_{D,Y} \) and \( F_G \) have little influence on the behavior of particle movement, which is mainly dominated by the unsteady forces \( F_{\text{PG,Y}} \) and \( F_{\text{VM,Y}} \). Due to the unsteady forces \( F_{\text{PG,Y}} \) and \( F_{\text{VM,Y}} \) produced by the pressure gradient in the radial direction, the core-annulus flow structure in the static CFB riser is formed.

![Figure 9 Time variation of forces acting on particles at the axial direction in CFB without rolling effect](image)
Figure 10 shows the variation of forces that acting on particles in the axial direction under the influence of rolling motion of the CFB. Equation (3) gives the expression of the forces acting on particles, wherein the expression of forces acting on particles caused by inertia show in Eq.(7) and Eq.(8). Moreover, The unsteady forces including pressure gradient force $F_{PG,y}$ and virtual mass force $F_{VM,y}$, are much smaller than other forces, such as the drag force $F_{D,y}$, the gravity force $F_{G,y}$. $F_{G,y}$ is fundamentally fluctuated near $-1.6 \times 10^{-6}$ N with a small amplitude; while $F_{D,y}$ is considerably varied with the rolling the CFB, especially $F_{D,y}$ reaches the maximum value at $t' = 1.25s$ and $t' = 3.75s$, when the CFB is at the maximum angular replacement. Moreover, the maximum value of $F_{D,y}$ at $t' = 1.25s$ and $t' = 3.75s$ is slightly smaller than that at 1.25s on account of the reducing difference between air and particle velocity. Apparently, the resultant force $F_{resultant, y}$ is dominated by the $F_{D,y}$ and $F_{G,y}$. It is the larger $F_{D,y}$ and uniformly distributed particle in the radial direction at the time $t' = 1.25s$ and $t' = 3.75s$ that result in the air's axial velocity has the same varied tendency (Fig.3) as the $F_{resultant, y}$ (Fig.8).
movement is not taken into consideration. \( \mathbf{F}_{\text{rebound}_x} \) is the resultant force of \( \mathbf{F}_{\text{coriolis}_x} \), \( \mathbf{F}_{\text{euler}} \), and \( \mathbf{F}_{\text{G},x} \). It is the \( \mathbf{F}_{\text{G},x} \) that primarily dominate the particle movement in \( x \) direction by comparing the amplitude of those different forces. Obviously, the variation of \( \mathbf{F}_{\text{G},x} \) is consistent with the sinusoidal function defined in Eq.(10). Therefore, the distribution of the particle concentration in Fig.7 is well explained by the varied tendency of \( \mathbf{F}_{\text{G},x} \). When \( t'=0 \)s, particles are aggregated in region3 because the direction of \( \mathbf{F}_{\text{G},x} \) is along the positive \( x \) axis before \( t'=0 \)s. However, as \( t' \) changed from 0s to 1.25s, particle concentration in region3 is gradually reduced to an equivalent value that is gradually increased in region1 at \( t'=1.25 \)s because the direction of the dominated force \( \mathbf{F}_{\text{G},x} \) is opposite to the \( x \) axis. Subsequently, the direction of \( \mathbf{F}_{\text{G},x} \) is not changed until at \( t'=2.5 \)s, and the particle concentration is equivalent again at \( t'=3.75 \)s. Therefore, the particle movement behavior in radial direction is mainly dominated by \( \mathbf{F}_{\text{G},x} \). Namely, the variation of particle concentration is caused by \( \mathbf{F}_{\text{G},x} \) in the radial direction.

5. Conclusion

This paper presents the CFD-DEM simulation of gas-solid two phases flow in a certain Circulating Fluidized Bed (CFB) under an unsteady circumstance. The rolling motion as an unsteady circumstance is supposed to be a sinusoidal function with fixed rolling period and rolling amplitude. The behavior of both air and particles are investigated. As a result, the following results were obtained:

(1) In case of the static CFB, particle movement in the radial is mainly caused by the unsteady forces pressure gradient force \( \mathbf{F}_{\text{PG},y} \) and virtual mass force \( \mathbf{F}_{\text{VM},y} \).

(2) It is the pressure drop and the variation of relative pressure that result in the highest value of the axial velocity of the air phase, in case the CFB reaches the maximum angular displacement.

(3) The gravity force \( \mathbf{F}_{\text{G},x} \) and the drag force \( \mathbf{F}_{\text{D},y} \) are mainly dominated the particle movement in the axial direction both in the static and rolling circumstances. More importantly, it is the coriolis force \( \mathbf{F}_{\text{coriolis},x} \), euler force \( \mathbf{F}_{\text{euler}} \), and the component of gravity force \( \mathbf{F}_{\text{G},x} \) that enable particle concentration to change periodically at region1 and region3 in the radial direction and that produce particle exchange behavior in the radial direction.

(4) Van der waals force \( \mathbf{F}_{\text{VDW}} \) and electrostatic force \( \mathbf{F}_{\text{E}} \) are ignored on account of the low particle collision frequency and the low particle concentration.

References

Wang Z L, Zhao T, LIU K, TAKEI M; Euler-Lagrange Simulation of Fine Particle Discharge Rate under Accelerated