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CFD modelling of multi-particulate flow through concentric annulus

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In this investigation, flow through concentric annulus has been considered with the inner cylinder (wall) rotating. This work will guide the research studies for petroleum industries in reference with the wellbore drilling. The hole-cleaning issue is of utmost importance for the wellbore drilling applications. In that too horizontal boring is given more priority. Various parameters like slurry flow velocity, inner cylinder rotational speed, inlet solid concentration that has an impact on the behaviour of hole cleaning is analysed. The effect of these aforementioned parameters on the distribution of solid phase concentration is studied. Flow is taken as steady, incompressible and multi-phase slurry flow with primary medium (which carries the solid phase) being water and silica sand with 6 different sizes as the six different phases. The present flow simulation has been done by taking the Eulerian approach. Silica sand is considered of spherical shape. ANSYS FLUENT software is used for modelling and solution. Graphs for comparison are done using Microsoft Excel.

Keywords**:** Multi-particulate flow, concentric annulus, drilling fluids, slurry flow, bed formation.

1. Introduction

Fluids are conveyed (transported) through closed conduits in numerous industrial processes. It is found necessary to design the pipe system to carry a specified quantity of fluid between specified locations with minimum pressure loss. It is also necessary to consider the initial cost of the piping system. Transportation of slurries through pipeline is common in many industries including foods, pharmaceuticals, chemicals and mining industries. Globally the scientists and researchers are striving for developing precise models of velocity profile and solid phase distribution in a slurry pipeline..

Escudier et al.[1, 2] studied both the concentric and an 80% eccentric annulus with and without centre body rotation for the shear thinning fluid flow. The most important part is hydraulics of this simulation, because it controls single handedly the ways to circumvent defects associated with drilling Darley & Gray[3], 1998 – that needs to be as minimum as possible. Nouri and Whitelaw[4] had considered axial, radial and tangential velocity components of Newtonian and Non Newtonian fluid. After the analysis it was concluded that inner wall rotation had similar effects both for Newtonian and Non Newtonian fluids, with a more uniform axial-flow across the annulus.

Kim and Hwang[5] have simulated a vortex flow inside the annulus. Two media i.e. water and 0.4% aqueous solution of sodium CMC (both fully developed flow) were considered to obtain skin friction coefficients and pressure losses. Cruz and Pinho[6] researched the helical flow of fluids in concentric annulus with inner cylinder rotation as well Poiseuille flow in a channel skewed by the movement of one plate in span-wise direction. Kelessidis and Bandelis[7] put forwarded the concept of coiled tube drilling which is efficient in transportation of drill cuttings however it is still in its early stages.

Han et al.[8, 9] presented the study of vertical wellbore system in which the slurry is constituted of non-Newtonian fluids and solid particles in a tight annulus. The effect of annulus angle, rate of flow, inner wall rotation was seen on solid distribution and pressure drop. Aqueous solution of sodium CMC (0.2 – 0.4%) and 5% bentonite solutions was taken for non-Newtonian fluid one by one. Frigaard and Ngwa[10] realized that the annular plug fluid was flowing in the influence of buoyant forces in their analysis considering the Hele-Shaw approximation. Gavrilov *et al.*[11] proposed a numerical algorithm for simulating steady and laminar flows of an incompressible fluid in annular channels with eccentricity and rotation of the inner cylinder.

In all the studies above mentioned, the approach to reach a solution is different according to the type and nature of flow. Oil and gas industries generally come up with Non Newtonian flows with turbulent nature. The main role of these fluids is to carry the cuttings generated and when the boring operation is not working then its role is to make sure that solids remain in suspended state.

2. Hole cleaning in oilwell drilling

The nature of flow of slurry is of utmost importance in hole cleaning. Annular hole is the return passage for slurry and if its cleaning is not done properly then many adversities can occur for example pipe sticking, premature wear of drill bit, slow drilling, excessive torque and drag etc. Hole cleaning can be made efficient by many parameters like annular velocity of flow, hole inclination angle, drill string rotation, rate of penetration (ROP), drilling fluid property, and characteristics of cuttings. The problems of this kind are generally associated with the physics of travelling of working fluid. For instance, the wellbore eccentric annulus has some thin zones where the cuttings can get struck if the turbulence in flow is not enough. This leads to hole cleaning predicaments. The economy of drilling is very much affected as to how the cuttings are carried in a well bore. If the process is not up to the mark then it can lead to several problems as stuck pipe, reduced weight of the drill bit leading to the reduced ROP, transient hole blockage leading to lost circulation condition, extra pipe wear and extra cost because of the additives in the drilling fluid, and wasted time also [Kelessidis and Bandelis[7]]. More over the nature of solid particles in the slurry influences life of the bore parts and its performance as well and because of this many almost all gas and oil producing houses have to take care of the making of formation sand in addition with oil and gas. The produced sand causes several problems such as potential damage to reservoir, sand accumulation in lines or equipment, sand separation issues, and erosion.[13]

3. Problem Definition, Boundary Conditions

This investigation analyses the flow features of sand slurry through a concentric wellbore and various parameters like inner wall rotation, linear speed of slurry, concentration of solid particles, size of solid particles are varied to see the effects on shear stress, solid phase distribution, bed thickness across different cross sections of the annulus. Flow is assumed as three-dimensional, incompressible, steady, and turbulent under the considered geometrical and kinematic values taken. Pictorial view of the geometry and boundary conditions are shown in figure 1. For the annulus, the outer diameter (D_o) is 8 mm, inner diameter (D_i) is 60 mm and length (L) is 1.5 m. Hydraulic mean dia. $DH = Do - Di$ is 20 mm. Centre of the inner cylinder is taken as reference centre for measurement**.** In the present work, the orthogonal gird has been used for meshing of the geometry considered for the flow system. For the final simulation run, the distribution of the mesh considered was of distribution 50×150×120 (radial × azimuthal × longitudinal, respectively) comprising the total 7,14,000 number of cells in the computational domain[13]. The governing equations in ANSYS FLUENT are solved using the segregated solver. In segregated solver, equations are solved sequentially unlike the coupled solver where the equations are solved in a coupled manner

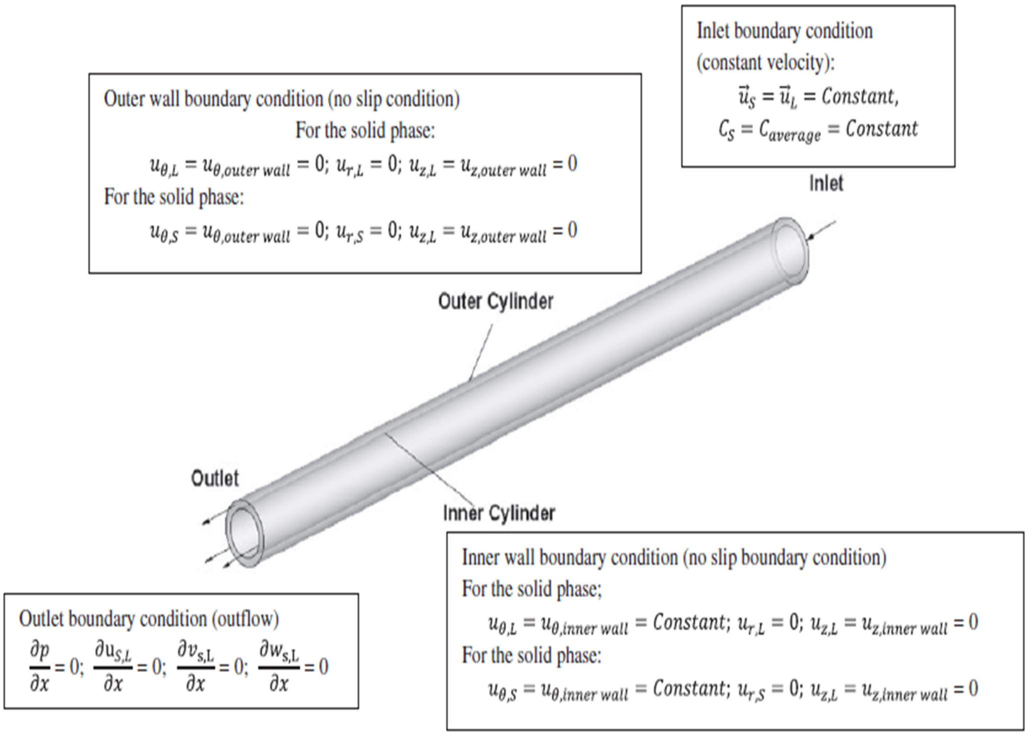

Fig. 1: Geometry and Boundary condition.

4. Mathematical and numerical methodology

The Eulerian model is the most complex of the multiphase models in FLUENT. It solves a set of n momentum and continuity equations for each phase. Coupling is achieved through the pressure and inter-phase exchange coefficients. The manner in which this coupling is handled depends upon the type of phases involved; granular (fluid-solid) flows are handled differently than non-granular (fluid-fluid) flows.

The governing equations for a two-fluid model with two continuous phases are shown below.

$$\frac{\partial \alpha_k \rho_k}{\partial t} + \nabla.(\alpha_k \rho_k u_k) = 0 \tag{1}$$

$$\frac{\partial \alpha_k \rho_k u_k}{\partial t} + \nabla.(\alpha_k \rho_k u_k u_k) = \rho_k C_k \alpha_k \nabla P + \alpha_k \nabla.\tau_k + (\alpha_k \rho_k g_k) + S_k = 0 \tag{2}$$

$$\frac{\partial \alpha_k}{\partial t} + \nabla.(\alpha_k u_k) = 0 \tag{3}$$

Here u is the mean velocity field and P is the mean pressure shared by the phases. The subscript k refers to the k^{th} continuous phase.

The pipe was first designed in Solid works and then imported to ANSYS workbench. Meshing is done and various zones (inlet, outlet, inner wall, outer wall) were recognized. Present study employs RNG k-∈ turbulence model, because it deals very well with the swirl nature of fluid flow. Long time researches have proved that this is the best model for study of slurry flow. [Pagalthivarthi and Gupta (2009); Kaushal et al. (2013); Dewangan and Sinha (2016)] [12–14]. For better study of the regions near wall, enhanced wall treatment option was activated. A total seven phase have been considered. This is as below;

a. Water (Carrier Phase); Density 998 kg/m^3, Viscosity 0.001003 kg/m-s

b. Silica Sand (6 Phases of different sizes); Density 2650 kg/m^3 [Refer Table 1]

Table 1: List of cases used for parametric studies of solid concentration

Case	d_p(μ m)	% C_{avg}	C_k % age of C_{avg}	d_w (μm)	Re_H	Ro_H
W3	750, 500, 250, 150, 100, 50	8, 12, 18	5, 10, 15, 15, 25,30	187.5	1.75E5	0.02, 0.04, 0.06, 0.08, 0.10, 0.12
W4	750, 500, 250, 150, 100, 50	12	20, 20, 20, 15, 15, 10	342.5	1.75E5	0.04, 0.08, 0.12
W5	900, 700, 400, 200, 125, 40	12	10, 15, 15, 15, 20, 25	320	1.75E5	0.04, 0.08, 0.12
W6	900, 700, 400, 200, 125, 40	12	16.67, 16.67, 16,67, 16.67, 16.67, 16.67	394.5	1.75E5	0.04, 0.08, 0.12
W7	738, 255, 180, 128, 91, 38	12	5, 10, 20, 40, 10, 5	167.5	1.75E5	0.04, 0.08, 0.12
W8	738, 255, 180, 128, 91, 38	12	5, 15, 30, 30, 10, 10	180	1.75E5	0.04, 0.08, 0.12
W9	750, 500, 250, 150, 100, 50	12	5,10, 15,15, 25, 30	187.5	1.75E5, 2.5E5, 3.5E5, 5E5	0.04

In the table 1, d_w represents the average diameter of the 6 phases; Re_H represents the linear Reynolds number and Ro_H represents the ratio of rotational Reynolds number to Re_H

$$Re = \frac{\rho v d}{\mu} \tag{4}$$

$$Ro_H = \frac{\rho \omega R^2}{\mu * Re} \tag{5}$$

5. Results and discussion

Present analysis has targeted the major problem of the horizontal drilling process, which is the accumulation of cuttings on the lower portion of hole as this becomes a source of multitudes of drilling defects. Parameters of input and output have been selected as per this consideration only. When the solid particles in the slurry does not get a chance to settle down then it is the only way for thinning of cuttings bed formation. Detailed results for water–sand slurry flow through the concentric annulus with inner cylinder in rotation are presented here. In the present work, the variation of concentration of different solid phases is studied with change in few crucial parameters such as bulk axial flow velocity (linear velocity) of slurry, rotational speed of inner pipe, and particle size of the solid phases etc.

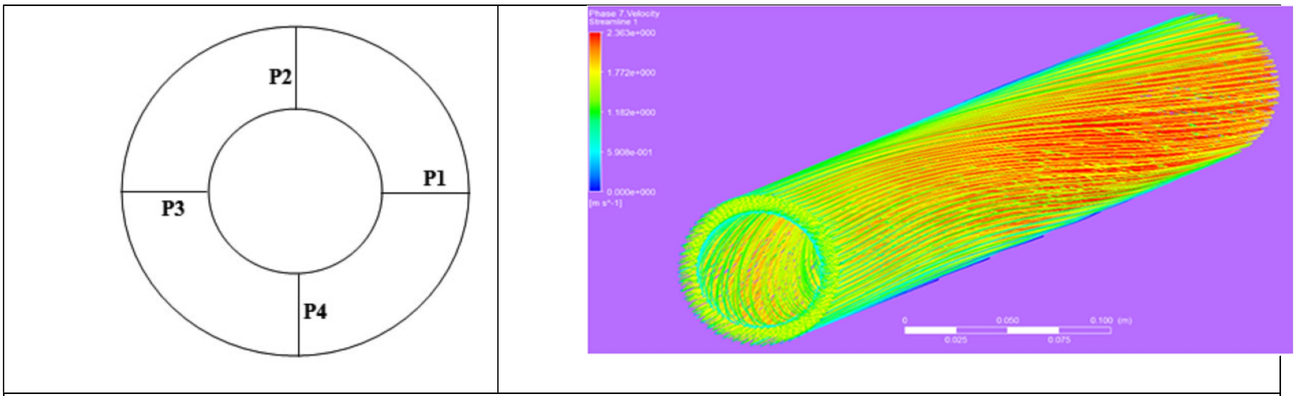

Fig. 2: (a) Locations of the radial planes P1, P2, P3 and P4; (b) Streamline flow

For insight into simulation within the flow geometry, a cross section plane at Z = 1.1 m is taken and four radial planes are selected along four perpendicular directions as shown in figure 2. Various cases (table 1) were run in ANSYS fluent and the stream lines are shown in figure 2.

5.1 Effect of slurry flow velocity on the volume concentration:

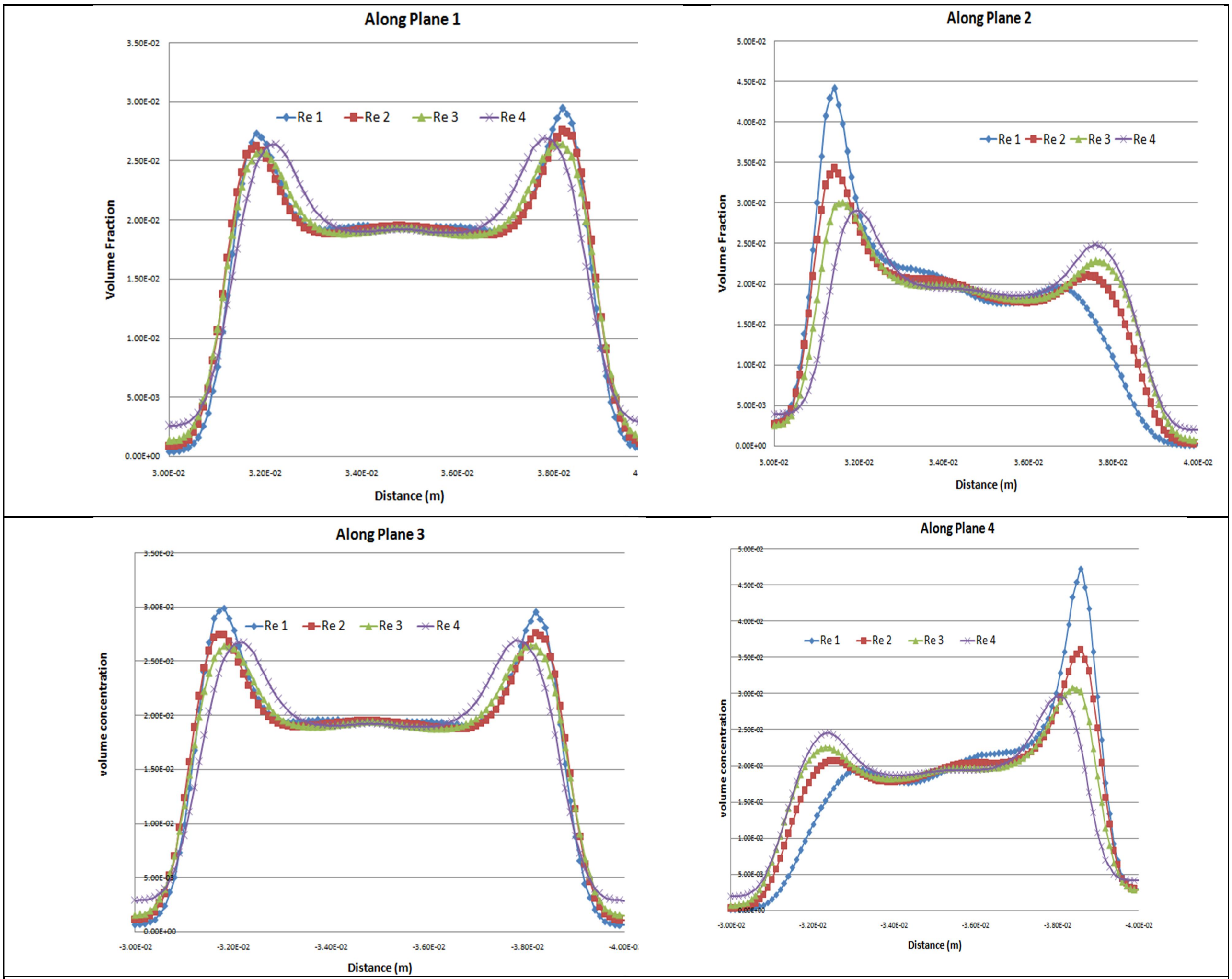

Fig. 3: Variation of solid phase volume fraction (for W9 slurry) for different slurry velocities at constant RPM of inner cylinder along plane 1, 2, 3 &4

Figure 3 is for W9 slurry with different Re values that denotes variation in axial velocities. From equation number 4, velocities calculated are : V1 = 7.78 m/s (corresponding to Re1), V2 = 11.58 m/s (corresponding to Re2), V3 = 15.55 m/s (corresponding to Re3) and V4 = 22.25 m/s (corresponding to Re4). From figure 3 it is observed along plane 1 and plane 3, the volume concentration is maximum towards the wall and minimum at centre of annulus. Along plane 2 and plane 4, gravity comes into effect and the solid concentration is maximum towards lower portion of the annulus. As the velocity decreases, the concentration at bottom of annulus increases. The pattern of solid concentration is similar across plane 1 and plane 3.

5.2 Effect of solid phase particle diameter on the volume concentration

Average diameter of solid particles has a great impact on the distribution of particles across the cross section of annulus.

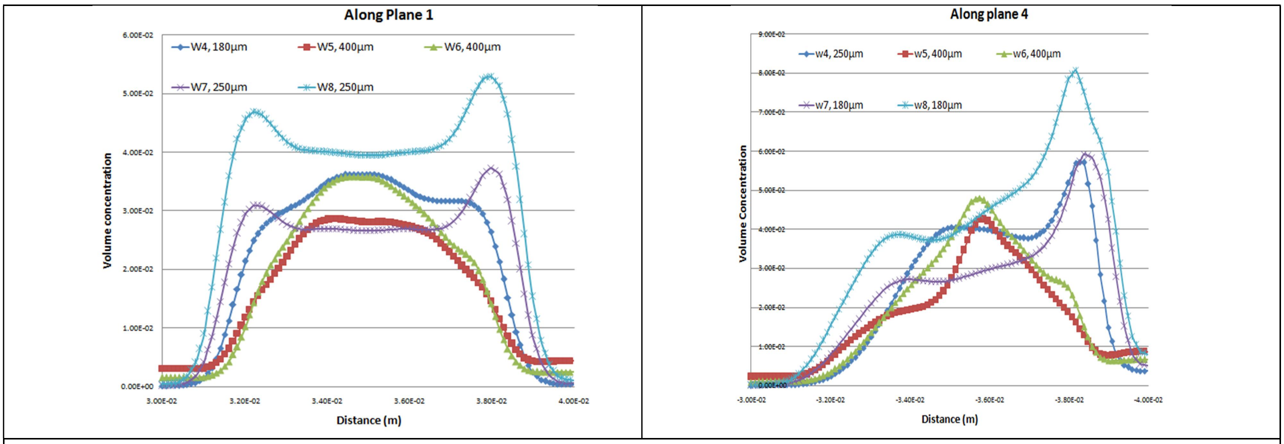

Fig. 4: Variation of solid phase volume fraction for particle sizes along plane 1&4

It is seen from figure 4 that the pattern of volume concentration along the plane is same for plane 1 and plane 3.The pattern of volume concentration along the is same for plane 2 and plane 4 in reverse direction (because of gravity).Along all the four planes as the average diameter increases, the concentration increases towards the centre and for lower diameters volume concentration is high at the walls. The possible reason can be momentum effect. As the size increases, the mass also increases and due to inner rotation of the wall, solid particles accumulate towards centre which prevents settling at walls.

5.3 Effect of rotation of inner wall of annulus on the volume concentration

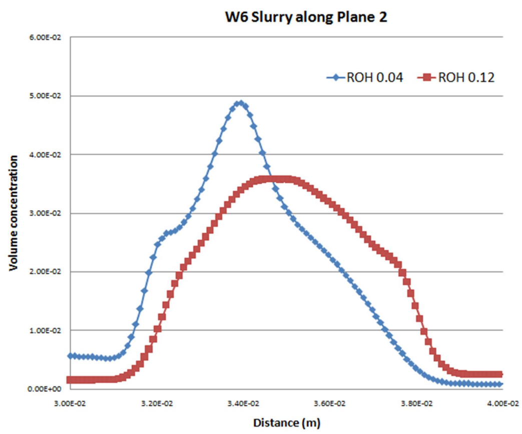

Fig. 5: Comparison of solid phase volume concentration for different rotational speed of inner wall at constant linear velocity [R_{OH} 0.04 = 70 RPM; R_{OH} 0.12 = 200 RPM]

Linear velocity, size of phases being same, volume concentration is compared across plane 2 and according to the graph shown above, one can conclude that as the rotational speed of inner wall speed increases the phases are more concentrated at the centre of the annulus rather than being concentrated at the inner wall due to gravity. Thus higher the rotation speed of inner wall settling down phenomenon will decrease but there is a upper limit to the RPM which is decided by the system capacity and requirements.

5.4 Effect of initial solid phase concentration of a slurry sample W3 [i.e. for constant particle diameter d_w] on the solid phase volume concentration distribution

As the solid phase percentage is increased in the slurry it is predictable that the volume concentration of solid particles will also increase in the proportional amount but the nature of the distribution along the cross sectional area will be nearly same for all the value of solid phase percentages. Following graphs are plotted for different percentages of solid concentration for R_{OH} 0.02 (33 RPM);

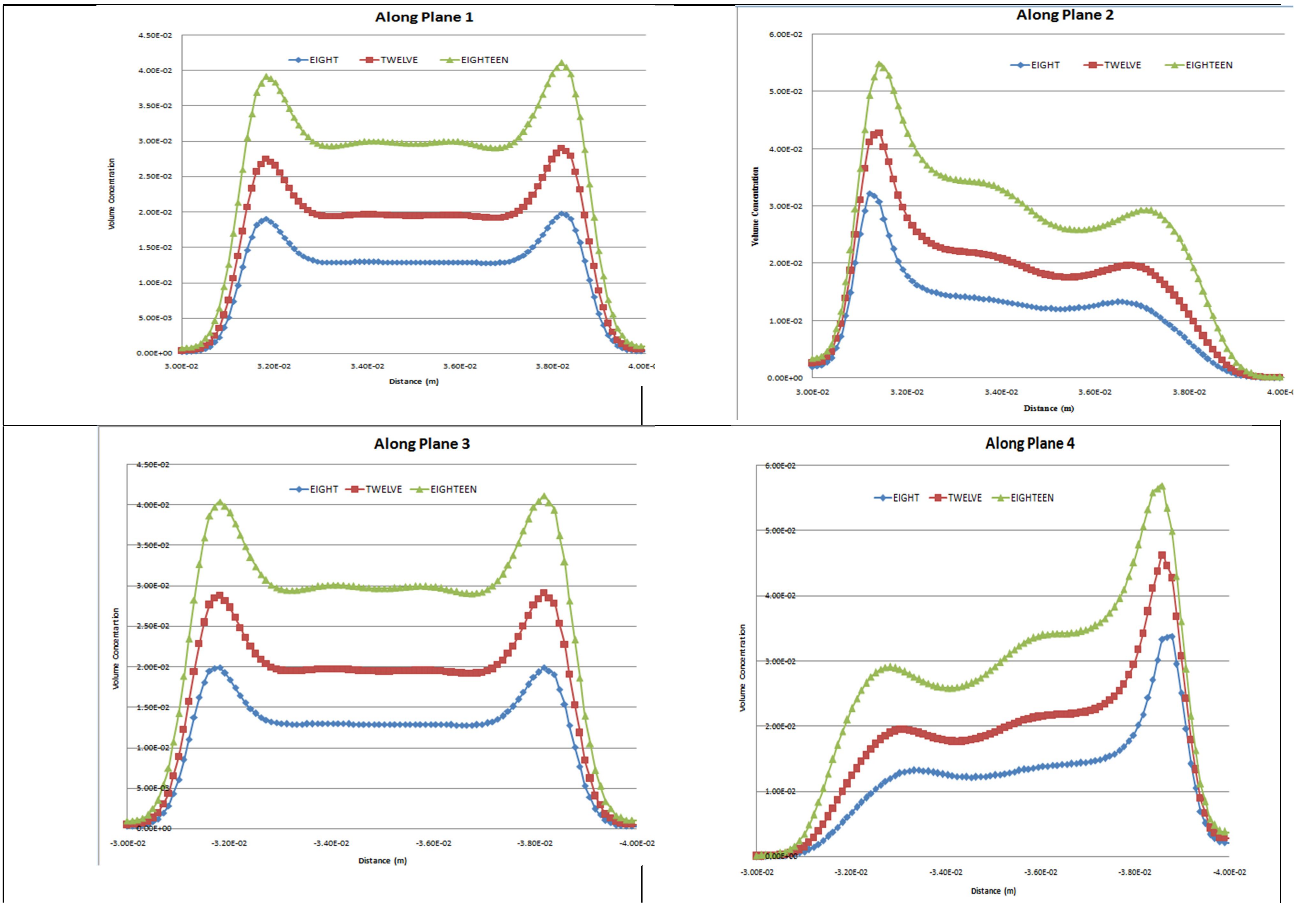

Fig. 6: Comparison of solid phase volume concentration for different initial solid phase concentration in slurry sample W_3 for R_{OH} 0.02 (33 RPM) and constant V = 7.78 m/s.

Fig. 6 shows the graph for W_3 slurry with R_{OH} 0.02 (33 RPM) and linear velocity is also constant i.e. 7.78 m/s. The only thing varying is the Solid phase content in the slurry. The nature of the concentration distribution of the solid phase across cross section is same for all the three percentages of solid concentration. As the percentage concentration increases in the slurry, the volume fraction of solid particles also increases in the proportional amount.

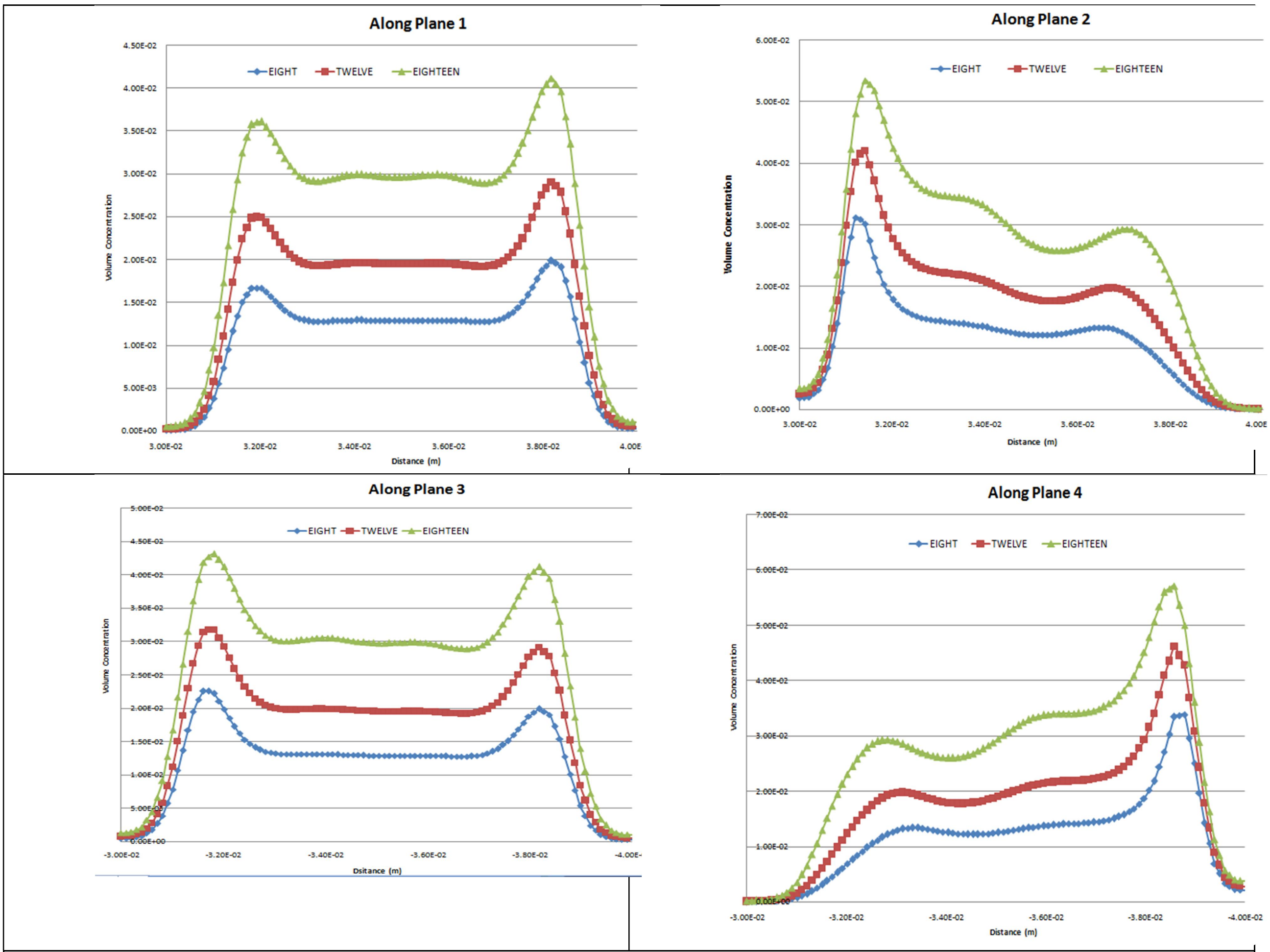

Fig. 7: Comparison of solid phase volume concentration for different initial solid phase concentration in slurry sample W3 for R_{OH} 0.08 (132 RPM) and constant V = 7.78 m/s.

The above curves are for W3 slurry with R_{OH} 0.08 (132 RPM) and linear velocity is also constant i.e. 7.78m/s. The only thing varying is the Solid phase content in the slurry. It is clearly seen from Fig.7 along plane 2 that with the increases in rotational speed of the inner wall, the volume fraction near the inner wall decreases and happen same for all the percentage concentration of solid phase. Along plane 4, the volume fraction increases towards the outer wall for larger RPM because of the combined effect of gravity and centrifugal force on solid particles.

Conclusions:

The concentration at bottom of annulus increases as the slurry velocity decreases. The pattern of solid concentration is similar across plane 1 and plane 3. As the size increases, the mass also increases and due to inner rotation of the wall, solid particles accumulate towards centre which prevents settling at walls. As the rotational speed of inner wall speed increases the phases are more concentrated at the centre of the annulus rather than being concentrated at the inner wall due to gravity. As the percentage concentration increases in the slurry, the volume fraction of solid particles also increases in the proportional amount

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