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CFD Analysis of Water Flow Behaviour Inside a Falcon Bowl

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Abstract

In mineral processing, techniques like classification; gravity concentration, thickening etc. require extensive understanding on fluid flow characteristics and relative movement of solids in fluids. The complexities in the geometries of the individual operations along with variable feed characteristics and limited computational facilities forced the researchers to optimize the performance through empirical. Though they are very useful in the mineral industry for a long time, better insight on the process physics can be achieved through computational based fluid dynamics modeling, design and simulation. Out standing developments in the computational facilities in the recent past have opened up avenues for process design and simulation through these techniques. The present study is an attempt to simulate the mechanism of water flow inside a rotating Falcon Concentrator bowl using a commercially available CFD package Fluent.

A 2D axi-symmetric geometry of Falcon SB-40 model was generated and about 1/3^rd^ of the bowl height from the bottom was patched with water phase and the remaining 2/3^rd^ volume was assigned as air phase. Simulation study was carried out under unsteady state condition for different time intervals using standard k-epsilon turbulence model. The results obtained on the change in the film thickness of water along the bowl walls are initially discussed. Further the velocities at different axial heights and along the radial positions with respect to bowl rotating time are discussed. The zones of maximum vertical and swirl velocities are identified and further discussed in terms of possible separation mechanism.

INTRODUCTION

Mineral concentration using gravity techniques is cost effective and eco-friendly, used to separate the mineral particles based on their relative density. Conventionally these techniques are suitable to recover particles down to 75 microns [Shiva Mohan et.al (1985)]. With the advent of enhanced gravity techniques, which employ centrifugal forces on particles, the separation limits have been extended down below 5 micron sizes [Burt (1995); Udaya Bhaskar et.al (1999, 2001, 2001); Mohan Rao (2003)]. These techniques achieve concentration of mineral particles based on superimposing the rotational fields on a conical bowl along vertical axis for rotation and a drum with horizontal axis for rotation. These units falling in the first category are knelson concentrator, Falcon concentrator that employs bowl speeds corresponding to a maximum of 300 *g forces on particles [Burt (1995); Honaker et.al. (1996, 1998); http://www.fci.bc.ca; http://falconfeb_2001_files/V4il.htm].The Multi-gravity separator belongs to the other category with rotational drum speeds corresponding to 25 * g forces on particles [Burt (1995); Udaya Bhaskar et.al (1999, 2001, 2001); Mohan Rao (2003)].

The water movement inside a rotating drum or a bowl will effect the separation characteristics. For better understanding the separation behaviour inside the rotating conical bowl, it is essential to have some idea on relative movement of solids in fluid media and also we should understand the velocity profiles of the fluid and the solid particles inside the rotating bowl.

In the recent past computational fluid dynamics techniques are gaining wide popularity in the area of mineral processing equipment design. The applications of these CFD based packages have been reported for performance simulation of different mineral processing units like hydrocyclones, spiral concentrators and heavy medium cyclones etc., [Hirt and Nichols (1981); Wood (1990); Zughbi et.al (1991); Rajamani and Milan (1992); Davidson (1994); Devulapalli and Rajamani (1996); Suasnabar and Fletcher (1998,1999) ; Matthews, Fletcher and Patridge (1996,1998 (a), 1998 (b), 1999)]. However, no attempt has been made any where in the world to understand the separation behaviour inside the rotating Falcon bowl.

In the present paper, important findings like water film thickness along the sides of the bowl at different axial heights inside the domain are highlighted. The results obtained interms of swirl, axial and radial velocity at different axial heights along the radial position are also discussed.

MODEL DESCRIPTION

Geometry

Standard Falcon–SB 40 model bowl geometry is used as a base model for simulation. The computational domain (Figure 1) consisted a 2D geometry of a conical bowl with a top diameter of 116.0mm; bottom diameter of 45.0mm and with a height of 99.0 mm. There are two ribs, which are provided at an axial height of 69.0 mm and 85.0 mm respectively. Since the geometry was axi-symmetric in nature, half portion of the bowl is modeled, with a symmetry boundary at the centerline.

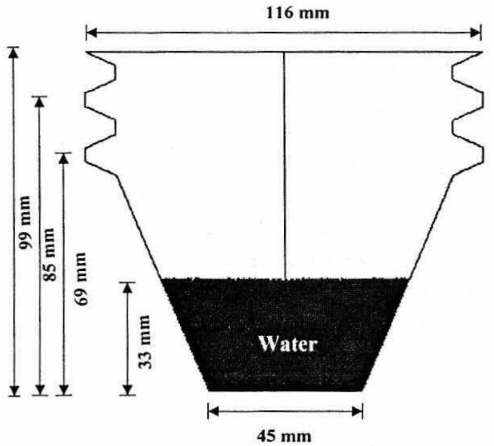

Fig. 1: Geometrical Details of Bowl

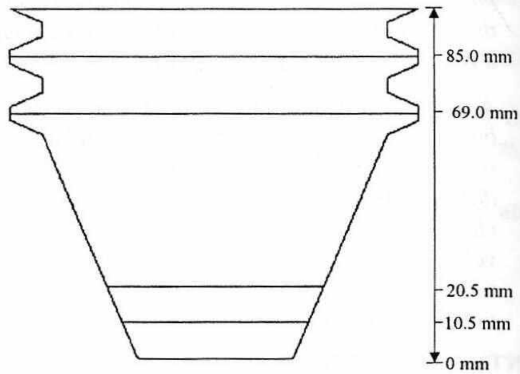

Fig. 2: Different Axial Heights Where the Water Film Thickness and Velocities are Computed

Meshing Scheme and Boundary Condition

All the edges of the bowl opposite to the centerline, is being meshed by reducing the spacing function to 0.5 and to the remaining edges spacing function 1.0 was used. Further, the face was meshed using triangular meshing scheme by giving the spacing of 1.0 in the interval size. The overall mesh density of 20067 computational elements was generated. The top surface of the bowl was designated as pressure inlet. The axis of the bowl was initially defined as symmetry, which was later, changed to axis and the side opposite to the axis of the bowl was designated as wall, to which angular velocity of 583 rpm is given.

SIMULATION METHODOLOGY

The 2D geometry of the bowl was solved using unsteady state segregated solver, with 1st order implicit body formulation. The segregated solver solves the governing Navier Stokes equations sequentially using iterative methods till the defined values of convergence are met. Axi-symmetric swirl was adopted for predicting the swirl velocity in the rotating bowl. The volume of fluid (VOF) was used for interface tracking. Standard k-epsilon turbulence model was selected for turbulence calculations [Launder and Spalding (1972)]. Air is used as a primary phase and water as secondary phase. The body-force-weighted pressure discretization scheme is recommended when solving a VOF problem involving gravity, was adopted [Fluent.Inc (2002)]. The Pressure-Implicit with Splitting of Operators (PISO), was used for pressure velocity coupling. The bottom one –third of the bowl is patched with water and a rotational speed of 583 rpm is maintained. The custom field function of ω = 3r for the swirl velocity is defined.

Simulations were carried out for about 15000 iterations by setting the time step size to 2e-04. The simulated results obtained on the axial, swirl and radial velocities at different axial heights and along the radial position are computed. Further, the water film thickness along the bowl wall is evaluated.

RESULTS AND DISCUSSION

Initially, the water film thickness along the bowl wall at different axial heights and along radial position is discussed. The general flow behaviour of water inside the swirling bowl and the results obtained on axial, swirl and radial velocities of water with respect to bowl spinning time are also discussed.

Effect of Spinning Time on Water Film Thickness

The changes in the thickness of the flowing film of water along the bowl wall at different axial heights for different time intervals i.e., 0.5 sec to 3.0 sec is shown in Table 1. The observation on changes in the water film thickness at different axial heights and along the radial position inside the swirling bowl is discussed separately as follows: -

Table 1: The Water Film Thickness at Different Axial Heights along the Radial Position Inside the Bowl

Axial heights (mm)	Water Film Thickness (mm)					
	0.5 sec	**1.0 sec**	**1.5 sec**	**2.0 sec**	**2.5 sec**	**3.0 sec**
10.5	26.50	26.50	26.50	3.74	0.95	Negligible
20.5	30.78	7.45	1.54	0.36	Negligible	Negligible
69	4.94	10.62	10.74	11.16	11.67	11.21
85	Nil	0.43	7.21	9.68	9.96	9.95

10.5 mm – It can be observed that there was no change in the water film thickness inside the spinning bowl between 0.5 sec. to 1.5 sec. However, it can be noticed that there was big decrease in the water film thickness from 26.5 mm to 3.74 mm between 1.5 sec. to 2.0 sec. and with further increase in spinning time between 2.0 to 2.5 sec, the thickness of the water film was further reduced to 0.95 mm. This may be explained as, due to rotation of the bowl the flow in the middle of the bowl is pull down by the gravitation forces and the flowing film of water tries to move along the sides of the bowl under the influence of centrifugal force.

20.5 mm – It may be observed from the table that the water film thickness decreases with increase in time from 0.5 sec to 2.0 sec. For instance, the water film thickness at 0.5 sec, 1.0 sec., 1.5 sec. and 2.0 sec are 30.78 mm, 7.45 mm, 1.54 mm and 0.36 mm respectively. With further increase in the spinning time of the bowl, it was found that the thickness of the water film is almost negligible, which indicates that there was no water near the walls of the bowl.

69.0 mm – It can be observed that the water film thickness was 4.94 mm till a time period of 0.5 sec. The film thickness started increasing from 0.5 sec to 2.5 sec and further decrease at 3.0 sec. This may be explained as; with increase in rotation of the bowl, the water at the bottom of the bowl is being pulled up along the side of the bowl and there was increase in the film thickness at these particular positions. With further increase in the spinning time of the bowl, the water film thickness at these positions was decreased due to downward flow of water on the outer layers, which experience relatively lower swirl velocity.

85.0 mm - Here, we can observe the similar trend as it is at 69.0 mm position. There was no water film till a time period of 0.5 sec. The film thickness started increasing from 0.5 sec to 2.5 sec and further decrease at 3.0 sec. The thickness of the water film at 1.0 sec was 0.43 mm. With increase in spinning time from 1.0 sec to 2.5 sec, the film thickness started increasing from 0.43mm to 9.96 mm and further the thickness was reduced to 9.95 mm at 3.0 sec.

Flow Pattern of Water As a Function of Spinning Time

Figure.3 shows the change in flow pattern of water inside a swirling bowl between 0.5 sec. to 3.0 sec. It can be observed from figure that the water level gradually decreases with increase in spinning time from 0.5 sec. to 3.0 sec. It also indicates that due to the rotation of the bowl the flow in the middle of the bowl is being pulled down and radially pushed out and up along the sides of the bowl by centrifugal forces. This causes the water level to decrease in the center of the bowl, as shown in contours of volume fraction of water.

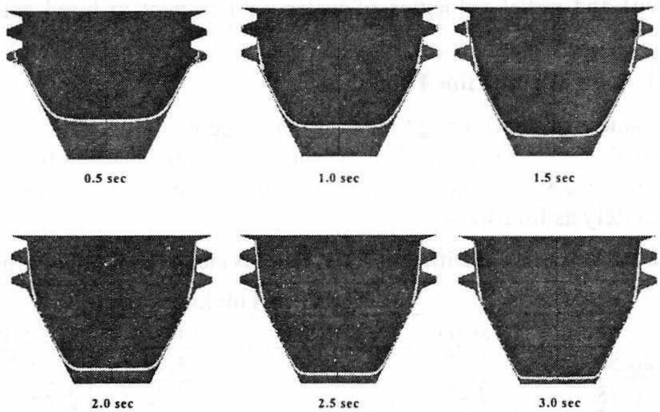

Fig. 3: Contours of Volume Fraction of Water at Different Time Intervals

Effect of Spinning Time on Axial Velocity

The results obtained on the axial velocity distribution at different axial heights with respect to bowl spinning time are plotted in Figure 4 to 9. From the figures it is observed that a maximum positive axial velocity values indicating a vertically upward flow of the water layers which may be observed near the bowl axis. With increasing radial distance, the axial velocity value decreases till it reaches zero at some distance away from the bowl axis.

The observations on changes of the axial velocity at different axial heights in radial position inside the spinning bowl are discussed separately as follows: -

10.5 mm and 20.5 mm - At these axial heights it can be observed that with increase in bowl spinning time from 0.5 sec to 2.5 sec, there was decrease in the axial velocity values for the water layer that is very much nearer to the wall and increase in the velocity values for the water layers away from the wall. This may be explained as, due to friction between the water layer and the bowl wall, which results in different vertical velocities in different layers. Thus, there is a decrease in the axial velocity values for 1 mm layer of water nearer to the wall boundary and increase in axial velocities for the water layers away from the wall.

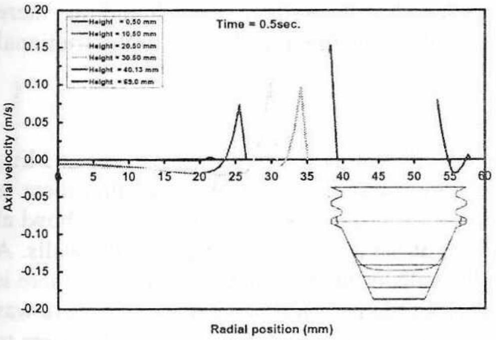

Fig. 4: Axial Velocities at Different Axial Heights Inside the Spinning Bowl at Time 0.5 Sec

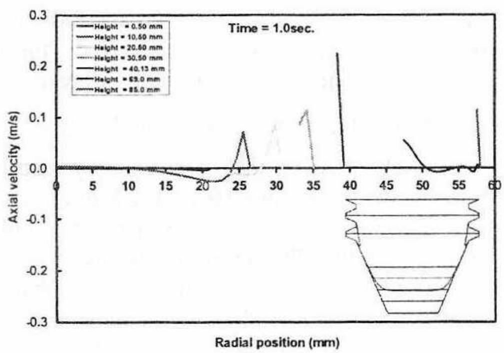

Fig. 5: Axial Velocities at Different Axial Heights Inside the Spinning Bowl at Time 1.0 Sec

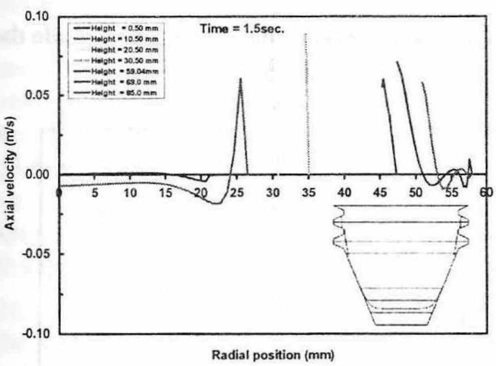

Fig. 6: Axial Velocities at Different Axial Heights Inside the Spinning Bowl at Time 1.5 Sec

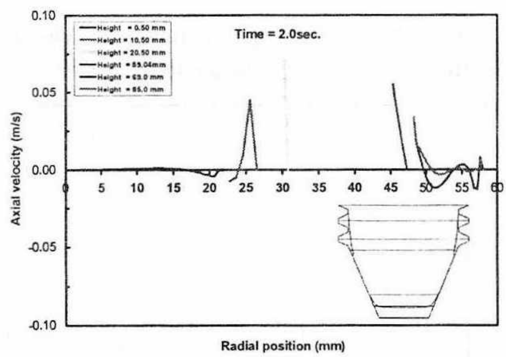

Fig. 7: Axial Velocities at Different Axial Heights Inside the Spinning Bowl at Time 2.0 Sec

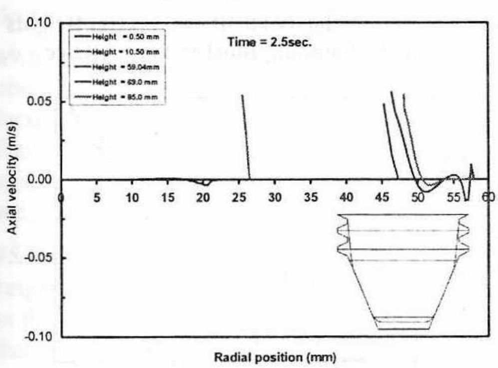

Fig. 8: Axial Velocities at Different Axial Heights Inside the Spinning Bowl at Time 2.5 Sec

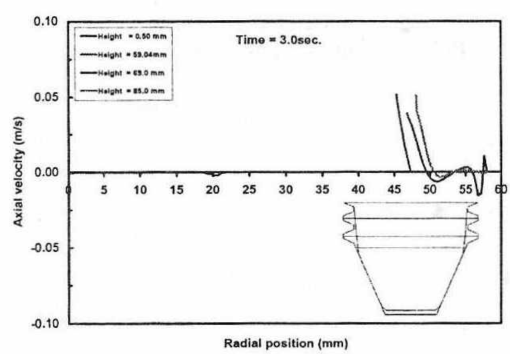

Fig. 9: Axial Velocities at Different Axial Heights Inside the Spinning Bowl at Time 3.0 Sec

69.0 mm and 85.0 mm – These are the axial heights of first and second rib of the bowl respectively. It can be observed from the axial plots that with increase in spinning time from 0.5 sec to 2.5 sec, there was decrease in the axial velocity values for the water layer nearer to wall. This may be due to more frictional forces between the water layer and the wall of the bowl. There was increase in axial velocity values for successive water layers that are away from the wall, which indicates that the water layer in this particular region tries to push up and radially along the bowl wall. Further, it was found that there was decrease in axial velocity values for the top most layer of water; this may be due to the frictional force between the air and top most water layer.

Effect of Spinning Time on Swirl Velocity

The results obtained on the swirl velocity distributions at different axial heights inside the swirling bowl are shown in Figure 10 to 15. From the swirl velocity plots, it can be observed that there is increase in the swirl velocity with increase in radial distance from the axis to the walls of the bowl at all the axial heights. The swirl velocity is grading from zero at the axis to a maximum at the walls. A maximum swirl velocity value of 3.5 m/s is observed at the walls of the bowl near the ribs and there is decrease in the velocity values as we move towards the axis. Further, it can be observed that there was drastic increase in the swirl velocity values for 1 mm layer of water, which are very much nearer to the walls of the bowl at all the axial heights and further there was decrease in velocity for successive water layers way from the wall. During bowl rotation a thin layer of water attached to the wall experiences more shear compared to the successive layers.

The observations on changes of the swirl velocity at different axial heights in radial position inside the spinning bowl are discussed separately as follows: -

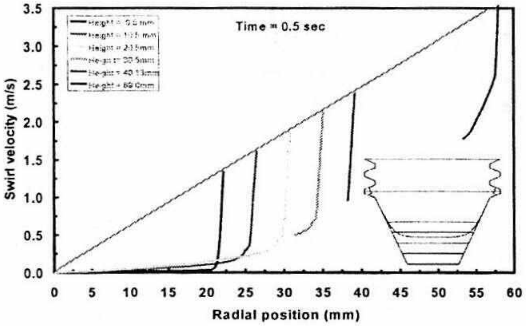

Fig. 10: Swirl Velocities at Different Axial Heights Inside the Spinning Bowl at Time 0.5sec

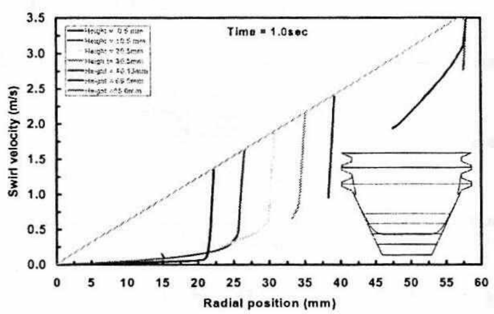

Fig. 11: Swirl Velocity at Different Axial Heights Inside the Spinning Bowl at Time 1.0 Sec

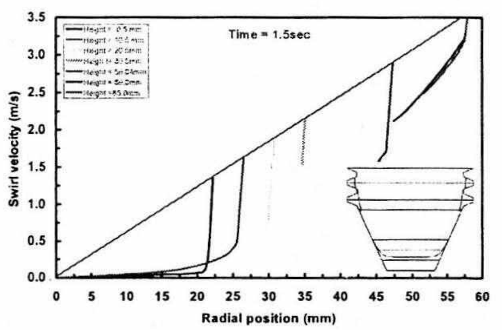

Fig. 12: Swirl Velocities at Different Axial Heights Inside the Spinning Bowl at Time 1.5 Sec

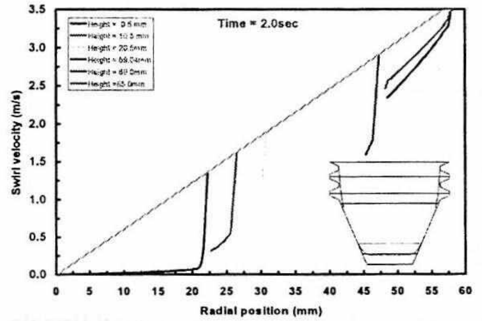

Fig. 13: Swirl Velocities at Different Axial Heights Inside the Spinning Bowl at Time 2.0 Sec

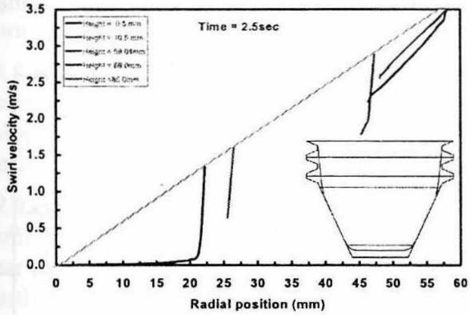

Fig. 14: Swirl Velocities at Different Axial Heights Inside the Spinning Bowl at Time 2.5 Sec

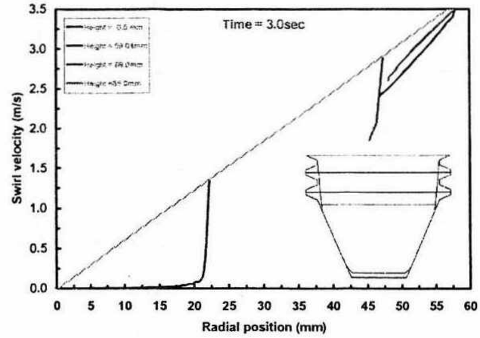

Fig. 15: Swirl Velocities at Different Axial Heights Inside the Spinning Bowl at Time 3.0 Sec

0.5 mm - At this height, the maximum swirl velocity observed at the wall was 1.617 m/s. There was no change in the water film thickness when the spinning time of the bowl was maintained between 0.5 sec to 1.5 sec. The water film thickness was 26.5 mm. There was not much change in the swirl velocity values between 0 to 25.5 mm, but there was steep increase in the swirl velocity values for 1 mm layer of water, that is very nearer to the walls. We observe that at this particular point i.e., 25.5mm,there was increase in the swirl velocity values with increase in the spinning time of the bowl, i.e. 0.382 m/s, 0.44 m/s and 0.488 m/s for 0.5 sec, 1.0 sec and 1.5 sec. With further increase in spinning time to 2.5 sec, the thickness of the water film was approximately 1 mm; the swirl velocity in this region was 0.64 m/s to 1.61m/s.

20.5 mm - At this axial height, the maximum swirl velocity observed at the wall was 1.87 m/s. When the spinning time of the bowl was 0.5 sec, it was observed that the water film thickness along the radial position was 30.78 mm. There was not much change in the swirl velocity values between 0 to 29.8 mm, but there was sharp increase in the swirl velocity values for 1 mm layer of water, that is very much nearer to the walls. When the spinning time bowl was 1.5 sec, it was observed that there was decrease in film thickness, and after 2.0 sec, there was no water along the radial position at this height.

69.0 mm - At this axial height, the maximum swirl velocity at the wall was 3.54 m/s. Here, it can be observed that with increase in spinning time of the bowl between 0.5 sec. to 2.5 sec, there was gradual increase in the swirl velocity values for the water layer at this position, and for 0.5 mm layer of water that is very much nearer to wall experienced sudden increase in the swirl velocity with increase in spinning time. The swirl velocity values at 57.5 mm point are 2.65 m/s, 3.23 m/s and 3.35 m/s for 0.5 sec, 1.5 sec, and 2.5 sec respectively.

85.0 mm - At this axial height, the maximum swirl at the wall was 3.54 m/s. Similar as 69.0 mm axial height, here also it can be observed that with increase in spinning time of the bowl, there was increase in thickness of the water layer near the wall. However, it can be noticed that 0.5 mm layer of water, that is very much nearer to wall experienced sudden increase in swirl velocity with spinning time. The swirl velocity values at 57.5 mm point are 2.76 m/s, 3.39 m/s, and 3.46 m/s for 0.5 sec, 1.5 sec, and 2.5 sec respectively.

Effect of Spinning Time on Radial Velocity

The results obtained on the radial velocity distribution at different axial heights inside the swirling bowl are plotted in Figure 16 to 21. Radial velocity of water has been found to be increasing from axis of the bowl till it reaches the bowl wall. However, it can be observed that radial velocity values is decreasing at or near the wall of the bowl due to frictional force between the water layer and wall.

The observations on changes of the radial velocity at different axial heights in radial position inside the spinning bowl are discussed separately as follows: -

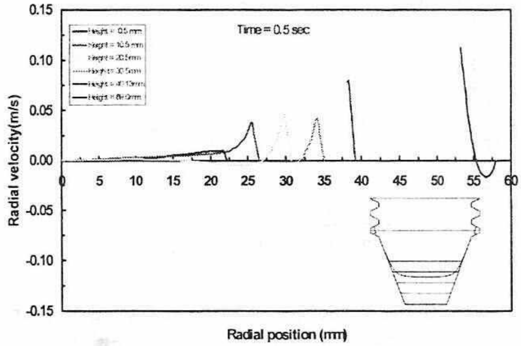

Fig. 16: Radial Velocities at Different Axial Heights Inside the Spinning Bowl at Time 0.5 Sec

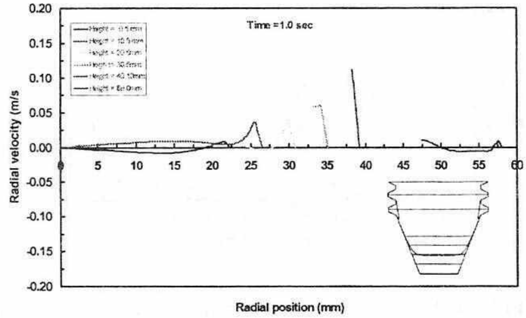

Fig. 17: Radial Velocities at Different Axial Heights Inside the Spinning Bowl at Time 1.0 Sec

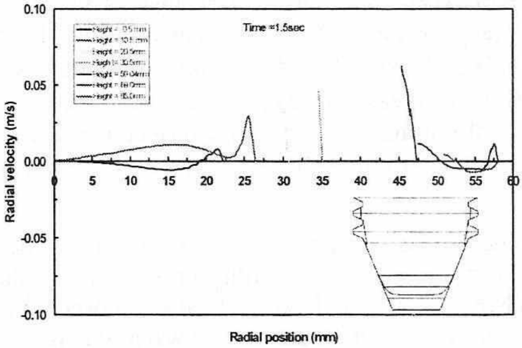

Fig. 18: Radial Velocities at Different Axial Heights Inside the Spinning Bowl at Time 1.5 Sec

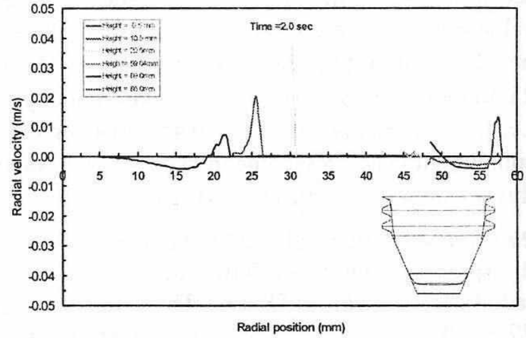

Fig. 19: Radial Velocities at Different Axial Heights Inside the Spinning Bowl at Time 2.0 Sec

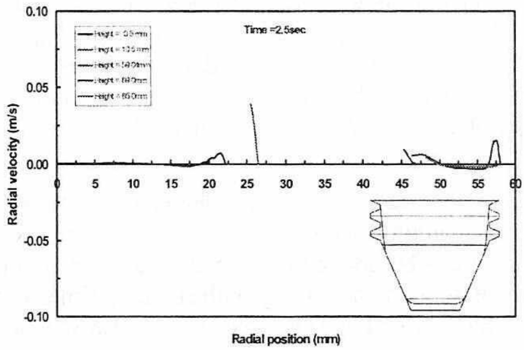

Fig. 20: Radial Velocities at Different Axial Heights Inside the Spinning Bowl at Time 2.5 Sec

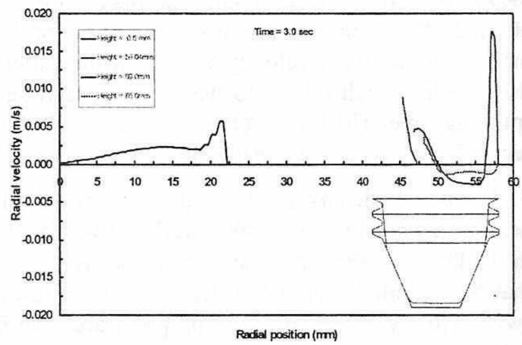

Fig. 21: Radial Velocities at Different Axial Heights Inside the Spinning Bowl at Time 3.0 Sec

10.5 mm - From the radial velocity plots, it can be observed that with increase in spinning time from 0.5 sec to 2.5 sec, there was increase in radial velocity values at the axis of the bowl. For instance at 0.5 sec, the radial velocity value was 0.0001 m/s. However, with increase in spinning time to 1.5 sec, 2.5 sec, the velocity values were increased to 0.0003 m/s, 0.0008 m/s respectively. This can be explained as due to the rotation of bowl, the water at the bottom of the bowl always tries to drive away from the axis and move radially towards the wall of the bowl.

20.5 mm- It can be observed that with increase in spinning time from 0.5 sec to 1.5 sec, there was increase in radial velocity values as move from axis to wall of the bowl and at the wall of the bowl velocity value was found zero. With further increase in spinning time, there was no water at this particular height, which indicates that water as risen to higher axial heights.

69.0 mm and 85.0 mm – At these axial heights, it can be observed that with increase in spinning time from 0.5 sec to 2.5 sec, there was decrease in radial velocity as we move from axis to water layer just near to wall of the bowl, which indicates that there is less movement of water layers towards the wall. Further, the radial plots also indicate that there was increase in radial velocity values for the thin layer of water attached to wall of the bowl, which indicates that the thin layer of water is moving radially towards the wall under the influence of centrifugal force.

CONCLUSION

The study has revealed a methodology for predicting the flow pattern of water inside the swirling bowl by adopting volume of fluid (VOF) with unsteady segregated solver; k-ε turbulence model and axisymmetric swirl. Having understood the flow pattern of water inside a swirling bowl by using unsteady state, in future further studies will be carried out on steady state condition to validate the simulated data with that of experimental values.

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