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An analytical approach to explain the generation of secondary circulation in spiral concentrators

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A R T I C L E I N F O

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A B S T R A C T

The spiral concentrator has been extensively used in the industry for decades. Gaps, however, appear to remain in understanding and explaining its unique flow pattern. Spiral is marked by the existence of high shear rate. Gravity, drag, frictional force between particles and trough, centrifugal force and lift force act in a particular manner to generate a unique flow pattern called secondary circulation. The present work attempts to explain how geometrical features and different forces help in generation of secondary circulation in pure fluid. A new concept of force balance from classical solid mechanics has been introduced to explain the generation of secondary flow and behavior of particles on the spiral trough. A modified form of Bagnold force equation has been presented along with simulation results.

1. Introduction

Spirals are widely employed for processing beach sand minerals, iron ore, gold, sulphide separation, glass sands, chromite beneficiation and in coal cleaning in the intermediate size range of 0.01 mm to 2 or 3 mm [1], because of their compact, fairly efficient, cost effective design which is rugged and required low maintenance [2–8].

The earlier understanding of spiral has been mostly empirical and design improvements have been made on trial and error based approach to meet the specific user requirement [1]. The performance of spiral is inferior when it is compared with the Dense Media (DM) separators, tables, and even jigs. DMC performance is not as desired for particle size range $-3 + 0.5$ mm because of the introduction of larger diameter cyclones, which increased the breakaway size [9]. Breakaway size is defined as the particle size below which the Ep of small particles starts to decrease significantly. Therefore in the US and Australia, the adopted flow sheet for coal cleaning are $-50 + 2/3$ mm by DMC/Jigs and fines i.e. $-2/3$ mm, are treated with spirals and flotation [10]. The particles in size range of $-1 + 0.25$ or $-1 + 0.10$ mm are mostly treated by spirals, because flotation of fines is very expensive and circuit is difficult to control [11]. Spirals are used in India for beneficiation of chromite, hematite, gold and beach sands. Because of difficulties associated with operating flotation circuits and increasing thrust on cleaning of fine size thermal and coking coal, a lot of thrusts is now on coal spirals. A closer examination of physical aspects of separation may explain the poor performance and indicate how the same can be improved.

Authors have stressed upon the need for extending the performance envelop of the spirals to cater to the need for beneficiation of inferior grade ore in the size range usually recommended for the spirals. Limited work has been published on the physics of particle separation in spirals and secondary circulation. Different models have been proposed to explain the working of spiral concentrator, but actual separation and secondary circulation has not adequately been explained. These models have been summarized in the Table 1:

The above models do not seem to have adequately explained, the generation of secondary flow and its role in particle separation, however, primary flow equations have been derived with different considerations. Some physical observations on the spiral trough have been made. This includes following:

- The water level at the outer concave wall of the trough exceeds that at the inner convex surface by an amount called super-elevation [7].
- The secondary flow is in the form of a vertically flattened helical spiral moving forward in a cork-screw fashion [7].
- The angles that inward bound and the outward bound flows make with the mean axial flow vary with depth and radial distance [7].
- Secondary circulation provides an inward flow at base of the trough and an outward flow at the free surface [12].

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Table 1
Summary of previous models on spiral concentrator.

Summary	Reference
Empirical models developed between 1940s till mid-1980s, based on experimental data.	Wills, 1996, [25]
Mechanistic models involving geometry of the spirals	Burch, 1962 [27],
Free motion theory based on gravity horizontal shear, and centrifugal forces	Holland-Batt, 1989 [17], H– Batt and Holtham, 1991 [12],
Fluid flow mechanistic models based on fluid mechanics equations for rectangular spiral sections. It was assumed that secondary flow would not affect the primary flow	Wand and Andrews, 1994, [37]
Force balance model Li et al.; without providing details of the model derivation	Li et al., 1995, [31]
A fluid flow investigation was done using coding with time considerations	Jancar et al., 1995, [30]
Model based on dynamic equilibrium in longitudinal direction and static equilibrium in transverse direction.	Kapur and Meloy, 1998, [6]
A CFD model of fluid flow was presented by Mathews et al. on spiral trough	Mathews et al., 1998, 1999 [32,33]
Glass and his coworkers have observed motion of particles in spiral through experiment, but did not explain the reason for such observation.	Glass et al., 1999 [14]
Dilute particle flow model with the use of isotropic RNG k–e turbulence model and Lagrangian method	Mathews et al., 1999, [34]
An empirical model was developed by Honaker et al. with the help of Box-Bahnken design, which accurately described the effect of three operating parameters and their inter-relationship for treating coal in the size range of −0.210 + 0.044 mm.	Honaker et al., 2007, [8]
A two-phase (water and air) computational model based on volume–of–fluid method was developed which took into account the effect of surface tension force. Also, four turbulence models were employed for simulation.	Doheim et al., 2008, [38,39]
A simulation tool based on discrete element method (DEM) to understand working of spiral and used it for design purpose	Mishra and Tripathy, 2010, [35]
A mathematical model to simulate the particle and flow behavior in an iron ore processing spiral, which expressed three main components, namely; spiral geometry, fluid motion and principal forces acting on particle	Das et al., 2010, [28]
Use of numerical simulation for PHOENICS, which gave a quantitative analysis about the distribution of flow field and pressure field for different viscosity and flow rate	Liang et al., 2011, [26]
A three-level Box–Behnken factorial design combined with Response Surface Methodology (RSM) for modeling process parameters of spiral concentrator such as feed rate, feed pulp density, splitter position for ultrafine chromite beneficiation	Tripathy and Murthy, 2012, [36]
Another study was done based on Eulerian approach and turbulence modeling. The results focused on particulate-flow characteristics such as the velocity, the distribution, and concentration of particulates on the spiral trough	Doheim et al., 2013, [29]

- Separation continues down the full length of the troughs even at a diminishing rate [13].

The influence of various operating and design variables on secondary circulation has not been studied in detail in the earlier works, however design parameter such as trough geometry and operating parameters such as flow rate, solids concentration, and wash water are expected to have major influence on the secondary circulation. Holland-Batt and Holtham [12] observed that flow rate has no significant influence on the direction of secondary circulation in the inner region, but could affect the outer region.

In this paper a detailed account of geometrical considerations and force balance has been presented to explain the generation of secondary circulation on a spiral trough with pure fluid and slurry at different solids concentration along with effect of design and operating variables. An attempt has been to explain, how combined effect of vertical stratification of particles in down-trough-flow and secondary circulation push heavy particles towards central column and lighter particles in the outer region. The behavior of particles in different regions on the spiral trough has been discussed multiple times in the literature through force balance considerations and experimental observations [12,14,7,6,15]. Selective separation under different flow conditions and at different points on the spiral trough does not seem to have been discussed in the available literature with proper and elaborate justifications. Application of force balance model from classical solid mechanics is an attempt to fill this gap in an easy and understandable manner.

2. Geometrical aspects

The deck of the spiral may be visualized an infinite number of axially adjacent non-interacting helical turns with a constant pitch for a given spiral. The calculation of primary slope and trough / secondary slope has been given elsewhere [6,7]. Accordingly, both the slopes can be determined by (Fig. 1):

$$\tan\alpha = \frac{P}{2\pi r} \tag{1}$$

$$\tan\beta = \frac{D_{max}}{r_o - r_i}\, tan\, \arcsin\left(\frac{r - r_i}{r_o - r_i}\right) \tag{2}$$

Where 'r' is the radial distance from the central column, r_i and r_o are inner and outer radius of the trough from the centerline.

3. Fluid flow on the spiral trough and generation of secondary flow

The geometrical configuration of spiral concentrator generates a unique flow pattern on the trough surface, which helps in easy and efficient separation of material into heavies and lights when the equipment is run within optimum operating conditions.

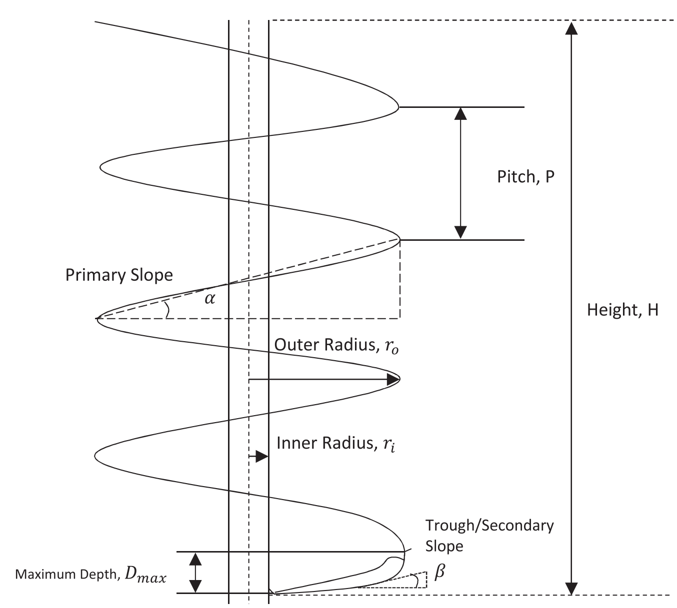

Fig. 1. geometrical configuration of spiral concentrator.