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Numerical simulation of water-air flow pattern in a Tri-Flo™ cylindrical separator.

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ABSTRACT

The hydrodynamics of the Tri-Flo™, a two stage cylindrical cyclone used in dense media separation, is studied using Computational Fluid Dynamics. The flow field is simulated with an Euler-Euler Volume of Fluid two-phase approach and the Reynolds stress turbulence model.

A unique feature of the device is that the separation medium suspension is pumped and introduced tangentially into the two cylindrical compartments while the raw feed is conveyed to the feed hopper and fed at the axial inlet. This feature allows to use less pumping energy and limits the unavoidable production of fines. The Tri-Flo™ complex flow pattern is little known but central to the efficiency of the separation.

The velocity field is computed within the two compartments of the separator. The interface of the air-core that forms in the inner axial part of the cylindrical sections is identified and visualized. The numerical results for a reduced-size 100 mm ID Tri-Flo™ are compared against laser Doppler measurements on a transparent acrylic model (Chinè, 1995) operated with water. The robustness of the model and its prediction capability are verified.

The possibility to accurately predict the velocity profiles within the vessel and their dependence on the main Tri-Flo™ operating and geometrical variables paves the way to a better understanding of the functioning of the separator, its design improvements and scale-up.

INTRODUCTION

The Tri-Flo™ device is a two stage dynamic dense medium separator. The two stages are integrated in a cylindrical vessel divided in two compartments. The first stage produces a sink (SINK1) and a float, the latter is retreated in the second stage; particles misplaced in the first stage as float have another chance to be properly separated by the second stage that produces a final float (FLOAT) and a second sink (SINK2). This results in a sharper overall separation-efficiency curve as a function of the density.

Feed and medium are introduced separately in the vessel. The separation medium suspension is pumped and introduced tangentially into the two cylindrical compartments. The raw feed is conveyed to the feed hopper and fed at the axial inlet. Only a small quantity of medium is poured by gravity with the feed material to wet the particles. This is a unique feature of the Tri-Flo™ that allows to use less pumping energy and limits the undesirable production of fines. The float is discharged at atmospheric pressure. The sink products are discharged with a counter-pressure adjustable with raised flexible pipes. Typical installation angle of the device are 15-30 degree with respect the horizontal depending on the application.

The first Tri-Flo™ prototype was built in the late 70's as a replacement of a Dyna-Whirepool vessel (DWP) for the revamping of the Masua lead-zinc concentrator (Sardinia). The metallurgical results (metal recovery vs. sink grade) where soon improved. Since then, a number of installations entered in operation worldwide for the separation of heavy minerals. At Geevor (Cornwall) tin pre-concentrator plant the Tri-Flo™ substituted a Wemco-Drum separator. In these applications the second stage acts as a scavenger unit.

The second stage of the separator can operate with medium of lower density than the first stage. With such a dual-density set-up at Prestavel (Stava, Trento, Italy) the first stage separated galena and sphalerite (SINK1) and in the second stage fluorite (SINK2) was separated by the gangue discharged with the float product.

In Figure 1 a simplified flow-sheet of a two cut density installation is shown. It integrates wet prescreening for eliminating fine particles and slimes, medium draining and rinse, dilute medium treatment for density regeneration and elimination of contaminating fines. These contribute to increase the medium viscosity that is detrimental for the sharpness of the separation. In most practical applications two magnetic separation stages are needed for proper media-fines decontamination (Ferrara & Schena, 1988).

Today most of the Tri-Flo™ applications are for coal washing and the second stage can be seen as a cleaning-stage delivering low ash coal at the float; the throughput of the larger (700 mm ID) vessels is 200-250 tonne per hour depending on the specific application.

The Tri-Flo™ is also used for metal recovery from slag and for the treatment of post-consume material. It has proved effective to separate high quality recycled glass by rejecting low and high density contaminants in glass separately collected as municipal solid waste.

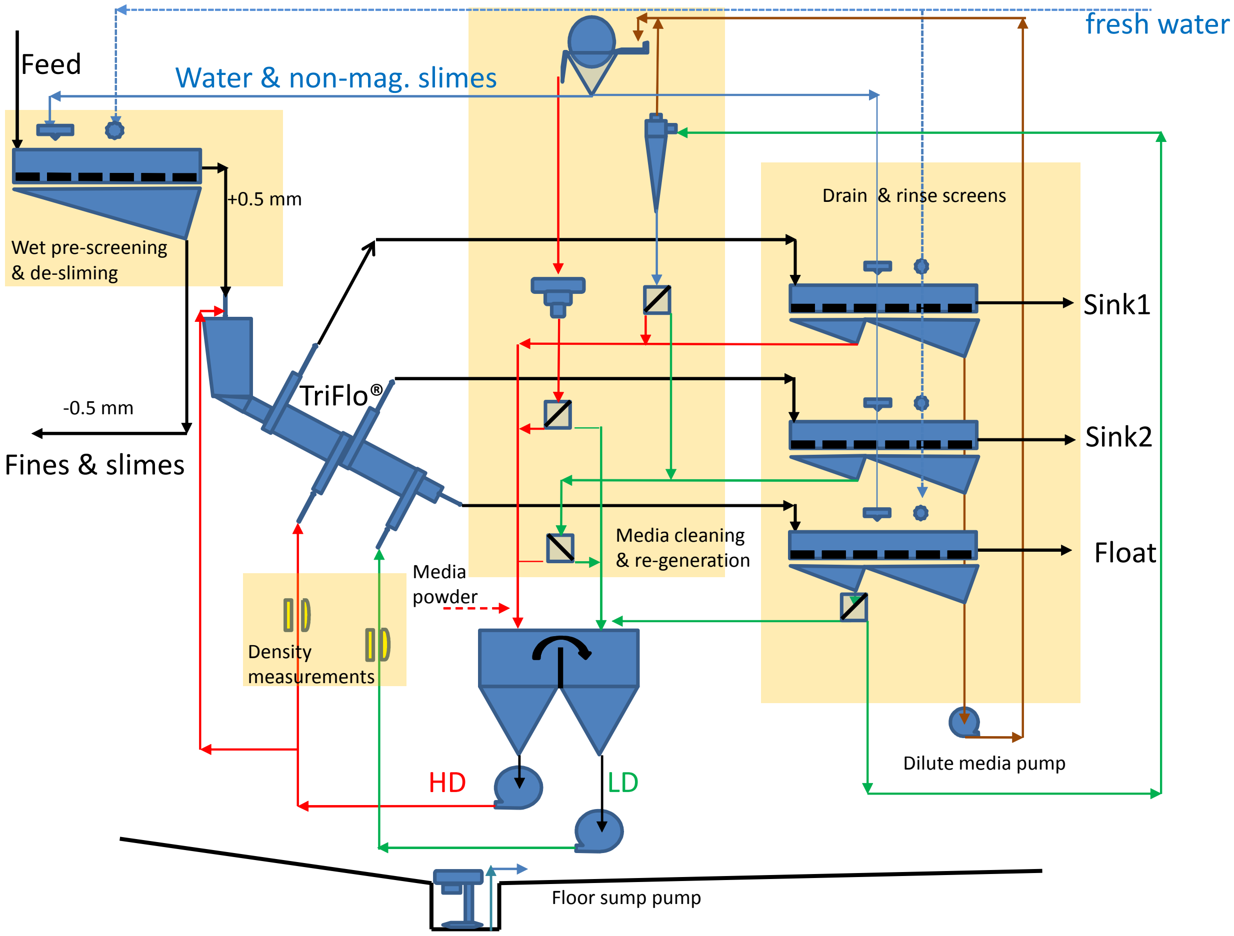

Figure 1 Simplified dense media separation flowsheet with a two cut density Tri-Flo™ device.

The design of the two stage cylindrical separator has been continuously improved through the years based on practical experiences accumulated in the industrial operations and on visual observations of the separation behavior made in small scale transparent acrylic material models operated with water and water-based brines. In particular the design of the tangential inlets has been subjected to re-design with the aim to reduce turbulence. An involute-like connection between the inlet and the cylindrical section is now adopted and a new feeding system for cylindrical separators (Dynafeed™) has been recently developed and patented.

The most used Dutch State Mines type cylindrical-conical separators -where the feed and the medium suspension are pumped together- have been studied thoroughly in recent years, also resorting to multiphase computational fluid dynamics (Delgadillo & Rajamani, 2005; Narashima et al., 2006,2007). In contrast the cylindrical separators has been receiving much less attention by CFD (Shi, 2010) . The velocity distribution within the two-stage Tri-Flo™ has been measured by Chine (1995) and Chine et al. (1997) with laser Doppler techniques.

The flow pattern of the highly swirling and turbulent flow affects the separation efficiency. The possibility to accurately predict the velocity field within the vessel and their dependence on the main Tri-Flo™ operating and geometrical variables paves the way to a better understanding of the functioning of the separator, its design improvement and scale-up. In spite of the Tri-Flo™'s simple geometry the swirling flow behavior is complex and include turbulence, air core vortex formation and stability, intricate velocity and pressure fields.

The aim of this work is to develop a proper fluid-dynamics model and its implementation within a computational fluid dynamics software, making it possible to simulate and better understand the behavior of dense medium cylindrical cyclone.

The simulation results were compared with the experimental data obtained by Chine (1995) on the reduced size two stages (inner diameter of 100 mm, about 1 meter of length and 15° of tilt) pilot Tri-Flo™ separator, made from transparent acrylic material and operated with water at different values of the operating parameters.

METHODOLOGY

The separator vessel and the inlet and outlet orifices were meshed with a hexahedral-cells block-structured computational grid (Fig. 2) encompassing ~300 k cells. The orientation of the domain is such that its z axis is the axis of the two cylindrical compartments. Ansys-ICEM® is the used for meshing. Special care is needed to join the mesh of the thinning inlet/outlet involute shapes to the rest of the computational domain using solely structured blocks.

The Volume-of-Fluid (VoF) model is used for fluid simulation as the two fluids are considered immiscible. Air enters the model from the axial feed inlet, while water enters tangentially at the bottom of both stages at the inlet of the separation medium. The flow of air and water within the two stage cylindrical separator is simulated with Ansys Fluent ver. 14.0.

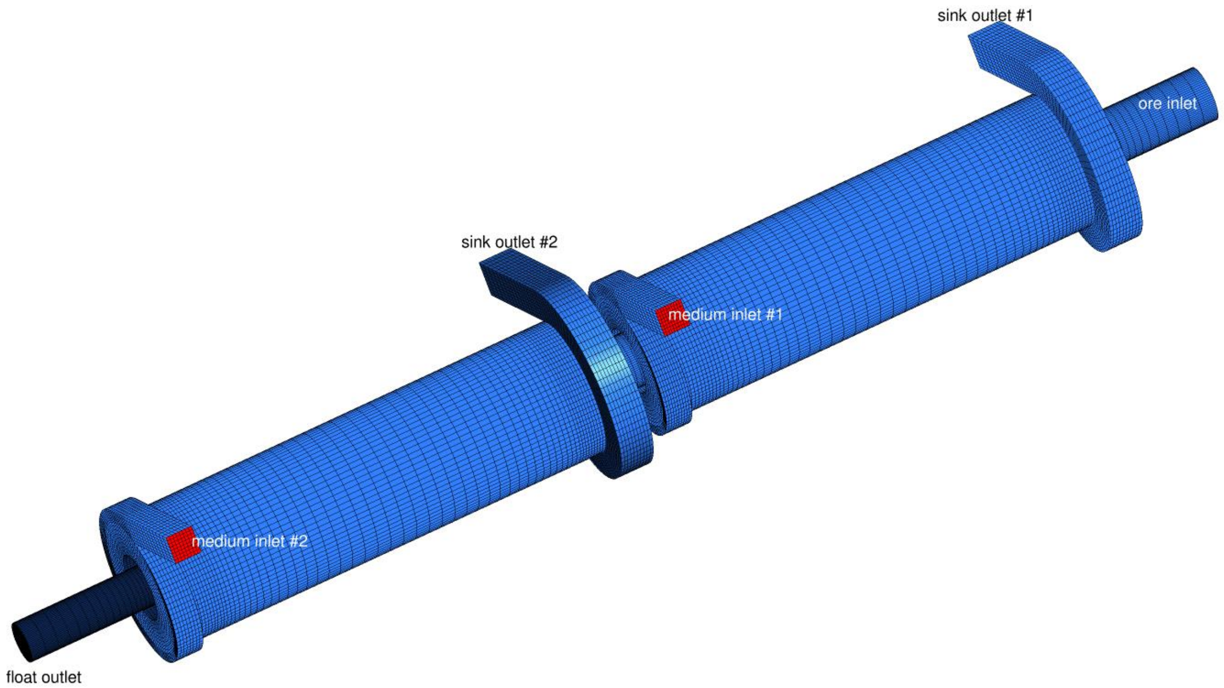

Figure 2 Block structured hexahedral mesh of the considered geometry

Medium inlets are defined as velocity inlets with the prescribed average normal velocity, turbulent intensity at both inlets was set to 5%. The sink discharge outlet are defined as pressure outlet with a static counter pressure. Axial orifices are defined with static pressure set to zero.

The high Reynolds number of the considered water flow prevents a direct numerical simulation of the turbulent flow through the cylindrical cyclone. Therefore, an Unsteady-RANS approach is followed, where the effect of high-frequency turbulence fluctuations on the low-frequency components of the flow is represented by a Reynolds-Stress (RSM) model. The RSM model solves transport equations for each Reynolds-Stress components and for the turbulent kinetic energy and turbulent energy dissipation. The surface tension that acts at the water – air interface is accounted for via the Continuum Surface Force (CSF) model as an additional body force. The body force is proportional to the surface tension coefficient and the local curvature of the interface and adds as a source term in the momentum equation (Brackbill et al., 1992). The geometric reconstruction method based on the piece-wise linear interface construction (PLIC) algorithms is used in the present work for interface tracking. Simulations were run on a low cost machine based on an Intel 3970X six core processor.

RESULTS AND DISCUSSION

Figure 3 is a snap-shot extracted from a long movie that visualizes the air core formation in the inner axial part of the cylindrical section and its time evolution. Here the air core is colored with the axial velocity. The air core is stable as it does not collapse during the simulation and if it rarely does then it recovers rapidly. The air-water interface is, however, not stationary as it wobbles in the middle of the device. Recorded movies show that the air core is not stable in shape and position and the degree of "wiggling" depends on the flow parameters.

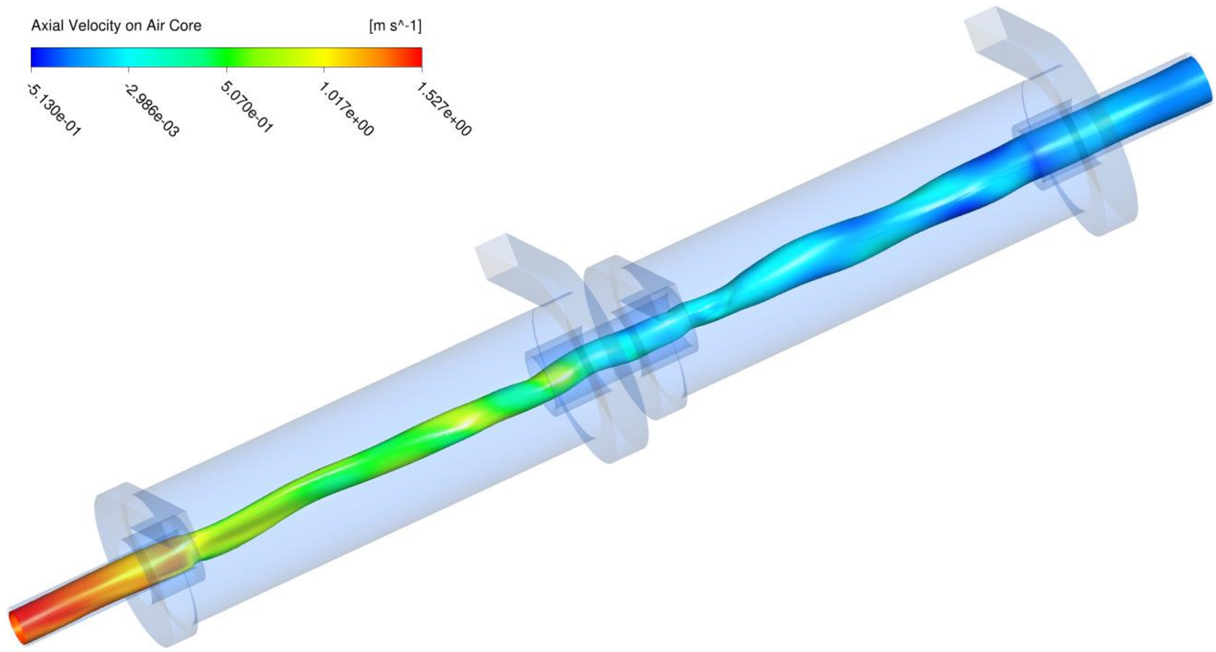

Figure 3 Computed air core colored by axial velocity

The observation of the fluid velocity components shows an upward axial velocity near the wall and a downward velocity near the air core. A zero axial velocity iso-surface can be drawn in between. The fluid (medium) that does not exit at the sink is subjected to flow reversal and directed down to the float outlet.

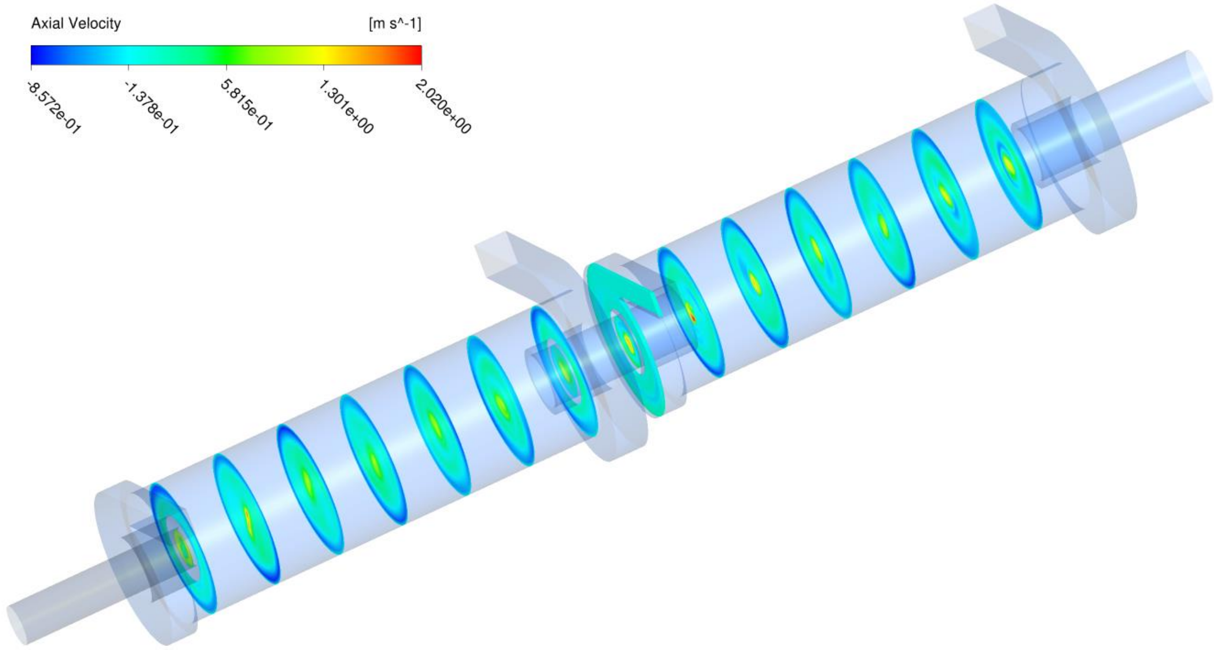

Figure 4 Axial velocity at several cross-sections

The axial velocity component is responsible for recovering the particles at the outlets. Particles close to the wall are reported to the SINK products by the upward axial velocity component. The downward velocity component accompanies particle close to the air-core to the FLOAT products at the axial float discharge.

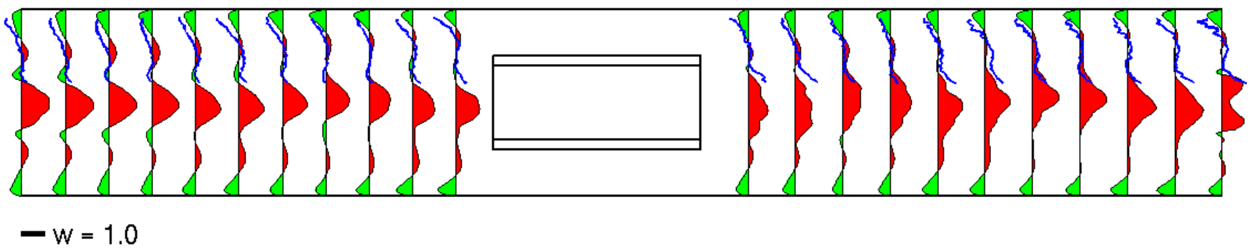

Figure 5 Calculated, time averaged and interpolated (red – positive, green – negative) fluid axial velocity fields. Laser Doppler measured profiles are in blue. Left side represents the 1-st stage, right side represents the 2-nd stage.

Particle on the zero axial velocity iso-surface can be indifferently reported to the sink or the float. Axial velocity distribution at several cross-sections is shown in Figure 4. Here negative values are for components toward the sink outlets and positive is toward the float discharge. The pattern is approximately symmetrical with respect to the device axis. At the cyclone device wall the axial velocity is zero. By moving from the wall toward the axis the upward component increases to a maximum value and subsequently decreases to zero. It turns sign and the module increases. The air core velocity is downward toward the float discharge and has a maximum at the central axis. Figure 5 overlaps the laser Doppler profiles (in blue color) to time averaged computed axial velocities.

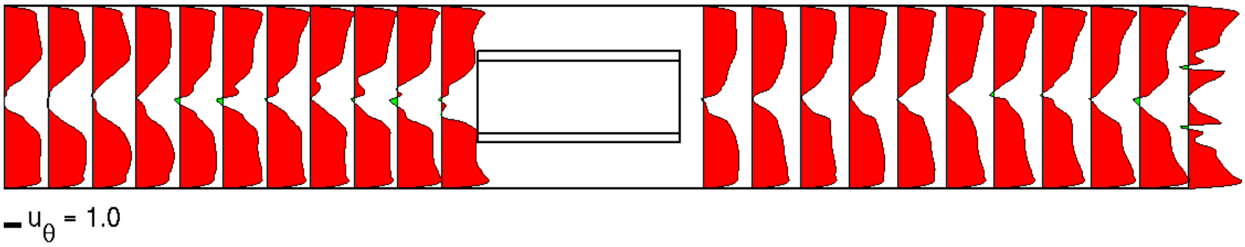

Figure 6 Calculated, time averaged and interpolated (red – positive, green – negative) tangential velocity fields.

The radial position of the particles is determined by the acting centrifugal force. The tangential fluid velocity is responsible for the centrifugal acceleration and force. Particles with high density and larger size tend to be pushed toward the wall and recovered with the SINK by the axial component. Comparison of velocity fields at different time instants indicates that the tangential velocity component does not change substantially in time. The tangential velocity is higher at the wall and decreases by moving to inward toward the air core, there is a discontinuity in the profile at the interface. The tangential velocity is pretty constant also moving axially (Fig. 6). This seems to be a peculiar characteristic of the Tri-Flo™ that is favorable to an efficient separation. The lowering of the back pressure at the sink outlet of one compartment produces a significant rise in the tangential velocity of the same compartment.

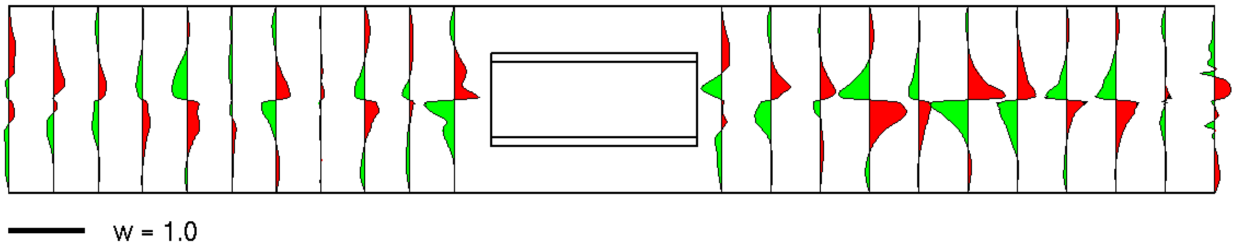

Figure 7 Calculated, time averaged and interpolated (red – positive, green – negative) fluid radial velocity

As for the cylindrical-conical hydro-cyclones also for the Tri-Flo™ the computed radial velocity component is about one order of magnitude less than the other two components (Fig. 7). The radial component is strongly affected by the air core instability in shape and position; in turn the degree of "wiggling" of the air core depends on the flow parameters. The angle of inclination of the device about the horizon is also a possible cause of un-symmetry. Other authors have noticed the asymmetry of the radial components in hydrocyclones.

CONCLUSION

Computational fluid dynamics methods allow to reproduce numerically and accurately the velocity fields measured experimentally with non- invasive techniques on small scale Tri-Flo™ models at the same operating conditions. Other results not reported here, due to limited space, indicate that also trends, i.e. variation of the velocity components at the change in important operating variables such as sink counter pressure, are in agreement with experimental measurements. The numerical methods appear as a tool suitable to drive the improvement of the application of the separation device design and the modification of its geometry. Future development of the methodology will provide the separation efficiency by simulating the release of groups of particles at the feed inlet by adding a Discrete Phase Model (DPM) to the existing model. The DPM should provide the ability to predict the probability of particle of given size and density of exiting the device through each of the outlets.

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