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CFD ANALYSIS OF SWIRLY FLOW FIELD IN CONICAL AND CYLINDRICAL CYCLONES FOR DEOILING APPLICATIONS

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ABSTRACT

Hydrocyclone is a key purifying component in deoiling process as it is passive, requires low maintenance and has a small footprint. Many studies have been dedicated to the widely used design being the counter current cyclone. Concurrent on the other hand receives less attention and the geometrical shape studied only focuses on cylindrical body. To the author's knowledge, conical body has yet to be studied which prompted this investigation. In this study, numerical method using ANSYS FLUENT is employed to study the flow field differences of conical and cylindrical concurrent cyclones such as on tangential and axial velocities and recirculation region at 45° and 72° fluid swirl angles. Analyses have shown that conical cyclone increases average tangential velocity by 6.4% and 16.3% at 45° and 51.1% and 34.2% at 72° (sampled at 25% and 75% lengths respectively) compared to cylindrical one. Axial velocity improvements to the outlets of 58.8% and 32.1% at 45° and 58.9% and 62.9% at 72° on average are registered at 25% and 75% length respectively. Recirculation in conical is also thinner and shorter and the presence of reverse flow at the annulus outlet is not detected compared to cylindrical cyclone. These improvements are beneficial for droplet separation for achieving high efficiency.

Keywords: liquid-liquid hydrocyclone, oil/water separation, deoiling, swirly flow.

INTRODUCTION

Phase separation works on the principle of density difference between the components. A common approach used is the settling tank that allows the denser phase to settle to the bottom of the tank using gravity as the driving force. Such system typically requires long processing time and spacious which may not be viable such as on oil platforms. The other alternative is to use cyclone separator based devices to artificially enhance this driving force. The unit has the edge of having faster processing time as well as smaller footprint. Cyclonic separator has been successfully employed in the separation process of solid from gas or liquid. The big density difference between the solid and the carrier fluid enhances the separation process. Considerable difficulties however arise in liquid-liquid separation in which droplet break ups, coalescence and emulsion can happen simultaneously in the unit. Moreover small density difference between the fluids can greatly hamper the separation process.

Several authors had investigated the applicability of implementing axially-inlet cyclone using swirl generator with a few studies on tangential inlets in liquid-liquid separation. Concurrent cyclone has lower pressure drop, and droplet breakup, symmetrical flow and more robust vortex profile compared to counter current unit [1]–[4]. All the studies mentioned used cylindrical body with only one using cylindrical-conical build. Only 2 authors studied the effect of the swirl generator designs though this is limited and complete details are absent. Dirkzwager[2] is the famous pioneer to suggest axial cylindrical concurrent cyclone and experimented with a single phase flow. The velocity fields including the fluctuating components were studied using LDV measurements. Dirkzwager however does not enclose the swirl design. Shi-ying *et al* [5]on the other hand experimented with the cylindrical-conical cyclone at 8% volumetric oil content. The water outlet was configured differently in which slotted wall was used. Stone [6] investigated concurrent cylindrical cyclone using tangential inlet cylindrical cyclone at various oil volume fraction (low, moderate and high). Swirl generator studies had been done by Campen and Rocha, though the swirl generator details are absent. Rocha [7] studied the effects of using pointy cone swirl generator tail on the flow using cylindrical body. Such design effectively reduced the reverse flow and increased the tangential velocity in the cyclone. Campen [3] employed a cylindrical cyclone in which 3 swirl generators were used at different angles. Strong dependence is observed on large flow deviation.

All previous concurrent studies only employ cylindrical body with only one cylindrical-conical body. The authors with the exception of Slot also did not enclose the swirl generator design which hampers further numerical studies by other researchers. The swirl generator design is crucial as it allows for better fluid motion prediction. These factors encourage the comparison investigation of cylindrical and conical cyclone bodies.

The present study aims at investigating the differences of 2 axial concurrent cyclones for bulk oil water separation being the cylindrical and conical cyclones for the possible use in the down hole oil water separation. The study employs ANSYS FLUENT and ICEM CFD in single phase scenario. Slot experimental data is used as the numerical settings validation. Aspects discussed are the differences of both units in terms of tangential and axial velocities and recirculation region.

NUMERICAL SIMULATION

Geometrical parameters

For the purpose of the experiment setup, cylindrical and conical cyclones are designed based on the allowable drilling tube diameter. The length of the overall

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units from the tail tip to the vortex finder tip vary as to keep the residence time constant. For present numerical study the nose and swirl generator are excluded from the CFD domain. Figure-1 shows the differences between the actual experimental and computational cyclone. A summary of the relevant CFD dimension descriptions are given in Table 1and portrayed in Figure-2.

Meshing scheme

ICEM CFD is utilized for the 3D mesh generation as it is more accurate than tetrahedral for a cyclone simulation. For this study the nose and swirl elements are excluded from the computational domain as it is found to have little impact on the solution[1]. Inlet area is defined as the D-d at the leading tail edge directly after the blade as shown in Figure-1. 3 different mesh densities are tested at 800 000, 980 000 and 1.4 million cells. Due to the expensive Reynold's Stress Model (RSM) cost, highest density meshes are found only to improve slightly compared to intermediate mesh count as in Figure-3.

Boundary Conditions

ANSYS Fluent version 15 is used in this work using 3D double precision segregated solver. The working fluid is water with density and viscosity of 1067.8 kg/m^3 and 1.183cP respectively. The geometries are tested with RSM turbulence model and scalable wall function is used with no slip boundary conditions at the wall. SIMPLEC is used for the pressure velocity coupling, PRESTO is used for the pressure discretization and QUICK is used for all the remaining discretization conditions. The last 2 conditions are found to be suitable for predicting highly swirling flow especially in a cyclone separator unit [1]. Numerical inlet as in Figure-1 is defined as velocity components with the axial and tangential velocities both set at 2m/s for a 45° fluid deflection. For the case of 72° the axial and tangential velocities are set to 2 m/s and 6.16 m/s respectively. The central outlet (in Figure-1), D_o, is set as mass flow outlet while the annulus outlet (in Figure-1), is set as pressure outlet. A flow split of 30% is imposed at the central outlet normal to the face boundary. The inlet and outlets turbulence intensities are set to 5% and 15% respectively. The simulation starts at steady state for 15 000 iterations and then switched to transient at 5ms interval. Data sampling is initiated after a statistically steady solution is achieved.

The general predicted fluid motion in terms of tangential velocity, V_{tan}, and axial velocity, V_{axial}, and swirl decay are discussed against available flow profile by several authors. Due to the differences both units lengths, the sampling locations are set at 25% and 75% of the total length starting from the tip of the swirl generator tail towards the exits. The velocities and sampling radii are normalized against the bulk velocity, V_{bulk}, and largest radius at the sampling location respectively. The bulk velocity is defined as the fluid inlet velocity before the nose of the swirl generator as in Figure-1 denoted by the shaded surface representing experimental inlet.

Validation results

Experimental data of Slot is used as the numerical validation for axial concurrent flow as it is the sole author that provides the complete swirl generator geometrical data. Slot investigated a cylindrical concurrent separator with a swirl generator in which the tangential and axial velocities are measured for single phase flow. The settings and geometry are used to resimulate Slot's geometry for accuracy as shown in Figure-3. It can be seen that the numerical data closely depicts Slot's numerical and experimental results. The differences could be caused by the differences in meshing techniques. Also, the presence of a very small gas core is observed in Slot's experiment and this has been excluded from the computational domain [1]. For the present study a mesh independent study is also conducted in which 980 000 is found to be suffice to achieve mesh independence.

RESULTS AND DISCUSSIONS

Tangential velocity

Figure-4 depicts the normalized V_{tan} profiles for both bodies at different normalized heights. The cyclones portray 2 velocity trends typical of a cyclone separator being the solid body rotation and free swirling flow for all fluid deflection angles. The conical body can pertain higher velocity at all downstream locations than cylindrical body which is beneficial in the separation process. For the case of 45°, the velocity gradient is roughly equal for both

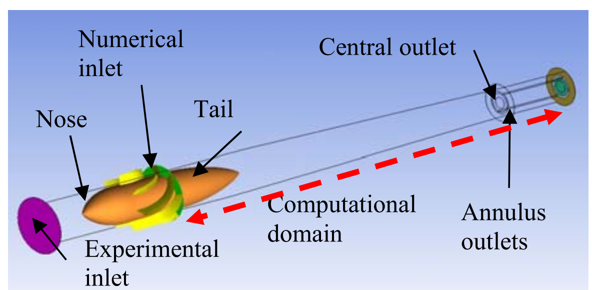

Figure-1. The numerical domain encompasses the trailing edge of the blade (numerical inlet) to the outlets, denoted by red dashed arrow. The experimental inlet is the area for bulk velocity calculation with a diameter D.

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Table-1. Relevant parameter description for the cylindrical and conical cyclone designs. Refer to Figure-2 for parameters representations.

Parameters	Cylindrical	Conical
D	**Diameter**	
D_s	-	Conical smaller diameter
d	Tail diameter	
L_t	Tail length	
H_b	Total length	
L_{vf}	Vortex finder length	
D_o	Central outlet diameter	

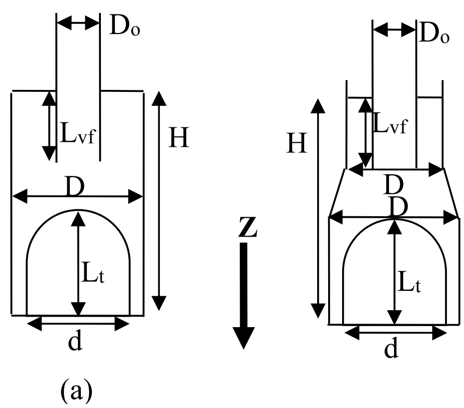

Figure-2. (a) Cylindrical cyclone (b) Conical cyclone. Axial direction is in the z-direction as shown.

cyclones at both locations as in Figure-4. Cylindrical body registers lower velocity going downstream, whereas the conical experiences the opposite. At 25% and 75% lengths, the conical cyclone has on average 6.4% and 16.3% V_{tan} improvements respectively at all radii location compared to cylindrical body. This implicates that higher centrifugal force can still be imparted further down.

For the case of 72° there is a big difference between the V_{tan} profiles with the conical body depicting the predicted Rankine vortex, while the cylindrical portrays a distorted version. The V_{tan} in a conical body on average are 51.1% and 34.2% higher at 25% and 75% length respectively compared to cylindrical body. 8.5% V_{tan} improvement is observed for conical body going downstream from 25% to 75% length. This again confirms that conical body can induce greater V_{tan} at all radii location downstream as in 45°. The cylindrical V_{tan} profile on the other hand is rather distorted and not displaying the typical Rankine vortex structure. At 25% and 75% length, Figure-5 registers high velocities at normalized radius, NR, 1 to 0.8 NR, dropping gradually from 0.8 to 0.4 NR and increases again very little from 0.4 to 0.1 NR. The V_{tan} maximum for cylindrical shape also has shifted at roughly 0.8 NR at bothlengths. In this case, cylindrical body performs worse with a maximum V_{tan} deficiency of 37.5% and 50% at 25% and 75% respectively relative to the conical body. Similar cylinder V_{tan} profile is also observed by Stone in which a short cylindrical concurrent separator is experimented [6]. It is speculated that the V_{tan} distortion is caused by the intense reverse flow from the outlets due to the low axis pressure.

Swirling flow in a long body suffers from swirl decay which is not favored for separation. Even though the cylindrical body is shorter, the use of conical body can increase V_{tan} despite being longer (different lengths simulated as to maintain equal residence time). Several authors in the field of heat transfer enhancement using swirling flow have installed numerous swirl blades at various pitch values to restore the swirling motion [8,9]. The conical body V_{tan} increase and the cylindrical body V_{tan} decrease are also evident from experimental data of Hoekstra [10] and Slack *et al* [11] of a gas cyclone. The conical portion maintains and increases V_{tan} downstream while degrading V_{tan} is observed in the cylindrical part downstream. These values represent the high improvements of a conical body in operating both at small and large flow deviation angles.

Axial velocity

Figure-6 and Figure-7 denote the V_{axial} profile downstream for both swirl angles. Positive value depicts the reverse flow towards the inlet whereas negative value portrays the favorable flow to the outlets. Reverse flow or recirculation region is not appreciated in liquid-liquid separation as it can induce droplet breakups which are difficult to separate [2]. The recirculation happens due to the adverse pressure gradient existing within the cyclone notably at the inlet where swirl is the strongest. The intense swirl close to the inlet induces lowest static pressure in the centre. Going downstream, the swirl decays and the static pressure increases again. This then leads to fluid at downstream to reverse its direction to reach the low pressure site upstream and thus creates the recirculation region [1], [3].

For the case of 45° deflection, it can be seen in Figure-6 that the conical body has greater V_{axial} magnitude at all radii downstream locations compared to the cylindrical body. The velocity gradient is roughly constant from NR 1 to 0.4, increases gradually to 0.25 NR and reduces steeply close to 0.1 NR at both lengths. Between 0.1 and 0 NR flow reversal happens with the maximum reverse velocity occurs at the cyclone's axis. Reverse flow radius in conical cyclone is not changing very much going downstream which in Figure-8 (a) shows rather a continuous filament to the exit. Similar V_{axial} profiles also exist in cylindrical cyclone but with a discontinuity as in Figure-8 (b). The reverse flow radius in cylindrical cyclone decreases downstream while the magnitude increases downstream as in Figure-6. This has been observed by Dirkzwager experimenting with cylindrical cyclone [2]. Overall, the conical on average has 58.8% and 32.1% higher V_{axial} to the outlet (not the reverse flow velocity) than the cylindrical at 25% and 75% length.

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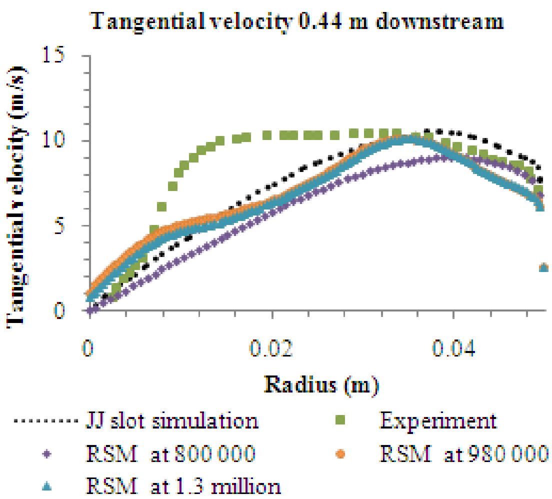

Figure-3. Comparison of Slot's experimental and numerical works with the present studies.

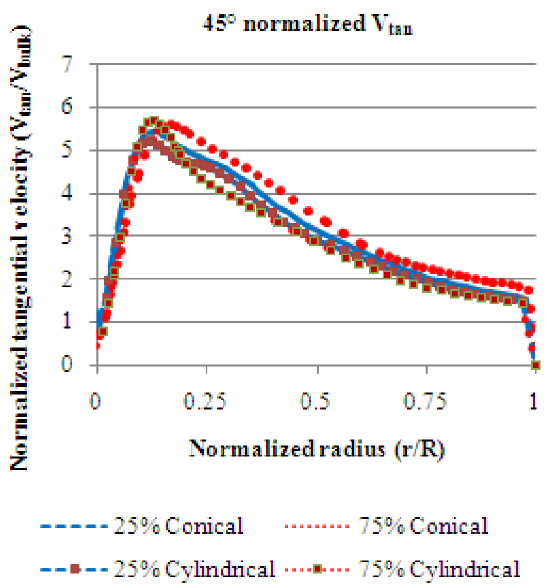

Figure-4. Normalized V_{tan} downstream at 45°.

The smaller frustum end constricts fluid outflow which leads to the kinetic energy translation to higher V_{axial} [12]. This practically indicates that the droplet will experience smaller residence time in conical than cylindrical [1]. This is beneficial as processing time can be reduced and production can be increased. In the case of reverse flow velocity only, the conical has on average 56.7% and 94.1% higher velocity at 25% and 75% length respectively compared to the cylindrical shape. It is more desirable to eliminate the reverse flow region but according to Gupta such profile will exists in any swirling flow with high swirl intensity [13]. Reducing the swirl generator hub can reduce the recirculation but this will come at a cost of lower V_{tan} which is deleterious to droplet separation [13].

For the case of 72° deflection, more profound differences are observed. In the conical cyclone, a steadier exit flow is encountered at 25% and 75% length. The latter location observed a reverse flow at a wider region roughly at 0.15 to 0 NR whereas the former location does not register such profile as in Figure-7. For the case of cylindrical cyclone at both lengths, the body depicts exiting flow from 1 to 0.6 NR. A high reverse flow area is observed from 0.6 to 0.3 NR at both lengths. The cyclone differences are easily viewed in Figure-8 (c) depicting that conical has thinner and shorter reverse flow regime compared to broader continuous profile in cylindrical as in Figure-8 (d). The recirculation region in the conical is noted to be only halfway the cyclone and not extended to the exits as in cylindrical cyclone. Lowering recirculation is vital as it will increase V_{tan} and V_{axial}, as seen in conical body pertaining higher V_{tan} and V_{axial} as in Figure-4 and Figure-7. It is worth to point out that conical cyclone has 58.9% and 62.9% greater favorable V_{axial} at 25% and 75% to the exit respectively compared to cylindrical cyclone.

The recirculation region at the central exit indicates that the central outlet will now be contaminated by product of the annulus outlet which in real world application will reduce oil separation efficiency. The scenario is well perceived in

Figure-9 of path line plots. The reverse flow around the vortex finder has been observed by Slot [1] and Stone [6], experimenting with cylindrical cyclones. The cylindrical reverse flow contaminations are calculated to be 0.761 kg/s (24.24% of inlet mass) and 0.063 kg/s (2% of inlet mass) for 72° and 45° respectively.

CONCLUSIONS

A numerical study of the flow field differences between conical and cylindrical cyclones have been demonstrated to investigate the applicability of such devices in deoiling oil water mixture. The aspects studied are tangential and axial velocities and recirculation region. The conical cyclone is found to have better flow fields compared to the cylindrical body. Conical has 6.4% and 16.3% V_{tan} average improvements at 25% and 75% lengths respectively at 45°. At 72°, 51.1% and 34.2% V_{tan} average increase at 25% and 75% length respectively compared to the cylindrical body. In terms of axial flow velocity at 45° to the exit, the conical has on average 58.8% and 32.1% higher velocity at 25% and 75% length respectively compared to the cylindrical shape. At 72°, conical has 58.9% and 62.9% greater favorable V_{axial} at 25% and 75% respectively. The conical cyclone also has thinner and shorter recirculation region than cylindrical. The absence of reverse flow in conical shape central outlet also proves to be beneficial in separation of oil-water mixture compared to cylindrical body for achieving higher separation efficiency. This implicates that the 72° conical cyclone is best suited for oil water separation compared to 45° and cylindrical at 45° and 72°.

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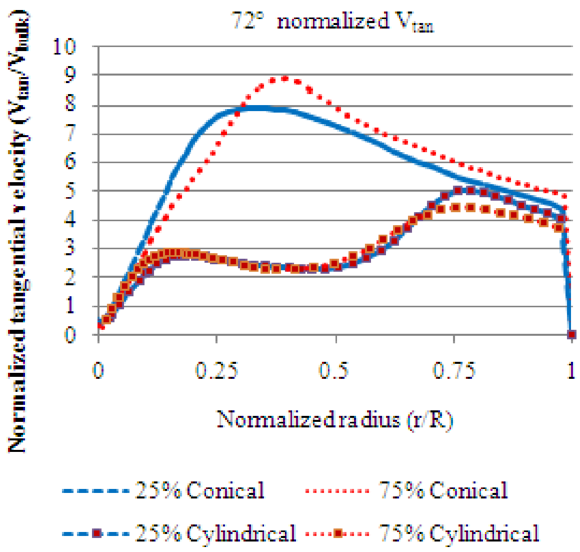

Figure-5. Normalized V_{tan} downstream at 72°.

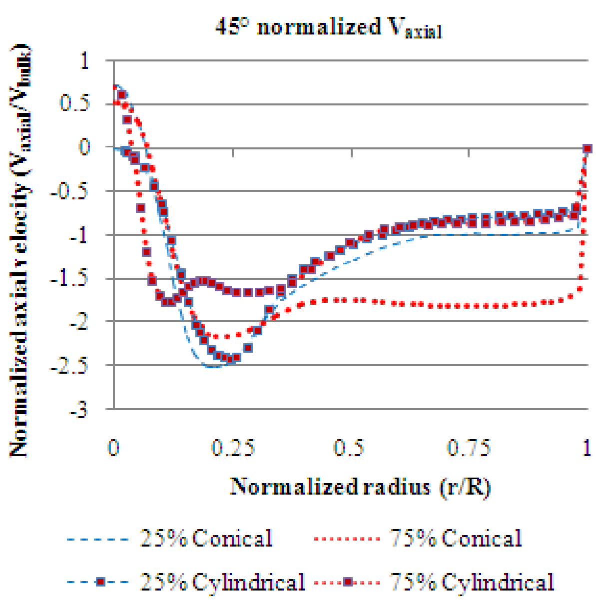

Figure-6. Normalized V_{axial} downstream at 45°.

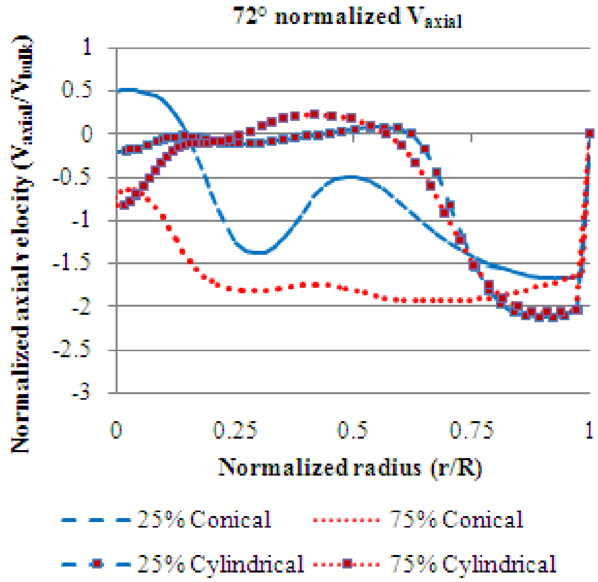

Figure-7. Normalized V_{axial} downstream at 72°.

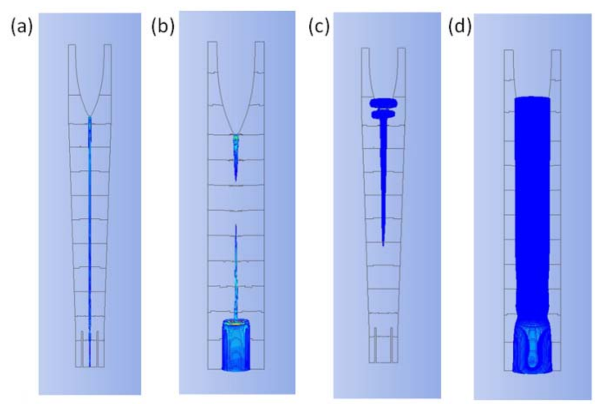

Figure-8. Isoclips of reverse flows in cyclones. (a) and (b) are the conical and cylindrical cyclone respectively at 45°. (c) and (d) are the conical and cylindrical cyclones at 72°.

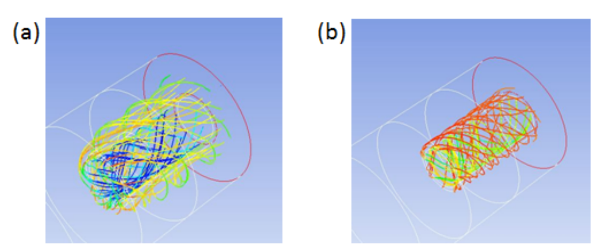

Figure-9. Reverse pathline at the annulus outlet. (a) and (b) denotes the cylindrical cyclone at 45° and 72°.

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