EFFECT OF GEOMETRICAL AND OPERATIONAL PARAMETER ON OIL-WATER SEPARATION IN AXIAL INLET HYDROCYCLONE

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ABSTRACT

To overcome the high water content in numerous oil fields, axial inlet hydrocyclone is considered an alternative device of oil-water separation technique that is used downfield. This type of hydrocyclone has a rare previous work compared to other vortex tube separators. Additionally, the accurate mechanism of the enhanced separation process by optimizing the separation technologies remains unclear. Therefore, an extensive study was conducted to expand the application range of the axial inlet hydrocyclone. This work presents a literature review of the different separation technologies for the axial inlet hydrocyclone. These are categorized into two groups: (i) geometrical parameters including, internal swirl element (ISE), swirl chamber, and (ii) operational parameters including, inlet flow rate, feed temperature, mixture fraction, and droplet size. The influence of these parameters on the velocity components profile and pressure drop were analyzed based on the separation performance parameters such as separation efficiency and pressure drop. This work could serve as an engineering tool that results in the enhanced economic workability of separation by hydrocyclone.

Keywords: Axial inlet hydrocyclone, swirl intensity, separation process, two-phase, separator

INTRODUCTION

The increasing world population and technological development lead to an increase in the demand for oil and gas. Furthermore, the worldwide oil demand, while fluctuating due to the circumstances, shows an increasing trend. From 2007 to 2035, world energy consumption is predicted to rise by 49%, figure(1) (Outlook, 2010). In the field of oil and gas, the increased amount of water production is the main problem, especially for mature fields. In 2007 the world usage of liquid fuels was 86.1 million barrels per day. The amount of this produced water reaches 227 million barrels every day. Feedback of water fraction in the oil-water mixture will increase the operational cost, and more money spent on storage facilities to contain the produced water also increase the corrosion that occurs in pipelines which leads to pipeline crack and oil leakage. This brings a great threat to personnel safety and causes serious environmental pollution (Mognon et al., 2015) (Xu et al., 2016) (Li et al., 2016) (Yu et al., 2017) (Huang et al., 2017). Hydrocyclone is considered one of the simplest separation devices that use liquid pressure to generate centrifugal force. It can be used and installed on the surface or downhole to overcome the water production problem by separating the oil and water at the well bottom. The separated oil is pumped to the surface while the water will inject back to maintain the reservoir pressure and increase the oil flowing into the well. Hydrocyclone used as an industrial separation device in the industry since the 1940s. It's found in wide engineering applications such as in the petroleum, chemical process, nuclear power plants, environment, food industries, etc.(Husveg et al., 2007). In practice, there are two types of hydrocyclone have been found which depend upon the direction of the oil extraction from the hydrocyclone: concurrent and counter-current cyclone. In the concurrent cyclone, the separated oil and water both flow downstream where they are subsequently extracted separately (Dohnal and Hájek, 2016). In a conventional counter-current cyclone separator, the fluid mixture enters the separation chamber by one or sometimes dual inlets, and then two separated fluid streams have opposite directions exit (Kharoua et al., 2010) (Tian et al., 2018) (Al-Kayiem et al., 2019). The dual inlet has not been spread in well bottom applications due to the space narrow and the difficulty of installing dual inlet hydrocyclone. Additionally, the tangential inlet of Downhall Oil/Water Separation (DOWS) increases the mixture turbulence inside the cyclone and increases the oil droplet broken into smaller ones and this has a negative effect on the cyclone performance (Noroozi et al., 2013). The concurrent axial inlet hydrocyclone is an alternative device for the well-bottom oil-water separation, due to its advantages, such as lower pressure drop, reduced residence time, less turbulence, and handling capacity more than conventional hydrocyclone (Cabral et al., 2019) (Zheng et al., 2019). The co-current axial flow type will be focused on in this work since it is still under development for the industry.

HISTORY OF AXIAL INLET HYDROCYCLONE

Three hydrocyclone separators are found, as gas-liquid separators (used in nuclear reactors to dry the steam before entering the turbine to protect it from the cavity and increase the economic efficiency), gas-solid separators (used infiltration process to remove solid particles from gas), and liquid-liquid separator. Hydrocyclone has been widely applied in multiple domains including mineral, chemical process, petroleum, environmental protection, biotechnology, nanotechnology, and thermal energy process (Klujszo, Songfack, et al., 1999) (Hsiao et al., 2010) (Ma Narasimha et al., 2014) (Neesse et al., 2015) (Bayo et al., 2015) (Ni et al., 2016) (Son et al., 2016) (Funahashi et al., 2016) (Wang et al., 2016)(Zheng et al., 2019) (Gopalakrishnan, 2019). Despite understanding the flow field inside liquid-liquid hydrocyclone (LLHC) that is necessary for design improvements and optimization of performance, previous studies including limited work that treated this type of hydrocyclone because of the small difference in the density between the two fluids which needs high accuracy in cyclone design to get high efficiency. (Dirkzwager, 1996) produced and design the first conventional van-type axial inlet hydrocyclone. The main components of this cyclone are shown in figure(2) and include the internal swirling element(ISE), separated pipe, and vortex tube. The ISE consists of curve vanes that deflect the flow when passes through it. The income axial flow has been analyzed into three components: axial, radial, and tangential velocity, and the last is a response on the vortex generated in the cyclone. This swirling flow than proceed in the separated pipe. As proceed in the settling zone the swirling flow is losing its strength due to the wall friction effect. The Light Phase droplets will be separated at the pipe core and exit from the center of the pipe. The heavy phase is pushed to the wall and exists from the annular section. The concurrent axial flow type will be sighted in this work since it is still under development for the industry. (Delfos et al., 2004) predicted a numerical model for liquid-liquid turbulent flow called (HAAS) and it showed that the HAAS model is very time efficient in the designed cyclone. This design further investigated by (Murphy et al., 2007), simulated a single-phase swirl flow in axial hydrocyclone by using two commercial CFD packages, It was found that the main features of the flow were qualitatively well represented in the numerical simulations, however large quantitative difference in velocity profile were found between the two CFD codes results. (Rocha et al., 2009) investigated numerically the oil-water mixture in axial hydrocyclone under laminar flow conditions to show the cyclone length required for the separation process. it shows that the swirl intensity is a function of the flow rate and cyclone geometry. (Ayinde, 2010) Computed numerically the laminar swirling flow in a straight tube by solving steady 3D Navier–Stokes equations. It's found that the strength of the swirling along the pipe length depends on the inlet swirl number, Reynolds number, the distance from the pipe inlet, the pipe diameter, and the nature of the fluid inlet. (Slot et al., 2011) Investigation experimentally and numerically of the oil-water separation in axial flow LLHC through a straight pipe separator. The behavior of the flow has been studied for both single-phase water and two-phase oil-water mixture. The numerical results agree with the LDA (laser Doppler anemometry) measurements for the single-phase flow. (Campen et al., 2012) used LDA to measure the tangential and axial mean velocity component in the cyclone and compared them with numerical results. (Zhang et al., 2014) show that by using a spiral shape inlet and the blade type inlet the maximum size of the two hydrocyclone was reduced by 1.4 and 1.2 times, and the separation efficiency is rise to more than 90%. (Shi and Xu, 2015) predicted the fluid flow for cyclone inserted with two designs for the guide vane and compare its results with that conventional cyclone. The simulation of the flow behavior through a cyclone showed that there is a high-pressure drop in the flow after it leaves the swirl element and this is companied by reverse flow in the core of the cyclone, this behavior has a negative impact on cyclone performance because the stable cyclone should operate in low-pressure drop condition. (Rocha et al., 2015) predicted that adding a cylindrical tube in the tail of the central element will reduce this effect. More details about the effect of design parameters of the swirl flow in axial hydrocyclone can be featured in the numerical studies. (Fan et al., 2017) (Rocha et al., 2017) showed that the increases in each the blade deflection angle, number of fans, and inlet flow rate increased the swirl intensity and that led to an increase in the separation efficiency, also the numerical simulation predicted that the vortex breakdown occurs at swirl number >2.5 and the swirl decay is only exponential for Re< 200 (Cabral & Rocha, 2018). (Liu et al., 2018) show the replacement of the cylindrical tube by the conical pipe cyclone reduces the reversed flow and enhanced the separation efficiency by increasing the swirl intensity and this is considered a worth improvement in the cyclone geometry. (Hamza et al., 2020) approved that the swirling generated in the separator is doubled when using the conical geometry instead of cylindrical geometry. The present study investigates a much smaller and cheaper alternative equipment for the oil-water separation, namely utilizing in-line concurrent van type conical axial cyclone that uses swirling flow to separate the phases, this survey provides a literature review of the main methods that are used to improve the cyclone geometrical design to meet the necessary specifications for transport and show the effect of the main parameters on the separation efficiency.

NUMERICAL MODELLING OF SWIRLING FLOW

The flow field inside liquid-liquid hydrocyclone is quite complex through the combination of time-dependent, turbulent, three-dimensional, high-intensity swirl, and multiphase flow with the interaction of two or three phases, including droplet breakup and coalescence. Knowledge of the flow behavior inside the hydrocyclone is fundamental for understanding predicting, and improving its performance (Narasimha et al., 2005). Many modeling procedures used in this investigation are presented previously. Two-phase flow is characterized by a complex topology with countless, continually changing interfaces between the two fluids. Resolving all details of the flow would be even more computationally expensive than for single-phase turbulent flow (Huang, 2005). For multiphase flows, the mixture model can be further simplified into the volume of the fluid model (VOF) for the separation of phases. (Brennan, 2006) used mixture models and VOF to simulate the air core. (Yin et al., 2016) adopted the VOF and mixture models to model the air core inside the gas/liquid cyclone. Their results are compared with experimental results. The predicted velocity profile per VOF and the mixture models were essentially identical. Also the VOF and mixture model has another advantage such that the variables of the macro flow, like the pressure or velocity profile, can be obviously distinguished. RNG –k ε model as well as Reynold Stress Model (RSM) are the main models that are used to investigate the axisymmetric velocity field and pressure drop for strongly swirling flow cyclones (Hanjalić & Launder, 1972) (Leschziner, 1990) (Leschziner, 2000) (Jawarneh et al., 2008) (Escue & Cui, 2010) (Javadi et al., 2016). (Kharoua et al. 2010) show that the RSM is more accurate in the predict the separation efficiency in the deoiling hydrocyclone compared with the RNG –k ε model. The RNG –k ε turbulent model is unable to capture the non-isotropic characteristic that introduces in swirling flow leading to a poor prediction of the size and strength of the recirculation zone that appeared in the axial velocity component, so the RSM is the better model used in swirling flow. (Hanjalí, 1999) (Kegge, 2000) (Lu & Semião, 2003) (Yeh & Lin, 2001) (Sloan et al., 1986). (Boysan et al. 1987) used hybrid turbulence model combined with the standard k-ε turbulence model where its shows the k-ε was weak in predicting the strong swirling flow. Later, (Fraser et al.1997) modified the k-ε turbulence model to investigate 3D swirling flow in the pipe. (Hoekstra and Derksen1999) made a comparison between velocity components obtained from three turbulent models, RSM, standard k-ε, and RNG k-ε, by comparing the CFD results with that experimental measurement. It concludes that the RSM is more accurate for simulating the gas core in a cyclone. But on the other hand, the RSM is not suitable for all conditions, (Saidi et al. 2013) show the RSM model is not accurate in the simulation of the liquid-gas mixture. (Jawarneh et al. 2008) predicted the separation efficiency for oil-sand flow by using RNG k-ε turbulent model, it shows that the numerical results have high accuracy when compared with the experimental results. By the comparison of the numerical results obtained from the RSM and RNG k-ε turbulent model for the swirling flow in a pipe, it’s concluded that the RNG k-ε is more accurate for the swirling number is less than 2. The

RSM is unable to predict the gas core in the weak swirling flow as the RNG k-ε model when compared with the experimental. (Talbot, 1952) (Escue & Cui, 2010) (Zhang, et al., 2018). (Ge & Chen, 2016) Used the mixture model with the Reynolds stress model (RSM) in modeling the two-phase oil/water mixture flow through predicted dynamic hydrocyclone. The effect of inlet flow rate and oil concentration on the hydrocyclone separation efficiency and pressure drop were presented. The numerical results show that the rotary cyclone wall increases the strength of the tangential velocity generated in the van section, and rotating the conical cylinder increase the flow stability. The flow field inside the gas-liquid separator under different geometrical parameters of the guide van and droplet size are investigated by (Yang et al., 2017). The numerical simulation was done by using RNG –k ε model and the discrete phase model (DPM). The results show that the pressure distribution and the separation process increase as the increase of guide vane numbers and the decrease of the blade outlet angle. Additionally, its shows that the separation efficiency is almost 100% when the droplet diameter is bigger than 40μm. (Cabral and Rocha, 2019) show the impact of Reynolds number and particle diameters on the particle trajectory in axial inlet hydrocyclone under laminar flow conditions. This numerical investigation was done by using the discrete Phase Model (DPM), where which do on tracing the discrete phase (oil particles) through a continuous phase (water). (Gopalakrishnan, 2019) Used Eulerian-Lagrangian CFD approach in the modeling of gas-solid flow in axial inlet hydrocyclone. Discrete phase modeling (DPM) with the RNG k–ε model was used in the turbulent flow to simulate the impact of particle size on the efficiency of the filtration process.

HYDROCYCLONE PERFORMANCE

The performance of the axial inlet hydrocyclone is dependent on the separation amount between phases and is measured by the separation efficiency and is influenced by the mixture inlet flow rate ($\dot{m}$), the pressure differential ratio (PDR), and flow split (Fs). These parameters could be show as follows: (Kitoh, 1991) (Dirkzwager, 1996) (de Zoeten, 2018) (Hamza et al., 2020). Flow split is defined as the ratio of the flow exit from the Light Phase Outlet (LPO) to the inlet flow as shown in the following eq (Slot et al., 2011):

$$\mathrm{Fs} = \frac{\dot{m}_{Lpo}}{\dot{m}_i} \times 10 \qquad (1)$$

Where $\dot{m}_i$ (m^3/h): The flow rate inter the hydrocyclone, $\dot{m}_{LPO}$ (m^3/h): The flow rate exit from the Light Phase Outlet (LPO). The pressure drop in the test section is measured experimentally by pressure gage and calculated from the following eq (Dirkzwager, 1996):

$$\mathrm{PDR} = \frac{\Delta P_{i-LPO}}{\Delta P_{i-HPO}} \qquad (2)$$

where $\Delta P_{i\text{-}LPO}$: The pressure difference between the inlet and LPO, $\Delta P_{i,HPO}$: The pressure difference between the inlet and Heavy Phase Outlet (HPO).

The separation efficiency (η) gives the fraction of the incoming oil that is separated and it's calculated as follows (Dirkzwager, 1996):

$$\eta = 1 - \left(\frac{\alpha_{o-Hpo}}{\alpha_i}\right) \times 100 \quad (3)$$

where α_{o-Hpo} is the concentration of oil in the HPO, $\alpha_i$is the total oil concentration in the inlet. A swirl number is a dimensionless number that expresses the ratio of the axial flux of tangential momentum to the axial flux of axial momentum, thus it gives a measure of the strength of the swirling flow and it is important for engineering purposes to understand the decay process of swirl intensity along the pipe (Slot et al., 2011):

$$S = \frac{2\int_0^R wur^2}{R^3 W_{avg}^2} \quad (4)$$

FLOW BEHAVIOR IN THE SWIRL FLOW

Several numerical models have been proposed in the literature survey to explain the separation phenomena inside the separator (Klujszo, Songfack, et al., 1999). When the fluid flow through the van section inside the separator the axial velocity is resolved into three components tangential, radial, and axial velocity. The radial velocity can be neglected because its effects are so small compared with others. The tangential and axial velocity profiles inside the hydrocyclone are discussed below. The fluid particles inside the separator will be under influence of two forces: drag force acting in the vortex and is dependent on the size of particles, and centrifugal force has an outward direction and is proportional to the mass.

Tangential velocity

The tangential velocity is the dominant velocity component in the separator and the key factor that responds to the centrifugal force. It has a direct effect on the drop separation efficiency, when the tangential velocity increases, the centrifugal force, and separation efficiency will increase. (Bhaskar et al., 2007). The swirl intensity has a maximum level after the separator region and decays gradually along the axial direction, this phenomenon is named swirl decay (Chen & Lin, 1999). As well as it increases radially from the center to the annular pipe and then decreases to zero at the pipe wall where there is a no-slip condition as shown in figure(3). The tangential component distribution conforms to Rankine vortex characteristics, the center is characterized by a forced vortex distribution, and the outside is surrounded by the quasi-free vortex distribution (Aksel and Kaya, 1992) (Steenbergen, 1995) (Shuja et al., 2002) (Benim et al., 2007) (Beaubert et al., 2016). The Rankine vortex distribution is very advantageous in the separation process, as the centrifugal effect of the forced vortex at the center is conducive to making the drops move to the external, the rotation strength to carry drops of the external quasi-free vortex is relatively lower, especially to large drops, which make it easier to be trapped on the wall (Fan et al., 2017).

Axial velocity

The axial velocity reaches its peak value in the annular region, this indicated the favorable forward positive velocity. Its value is rabidly decreased toward the wall, where it falls to zero on the wall (no-slip condition). With a positive axial velocity near the wall and in the center, the radial distribution of the axial velocity is W-shaped, figure (4), (Zhen-Bo et al., 2011). This mechanism does not give a complete explanation for all instances of swirling flow in which a V-shaped distribution of the axial velocity is observed. For the current situation, it shows a double reversal or W-shaped distribution of the axial velocity, but it fails to reveal the cause of the observed flow pattern. The W-shaped profile has been observed before by (Mattner et al., 2002) and (Brücker, 2002) for swirling pipe flow at very high swirl numbers associated this flow pattern with the phenomena of vortex breakdown.

Pressure drop

Pressure drop is another operation parameter that influences the separation performance of the hydrocyclone (Churchill and Usagi, 1972). Also, it has direct proportional to the energy cost. The large pressure drop in the pipe core indicates the high tangential velocity and increases the cross-sectional area in the region after the separator. This leads to a large pressure drop near the wall and in the pipe core. The pressure drop mainly affects the generation of the recirculation zone and causes adverse axial velocity. (Jiang and Zhao, 2007). Through this survey, many geometrical and operation parameters take into account to reduce this effect (André Damiani Rocha et al., 2015) show the pressure drop has direct proportional to swirl intensity and inversely proportional to Reynold’s number. (Shi and Xu, 2015) show that taking the suitable van deflection angle and perfect design for the tail section will improve the pressure distribution in the cyclone and decrease the recirculation region. In recent years the literature survey shows the high-pressure drop decreased by changing the cylindrical tube to a conical tube, but this idea needs more study in detail. (Al-Kayiem et al., 2019).

SEPARATOR DESIGN

One of the design specifications is that the separator does not contain any moving parts, that is the swirling motion has to be flow-induced (Sheng & PE, 1977). Various configurations have been considered as the prototype. They are compared in terms of pressure drop, velocity distribution, swirl intensity, and separation efficiency (Klujszo, Rafaelof, et al., 1999) (Cai et al., 2014). Acknowledgment of the flow behavior inside the hydrocyclone is important for understanding, predicting, and improving its performance. In the preceding years, many research works focused on numerical analysis to simulate the flow field in axial separators to develop the cyclone performance and get optimization design by showing the effect of geometric parameters (swirl deflected angle, vans number, gap width, pipe length) and operation parameters (inlet flow rate, drop size) on the separation efficiency (Rietema & Maatschappij, 1961), (Kharoua et al., 2010a). Table (1) summarizes the evolution of the characteristic dimensions of the axial hydrocyclone.

Separation enhancement by optimization of geometrical parameters

The main geometrical parameters that command the flow structure inside the hydrocyclone and have further attention in design are:

Internal swirl element(ISE)

The stationary internal swirl element (ISE) is the first internal component that is affected in the separation process for the hydrocyclone, so its design got high attention in the previous work (Prandtl & Bleyer, 1910) (Shepherd et al.1939). (Dirkzwager, 1996) designed and investigated the traditional ISE and then developed by (Delfos et al.), its consists of three sections central body surrounded by vans that deflect the axial inlet fluid and generate the swirling flow, the nose section, and the tail section as shown in figure(6). The geometrical variations which should be considered in the design of the vanes are listed in the table (2). (Zhang et al., 2014) suggested two structures of the inlet guide vans to improve the cyclone performance, spiral shape and blade type as shown in figure (6). It's found that the predicted structure Couse a reduction in maximum cyclone size by 1.4 and 1.2 times and increases the maximum efficiency up to 90%.

Swirl Chamber

The test section or separation section is the second section in the cyclone and its location from the tail tip to the vortex finder tip. The test section has a cylindrical shape in all literature that deals with the axial concurrent cyclone and its length depending on the other parameters, (Dirkzwager, 1996) shows that the suitable tube length should be limited in range (30-40 D). The wall friction reduces the momentum flux near-wall region and this causes swirl decay downstream tube, so further increase in tube length over a certain limit has a negative influence on the cyclone design cost and its performance (Baker & DW, 1974) (Steenbergen, 1995) (Sheen et al., 1996). (Nor et al., 2015) replaced the conventional cylindrical tube with the conical tube to relay from the swirl decay and decrease the recirculation flow to improve the separation process. From the literature survey, the explanation of this development of the cyclone is not available and it has more investigation. (Nunes et al., 2020) developed the cyclone performance by adding a membrane of a porous ceramic to the conical tube to enhance its filtration process. Downstream of this tube, a device needs to be placed to remove the swirling motion from the flow, to avoid high mechanical loads on downstream equipment (Shi et al., 2010).

Separation enhancement by optimization of operational parameters

Generally, the enhanced hydrocyclone performance by optimization operational parameters is generally limited to four variables: flow rate of the inlet mixture, mixture fraction, feed temperature, and the particles droplet size.

Inlet Flow Rate

The inlet flow rate is considered the main variable that influences the separation process in the hydrocyclone, as the inlet flow rate increase the tangential velocity generated in the vanes section and is responsible for the separation process will be increased (Meldrum, 1987). With the smaller inlet flow rate the particle remains closer to the center and reaches a stable radial position, This means that for a larger inlet flow rate, a larger tube length is required to decay the swirl and reaching to the stable condition (André Damiani Rocha et al., 2017). These conditions are important for the design of a pickup tube, it is necessary to optimize the position where such apparatus should be installed to remove the dispersed phase of the continuous phase (R. V Cabral and Rocha, n.d.2019) (Hamza et al., 2020).

Mixture Fraction

For oil/water separation in hydrocyclone, an increase in the oil fraction leads to a decrease in pressure. This is due to the increase in the interring mixture viscosity of the cyclone and high shear resistance to fluid motion of the oil portion near the interior wall of the cyclone and between the vanes. So the increase in the oil fraction requires further development in the cyclone performance to get high separation efficiency, the earlier researches show a weak study on this point of requirement.

Feed Temperature

The inlet mixture temperature has a direct influence on the liquid density and viscosity so this influence is reflected in the pressure drop and the separation performance. But this effect is not taken into account in the literature work. (Hamza et al., 2020) based its study on 80 °C and 50 °C. The results show that the mixture temperature is proportional to the separation efficiency and inversely proportional to pressure drop but this study is not sufficient to show in detail the flow behavior under the temperature effect. So the temperature effect on the flow pattern inside the hydrocyclone wants more investigated

Droplet Size

The inlet drop size has also a considerable effect on the flow behavior inside the cyclone and then effected on the separation efficiency (Flanigan et al., 1988). When the particles enter the swirl generator, these get swirled radially outward due to the effect of the centrifugal field. This field increase with a decrease in the oil fluid particle and make it closer to the wall, so the small oil particles have a longer separator length to pike up it by the vortex finder tube (Xiong et al., 2014). Downstream of the generator, the fluid particle spin is dampened due to viscous effects. Drag and density are the main terms affected by fluid particle size. The figure demonstrates the influence of the droplet size on the separation process for particle diameter (50)µm and (100)µm (Slot et al., 2011). (Fan et al., 2017) illustrate that the separation efficiency has little sensitivity for the droplet diameter of less than 10µm. While the separation efficiency is obviously increased when the droplet size is greater than 10µm and is concluded that to ensure high separation efficiency, the droplet size is preferably more than 20µm for different structures separator.

CONCLUSIONS

The hydrocyclone technique for oil-water separation has become one of the most efficient and proven oil-water separation technology due to its simplicity, compactness, robustness, low manufacturing and maintenance costs. The enhanced separation designs are presented and analyzed according to the separation performance parameters of the hydrocyclone including separation efficiency, split ratio, pressure drop, high capacity, and the swirl intensity along with the cyclone. The main conclusions are:

1. Most of the previous work has been done numerically by using CFD simulation with limited experimental works. Several simplifications are used in numerical models to simplify the complex flow inside the hydrocyclone. So these results approximated far from true conditions and results.
2. In this review, the proposed technologies and methodologies were developed in specific conditions such as temperature, flow rate and phases volume fraction. So, extra ranges of work conditions are required to improve the universal cyclone predicted technologies, which can be used in more application fields.
3. Some suggested designs were observed in the literature survey to optimize the axial inlet LLHC efficiency and reduce its size. These designs need further investigation in detail to improve their performance by showing the influence of varying the operational parameters (inlet mixture flow rate, oil/water fraction more than 30%, oil droplet diameter, and split ratio) experimentally.
4. Literature survey shows a limited range of flow rates where it works under laminar conditions (Reynolds number <3000), so some phenomena need more attention like the effects of turbulence on droplets motion, breakup, coalescence, phase behavior, and core shape.

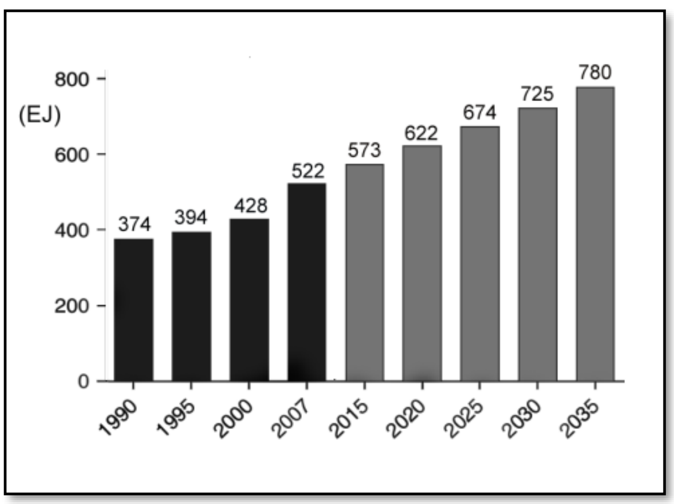

Fig 1. World marketed energy consumption in exajoule (EJ), 1990-2035. Adapted from (Outlook, 2010).

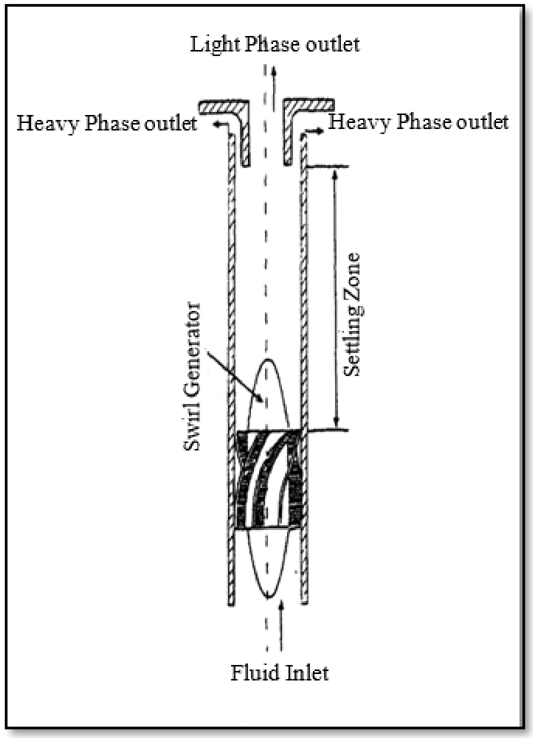

Fig. 2. Conventional type of the hydrocyclone (Dirkzwager, 1996).

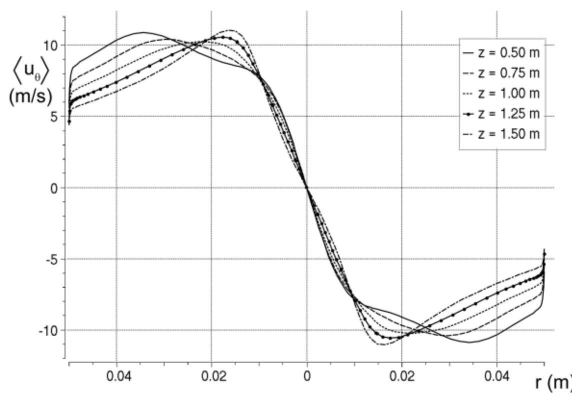

Fig.3. Tangential velocity profile along the axial direction (Najafi et al., 2011).

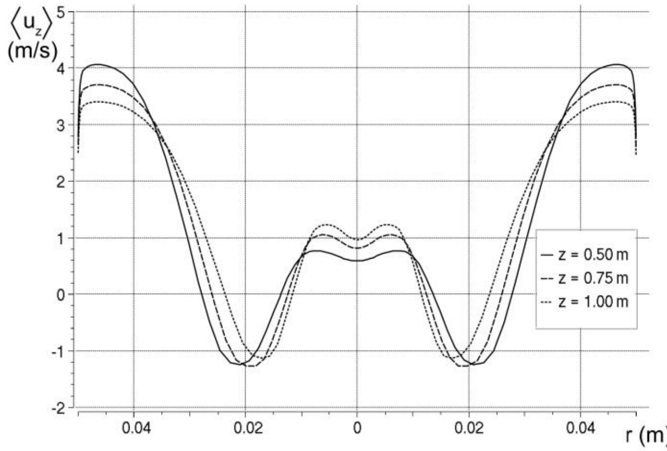

Fig.4. Axial velocity distribution at three axial sections z=0.5m, 0.75m, 1m after separator(Slot et al., 2011).

Table (1): Geometrical dimensions of models and operational limitation.

Ref.	**type**	**Working fluid**	**Re**	**L3**	**D_o(mm)**	**D_i(mm)**
(Slot et al., 2011)	Cylindrical	Oil-water		1700		100
(Nor et al., 2016)	Conical	Oil-water		670	20	
(Nor et al., 2015)	Conical	Oil-water		670	50	100
(André Damiani Rocha et al., 2015)	Cylindrical	Water-glycerin	500- 1300	7500	50	50
(Hamza et al., 2020)	Conical	Oil – water	1.5-4 m^3/h		20	40
(Shi & Xu, 2015)	Cylindrical	Deionized water – silvercoated glass				72
(van Campen et al., 2012)	Cylindrical	Brine-oil	56.5 m^3/h	1700	50	100
(Gopalakrishnan & Arul Prakash, 2019)	Cylindrical					

(Fan et al., 2017)	Cylindrical	Water-gas		1028	140	200
17,23(André Damiani Rocha, n.d.) و(Vidal Cabral & Damiani Rocha, 2019)	Cylindrical	Water oil	<300	2270		91.2
(S. Liu, Yang, et al., 2018)	Cylindrical	Liquid gas	8-18 m3/h 28300-63700			
(Dirkzwager, 1996)	Cylindrical	Water oil			50	

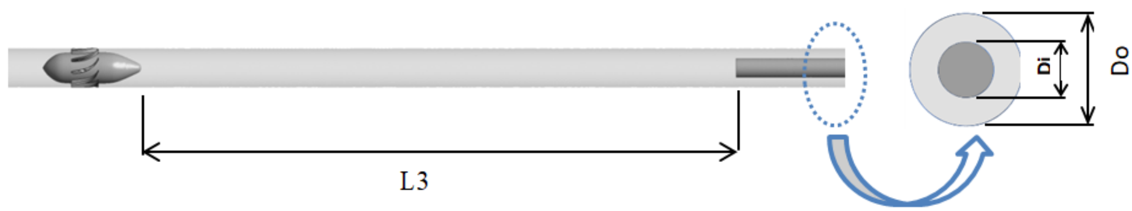

Fig.5. Axial inlet hydrocyclone.

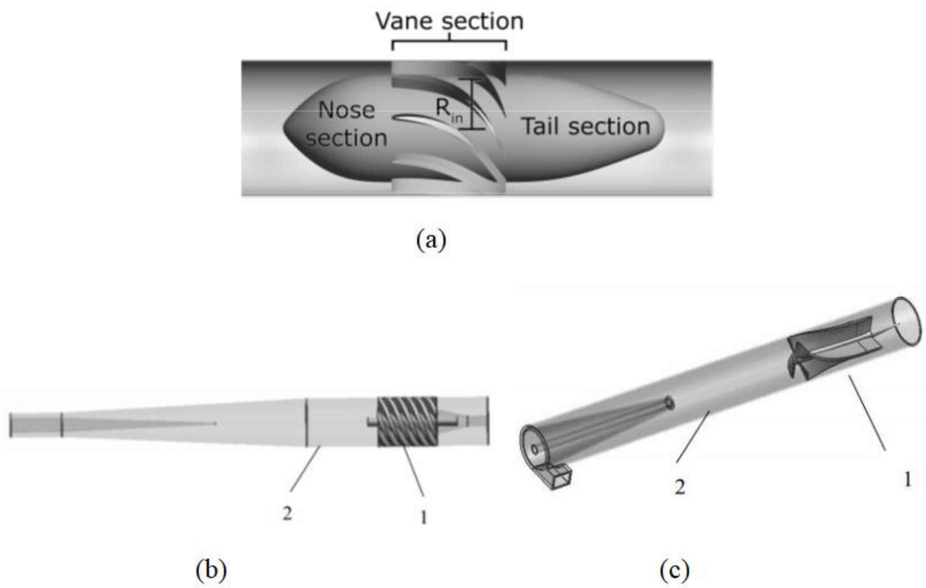

Fig.6. Structure of the internal swirl element(ISE) (a)Traditional separator, b) Spiral shape, c) Blade type. (Shi and Xu, 2015)

Table (2): List of main factors that affected the separator design

Variation	Effect
Deflection angle	Increased deflection angle over a limited range has a negative effect on the velocity field inside the cyclone, also causing break droplets and remixed the phases.
Gap width	A moderate annular gap should be designed in carefully to achieve the highest velocity component with a low-pressure drop.
Van length	A larger flow deflection can be accomplished with longer vanes. The mechanical strength will increase for longer vanes and generate more turbulence, and longer shear layers along their surfaces (Gopalakrishnan, 2019). So these effects should be taken into account in the design of the van
Number of vans	It has a direct effect on the frictional losses and pressure drop. Also, the lift force per van has inversely proportional to the number of vans Fan et al., 2017). So it is important to check the suitable number for each new separator design. From literature, its range is>3 and <12

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