TITLE PAGE

Computer Simulation Development of Hydro-cyclone Performance in Solid Liquid Separation

by

Santie Chai Khamkeo A/L Su Rat
22696

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Mechanical Engineering
With Honours

JANUARY 2020

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CERTIFICATION OF APPROVAL

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Approved by,

AP Dr Mohammad Shakir Nasif

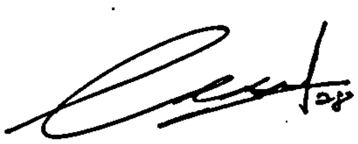
UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR, PERAK

JANUARY 2019

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.



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SANTIE CHAI KHAMKEO A/L SU RAT

ABSTRACT

The separation of particle and fluid using device called hydro-cyclone has been widely adapted in various industry especially oil and gas field. The solids mainly the sand flow out from the well with the oil need to be separated out before the oil can be flown to the production facility as sand can corrode the equipment and lead to higher cost consumption for the production. In oil field, the produced crude from the well may vary in the properties especially the density and the viscosity. The two properties are among the properties that will influent the separation performance of the hydro-cyclone. However, significant of the relation between these parameters to the separation efficiency is unclear and to investigate it experimentally will be expensive and time consuming. The objective of this study primarily to investigate the relation of the oil density and viscosity to the separation performance of the hydro-cyclone operating at several inlet velocity by simulation. To do that, the cyclone model will be developed in Computational Fluid Dynamic software, Ansys FLUENT to investigate the relation of these parameters. Three type of crude oil of difference API heaviness and inlet velocity will be used as manipulated variables. The outcome of the study shown that the separation efficiency increases with velocity and decrease with medium viscosity and density.

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My sincere thanks also go to UTP and IRC, which provided me which the enough information resources to conduct the study. Additionally, thanks to my classmates, and friends who always gave advises on conducting the CFD simulation work, cheered me up and gave a moral support to me. Lastly, I wish to thanks to my family who always support and encouraging me to finish my study.

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NOMENCLATURES

Symbol	Meaning	Units
F_D	Drag force	N
Fc	Centrifugal force	N
Fb	Buoyancy force	N
u_r	Radial velocity	m/s
u_t	Tangential Velocity	m/s
d	Diameter	m
r	Radius	m
D_c	Cylinder's diameter	m
D_i	Inlet's size	m
D_o	Vortex finder's diameter	m
D_u	Underflow's diameter	m
L_v	Vortex finder's depth	m
L_c	Cylinder's length	m
L	Cone's length	m
a	Cone's angle	m
P	Pressure	Pa
ρ_m	Medium density	kg/m3
ρ_l	liquid density	kg/m3
ρ_s	solid density	kg/m3
M_f	Amount of particle at feed	-
M_u	Amount of particle at underflow	-
M_o	Amount of particle at overflow	-
η	Efficiency	%
µ	Viscosity	kg/m-s
T	Temperature	K
D_{50}	Cut size	µm

CHAPTER 1

1. INTRODUCTION

1.1 Background of Study

Hydro-cyclone is a simple device with the shape of cylinder and cone. This device also normally is referred as cyclone and its function is to classify and separate particle or any heavier medium out of the pressurized mixture that flow into the cyclone. The separation can be done on any phase of mixture like gas-liquid, liquid-liquid, solid-liquid, or gas-solid. The usage of this device is very popular in many of industry as it consumes lesser capital and maintenance cost because of its simple mechanism and has no moving part. It is just a cylinder cone shape column that normally welded together. For example, this device is used widely in oil and gas industry for wellhead de-sanding (Opawale et al., 2016) , use in wood mill to remove saw dust from the air, use in water treatment, use in mining to classify the coal by size and many more. This device consists of six parts which are the inlet, overflow, vortex finder, underflow, cylinder section and cone section as in FIGURE 1 (Cullivan, Williams, & Cross, 2003).

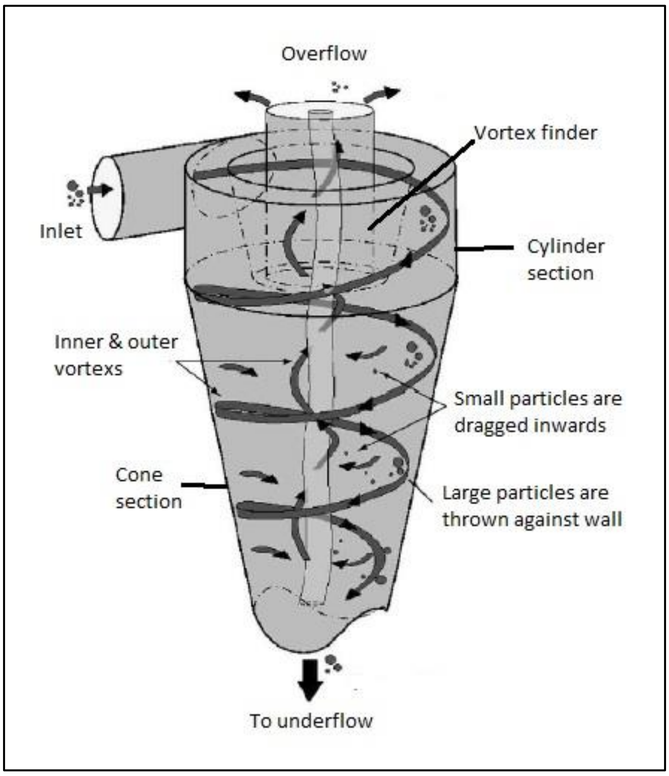
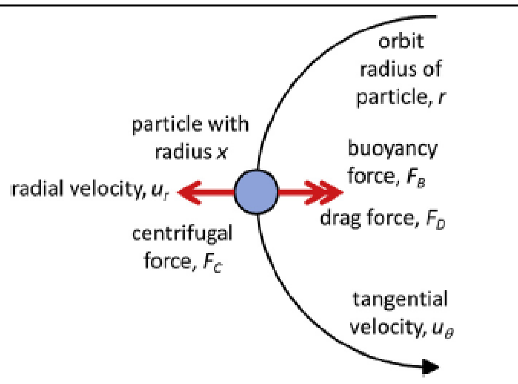


Figure 1.1: Hydro-cyclone's components and flow structure (Cullivan et al., 2003)

The hydro-cyclone work by using the rotational effect of the flow that injected into the cyclone tangentially and create the vortex flow that flow out to both top and bottom output. By theory, particles that injected into the hydro-cyclone are exposed to two main adverse forces which are the centrifugal force that point outward and the drag force in opposite direction. Heavier solids are separated by the acceleration of centrifugal force that drag it toward the wall and flow out through underflow, while the drag force will drag the lighter particles inward to low-pressure region along the axis of the hydro-cyclone and being moved upward through the vortex finder to the overflow exit. The separation of the particle from the particle will be only happen when the density of the particle is much larger than the fluid. As shown in the Figure 1 is the basic equation showing the force balance acting on the particle which consist of the centrifugal, drag, and buoyancy force (Aldrich, 2015). If the solids density is larger than fluid medium density, the effect of gravity is neglected because the gravity is much lesser than centrifugal force.



$$F_D = 3\pi d\mu u_r$$

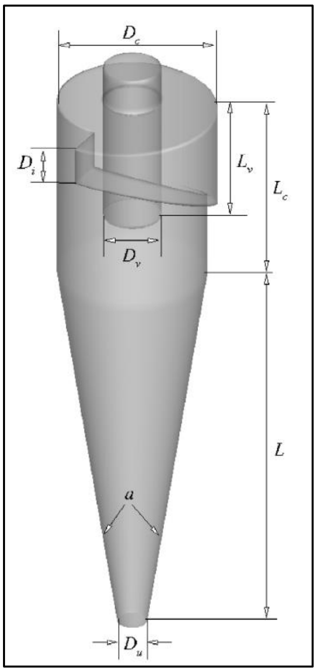
$$F_C = \frac{\pi d^3}{6}\rho_s \frac{u_\theta^2}{r}$$

$$F_B = \frac{\pi d^3}{6}\rho_f \frac{u_\theta^2}{r}$$

$$F_C - F_B - F_D = 0$$

Figure 1.2:Particle's force balance in hydro-cyclone (Aldrich, 2015)

The operation of the hydro-cyclone depends on these two major parameters which are the characteristic of the inlet feed stream and the geometry size of the hydro-cyclone. The characteristic of the feed medium consists of particle diameter, concentration, shape, inlet pressure, flowrate, density and the viscosity. While the geometry of the hydro-cyclone consists of the cylinder diameter, overflow diameter, underflow diameter, total height, cylinder height, vortex finder length, inlet size, and cone angle. These two major parameters are the prime parameter that will define the efficiency of hydro-cyclone.



D_c, Cylinder’s diameter

D_i, Inlet’s size

D_o, Vortex finder’s diameter

D_u, Underflow’s diameter

L_v, Vortex finder’s depth

L_c, Cylinder’s length

L, Cone’s length

a, Cone angle

Figure 1.3:Geometry of hydro-cyclone (Ghodrat, Qi, Kuang, Ji, & Yu, 2016)

1.2 Problem Statement

The hydro-cyclone is used widely in oil & gas industry to separate the sand from the effluent. When the flowing the oil to the surface, sand is most common solid particle that will flow out from the well together with the oil and damage the surface's facilities so the separation of the sand has to be done before letting the oil flow into the surface equipment. The efficiency of using cyclone in the separation is uncertain and based on many aspects. One of it is oil properties which is density and viscosity. Moreover, the feed velocity is one of the parameters that always being manipulated during the operation. This study is to investigate the relationship of feed velocity, oil density and viscosity to the separation efficiency. However, to investigate this experimentally will take more time and consume more cost. So, doing the CFD simulation will be the most applicable solution.

1.3 Objectives

- To identify the effect of oil properties which is density and viscosity to the separation efficiency of cyclone by observing the amount of particle reported to underflow and overflow.
- To identify the effect of feed velocity to the separation efficiency of cyclone by observing the amount of particle reported to underflow and overflow.

1.4 Scope of Study

- Covering simulation study and no experimental work. Simulation will be done using Ansys Fluent.
- Two phases mixture
- Feed velocity, crude oil density and viscosity as manipulated variable.
- Sand particle with 2700 kg/m^3 will be used as constant variable
- Responding variable is the amount of particle reported to underflow
- The turbulence model will be more focus on using Reynold Stress Model.

In conducting this simulation study, there is a limitation where the minimum and maximum energy or flowrate that will allow the swirl flow to happen inside the cyclone cannot be identified. This study is only involving flow velocity range of 1 to 10 m/s. At these velocities, the swirl flow will exist. This limitation is to make sure the simulation and the study can be finish on time to achieve the main objectives. Further study is needed to study on the maximum and minimum energy that is allowed to create the swirl flow inside the cyclone.

CHAPTER 2

2. LITERATURE REVIEW

2.1 Hydro-cyclone Geometry

To get the optimum separation performance of any mixture, a lot of designs of hydro-cyclone had been proposed and created. Various size and geometry of the hydro-cyclone were designed to suit with their specific industry. In spite of the fact, most of the hydro-cyclone used in the industry are the simple shape hydro-cyclone, as shown in FIGURE 3 due to its simplicity, ease in operation and low maintenance cost. The main parameter of the cyclone is the diameter, while basically the hydro-cyclone will be classified using its cylinder section's diameter. The process of the separation and particle trajectories will be directly affected even a small alter in the geometry (Kyriakidis, Silva, Barrozo, & Vieira, 2018). The cylinder section diameter of commercial hydro-cyclone can range from 10 mm up to 2500 mm and competent of separating the 2700 kg/m3 particle of size 1.5 to 300 micrometre (Aldrich, 2015).

It is not only the diameter of the cylinder section that will determine the separation performance. The diameter of underflow, vortex finder, vortex finder depth, and so on will affect the separation process as well. According to Kyriakidis et al. (2018), the hydro-cyclone with larger underflow flow outlet and intermediate vortex finder depth have a better separation performance as it reduced the Euler number and will consume lowest energy. However, the study showed that the vortex finder depth has no serious effect on the performance of hydro-cyclone and this agreed by Silva, Silva, Vieira, and Barrozo (2015). This is because the vortex length only interferes the particle movement from the internal to the external vortex of the hydro-cyclone, but not in the fluid flow. Furthermore, the study by Motsamai (2015) found that the performance of separation peaked at the larger underflow diameter as it allow more coarse particle accumulate near the spigot exit and flow out.

2.2 Feed Properties

The characteristics of the feed medium flow into the hydro-cyclone is another parameter that driving the separation performance of the hydro-cyclone. The characteristic of the feed stream consists of particle size, concentration, shape, inlet pressure, flowrate, velocity, density, viscosity and so on.

The initial parameter of the flow that can be considered is the feed flowrate. Velocity is the component of the flowrate. The increases of the inlet velocity will increase the separation efficiency (Patra, Chakraborty, & Meikap, 2018). At high flow velocity, the particle will be rotated at high centrifugal force and more tend to be thrown toward the wall of the cyclone ang flow down to underflow. Bai et al. (2019) This theory is agreed by the other study that proved the increase of the feed velocity will increase the swirl intensity and so improve the separation performance of hydro-cyclone. High velocity means high flowrate and it can increase the separation performance. However, the flowrate can not be too high as it may contribute to unacceptable large pressure drop increase the energy losses of the flow (Tian, Ni, Song, Olson, & Zhao, 2018).

Beside the flowrate, pressure is another important parameter of the feed inlet. The inlet pressure is proportionally related to the energy consumption and the separation performance of the cyclone. The high inlet pressure that applied to a small cyclone may get a smaller cut sizes of particle (Tian et al., 2018).

For cyclone, the rule of thumb is that it can deal with solid up to one over three the size of the smallest opening usually the inlet or spigot opening at the underflow (Rawlins, 2017). In hydro-cyclone separation, the performance is predicted to increase with the particle size. Very fine particle size will bypass and flow to the overflow as it do not have enough drag force to withstand moving with the feed medium (Motsamai, 2015). His study found that by rising the centrifugal force, the bypass of the tiny particle can be reduced as the underflow stream will be concentrated with the solid particle. Even though the larger particle is better for separation performance, but there is still a critical diameter for the particle depends on the flow condition and the cyclone geometry. The particle exceeding the critical diameter tend to retain on the wall as result of the balanced forces and lead to unstable flow (Wang, Chu, & Yu, 2007).

The separation of the solid from the medium will be reduced when the density of the medium increase as the lower pressure region will be increase outward to the wall and increase the pressure drop of the hydro-cyclone (Motsamai, 2015). The best performance of separation will occur when the relative density difference between particle and the medium is huge. If the density of fluid medium and the particle are close to each other, particle may go to both overflow and underflow. The separation will perform better with larger centrifugal force and this can be obtain be using the larger feed densities differences (Tian et al., 2018). The centrifugal forces tend to pull the denser particles outward the and flow on the wall and exit to the spigot underflow outlet. However, the less dense particles tend to be pulled inward to the centre by the pressure difference forces (Ghodrat, Qi, Kuang, Ji, & Yu, 2016). Furthermore, the density has a relation with the pressure drop which expressed as (Ghodrat et al., 2014):

$$\Delta p = \int_0^{\frac{D_c}{2}} \rho_m \frac{u_t^2}{r} dr \qquad (1)$$

Pressure drop refer to the variation of static pressure between inlet and underflow outlet. Hydro-cyclone work by converting the pressure energy to the dynamic energy and come together with the energy losses. When the pressure drop increases, it means that the pressure losses is huge and the total pressure energy converted to the kinetic energy will be lessen (Zhao, Cui, Wei, Song, & Feng, 2019).

Next, the viscosity of the feed has big influence in the separation performance of cyclone. This can be proved by the relation of the viscosity to the static pressure. When the viscosity of the feed increase, the magnitude of the static pressure at the outlet drop which lead to the decreasing of the differential pressure (Murthy & Bhaskar, 2012). This cause decreases in radial fluid flows to the core area and reduce the mass splits to the vortex finder. Furthermore. The separation efficiency will drop when the viscosity of the medium increased (Hagemeijer & Jagernath, 2003). In the study conducted by Marthinussen (2011), he used the sucrose to alter the viscosity of the test medium and the result proved that the total efficiency decreased as the viscosity increased. His study show agreement to the other researcher's studies as well. From the grade-efficiency curves obtain by Marthinussen (2011), it shown that the larger particle cut size will be obtained at higher viscosity of the carrier medium. So, in order to filter smaller particle, lower viscosity should be used instead.

2.3 Separation Efficiency

The efficiency of the hydro-cyclone means that how good is the hydro-cyclone can separate the mixture phases into two that will be flow to underflow and overflow. The recovery efficiency is measured by the total amount of particles that collected at the underflow divided by the total amount of inlet particles (Rawlins, 2017). In considering the performance of the hydro-cyclone, there are three particles fractions that need to be concerned which are the feed particle, collected particle at underflow, and bypass particle at overflow.

$$M_f = M_u + M_o \quad (2)$$

As shown above is the mass balance of the particles in the hydro-cyclone where M_f, M_u, and M_o represent mass of particle at feed, the underflow and overflow respectively. From here, the total efficiency of the cyclone can be concluded into the following formula (Marthinussen, 2011):

$$\eta = \frac{M_u}{M_f} = \frac{M_u}{M_u + M_o} \quad (3)$$

Here, the efficiency is measured by collecting the solid particle and scaling two of the fractions and it is normally what used in the industrial mostly.

2.4 Computational Fluid Dynamic

CFP or Computational fluid dynamics is a division of fluid mechanics that utilise numerical analysis and data structures to calculate and solve issues that contains fluid flows and it is proven as an efficient technique for flow field and separation performance predictions of hydro-cyclones.

k–epsilon or Reynold Stress Model are the main turbulence models that used in simulation of hydro-cyclone. However, k–ε is less preferred as the model is depending on Bousinessq likeliness that assume the turbulence is isotropic and not suitable for vortex flow (Mokni, Dhaouadi, Bournot, & Mhiri, 2015). For better accuracy, RSM is preferred as it suitable for anisotropic turbulence in cyclone. The study conducted by Bhaskar et al. (2007) also proved that among three model that they used which are k–ε RNG, standard k–ε, and RSM, RSM gave better outcome. The marginal error of his simulation to the experiment is only between 4 to 8 percent. The cyclone flow is modelled by Newtonian water flow and RSM. The following equations describe the Reynolds-averaged Navier-Stokes (Hsu, Wu, & Wu, 2011).

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial x_i}(\rho v_i) = 0 \tag{4}$$

$$\frac{\partial}{\partial t}(\rho v_i) + \frac{\partial}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial v_j}{\partial x_j}\right)\right] + \frac{\partial}{\partial x_j}(-\rho\overline{v'_\iota v'_J}) \tag{5}$$

The actual Reynolds stresses, $\rho v'_t v'_j$, transport equation can be written as:

$$\frac{\partial}{\partial t}\left(\rho\overline{v'_\iota v'_J}\right) + \frac{\partial}{\partial x_k}\left(\rho v_k \overline{v'_\iota v'_J}\right) = -\frac{\partial}{\partial x_k}\left[\rho\overline{v_\iota v_J v_k} + \overline{p\left(\delta_{kJ} v'_\iota + \delta_{\iota k} v'_J\right)}\right] + \frac{\partial}{\partial x_k}\left[\mu\frac{\partial\overline{v'_\iota v'_J}}{\partial x_k}\right] - \rho\left(\overline{v'_\iota v'_J}\frac{\partial v_j}{\partial x_k} + \overline{v'_J v'_k}\frac{\partial v_i}{\partial x_k}\right) - \rho\beta\left(g_i\overline{v'_J\theta} + g_j\overline{v'_\iota\theta}\right) + \overline{p\left(\frac{\partial v'_\iota}{\partial x_J} + \frac{\partial v'_J}{\partial x_\iota}\right)} - 2\mu\overline{\frac{\partial v'_\iota}{\partial x_k}\frac{\partial v'_J}{\partial x_k}} \tag{6}$$

On the right-hand side, these terms represent turbulent and molecular diffusion, stress production, buoyancy production, pressure strain and dissipation terms respectively. While on the left-hand side represents local time derivative and convection terms.

CHAPTER 3

3. METHODOLOGY

3.1 Simulation Procedure

In conducting the study, the Computational Fluid Dynamic software, ANSYS FLUENT 2019 R2 version will be used to model the hydro-cyclone and run the simulation and observe the performance. ANSYS FLUENT, a CFD program contains the comprehensive, physical modelling abilities needed to model flow, turbulence, heat transfer and reactions for the hydro-cyclone application.

3.1.1 Geometry Modelling

Using the Ansys CFD software, the model of the hydro-cyclone with following geometry will be modelled in Ansys Workbench. The geometry of the hydro-cyclone model used for the simulation is displaced in FIGURE 4. The diameter of cylinder, overflow, and underflow are 75, 25, and 12.5 mm, respectively. The size of the inlet will be 22.16^2 mm^2. The depth of vortex finder is 50 mm, while the cone angle 20º, making the cone length to be 186 mm. The small size of model is used is to reduce the complexity of calculation and reduce the calculation time. The model size is same as model used in Hsieh (1988) study. Same size of model is taken to ease the model validation process after.

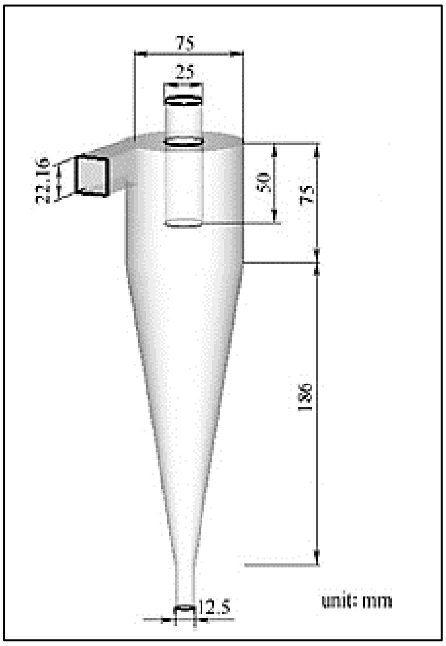


Figure 3.1: Geometry of hydro-cyclone model

Table 3.1: Geometry of the model

Parameter	Symbol	Magnitude
Cylinder’s diameter	D_c	75 mm
Inlet size	D_i	22.16^2 mm^2
Vortex finder/Overflow’s diameter	D_o	25 mm
Underflow’s diameter	D_u	12.5 mm
Vortex finder’s length	L_v	50 mm
Cylinder’s length	L_c	75 mm
Cone’s length	L	186 mm
Cone’s angle	a	20^o

3.1.2 Meshing and Quality Check

Once the model of the hydro-cyclone is drawn, the model will be meshed up. The initial mesh or element size will be start with large size first (The actual mesh densities will be defined during the actual simulation stage). Once the meshing is done, mesh quality needed to be done in order to get a good model and will reduce the error of the result. First, the grid of the mesh had to be as structured as possible as it will give more accurate calculation. The element grids had to be aligned to the flow direction as much as possible. It is not only giving better result but reduce the calculation time as well. Next is the aspect ratio of the mesh. Aspect ratio of mesh is interpreted as the fraction of the longest to the shortest dimension of a quadrilateral element. Here, the aspect ratio had to be as low as possible (less than 5) to give more accuracy. High Aspect ratio causes error, because the effect of a change in one or more of the variables will propagate faster in one direction than the other direction. Furthermore, the skewness of the mesh has to be kept below 0.7 following rule of thumb. Generally, the skewness can be within 0 to 1.

3.1.3 Mesh Independence Test

The mesh independence study had to be done to get the optimum mesh size for the simulation. This mesh sensitivity study will be done by increasing the mesh size. The setup for the simulation in independence test will be using water as medium that will be injected into the hydro-cyclone. All the setup will be a simple setup, all the default setting will be used. The pressure drop from inlet to underflow will be recorded for each mesh size. The simulation will be repeated as the mesh size is refined. The process will be repeated until there is no much change in the pressure drop when the mesh size in decreasing. This stage means that the model had reach the mesh independence solution which means any rising in the number of mesh will not result in any change on the results and hence there is no point in increasing the mesh further.

3.1.4 Simulation Setup

To study the effect of the medium viscosity and the density of the oil type on the working performance of the hydro-cyclone, 1 light crude, 1 medium crude, and 1 heavy crude with different API is chosen, which are Malaysia Tapis crude, Iraq Basrah Light Crude, and Nigeria Ebok Crude respectively("Crude oil blends by API gravity and by sulfur content," 2019). The properties of these 2 oil types is shown in TABLE 2.

Table 3.2: Manipulated variable, oil type.

Type	**Crude oil**	**API**	**Density, kg/m^3**	**Viscosity, kg/m-s**
Light	Malaysia, Tapis crude	42.7	811.2	0.00373
Medium	Iraq, Basrah Light crude	29.9	876.14	0.01682
Heavy	Nigeria, Ebok crude	19.8	934.05	0.17841

The medium will be fed into the inlet with velocity of 1 to 10 m/s. For the overflow and underflow, the temperature and the pressure will be kept at normal temperature and pressure (NTP) which are 300K and 1 atm respectively. Then, the concentration of the sand particle in the feed medium will be kept as 50 percent of the feed volume. The particle size of 5 μm with density of 2700 kg/m^3 will be used.

Table 3.3: Boundary condition

Parameter	**Magnitude**
Inlet	Velocity-inlet
Overflow	Pressure-outlet
Underflow	Pressure-outlet
Feed velocity	1, 3.5, 5, 7.5, 10 m/s
Underflow pressure, atm	1
Overflow pressure, atm	1
Temperature, K	300
Particle size, μm	5
Particle density, kg/m^3	2700

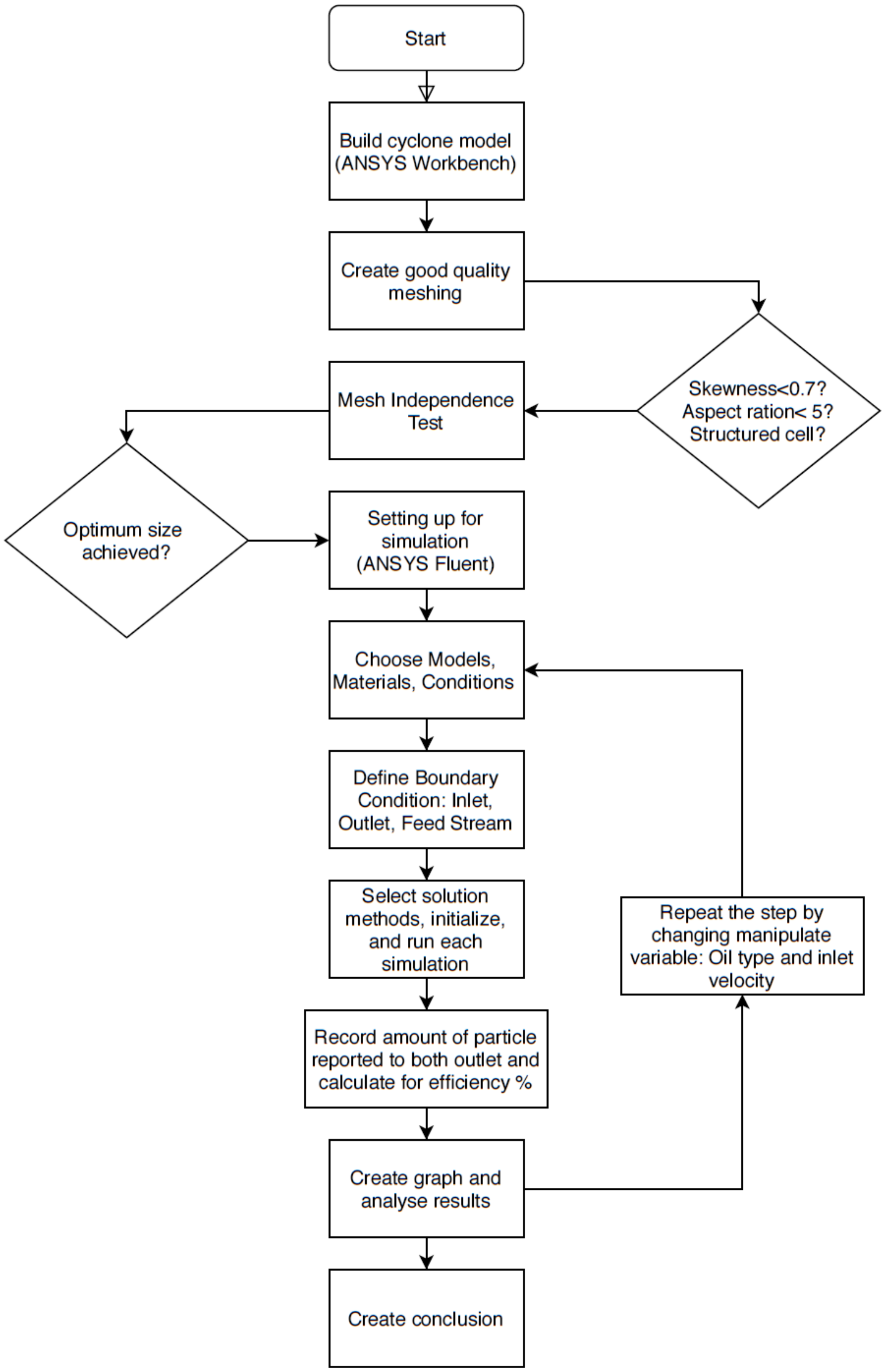
The boundary condition for the inlet will be velocity inlet. However, the boundary condition for the overflow and underflow will be pressure outlet. The standard wall function will be used. The simulation will be run in steady state with Reynold Stress Model (RSM) and Discrete Phase Model (DPM). Reynold Stress Model turbulence model will be used to interpret the turbulent characteristics of the vortex flow. This model is chosen because according to the literature review, most of the researcher' result showed the agreement that RSM is the most accurate model for conducting simulation of swirling flow. However, DPM will be used to track the particle movement inside the cyclone. The SIMPLE pressure-velocity coupling and pressure staggered option (PRESTO) option are chosen. PRESTO will be useful to predict the high vortex flow characteristics that happen inside the hydro-cyclone and SIMPLE will uses the combination of continuity and momentum equation to derive the equation for pressure (Hsu et al., 2011). Second order upwind models will be selected for discretization of other variables (Zhang et al., 2017). The Ansys Fluent CFD program will solve the equation (4) to (6) together with the defined boundary conditions.

3.1.5 Simulation Run

First, the mixture of Tapis Light Crude oil and sand particle of size 5 micron will be injected into hydro-cyclone with feed velocity of 1 m/s. The amount of particle escaped through underflow and overflow will be recorded. Then, the amount of incomplete particle that keep rotating inside cyclone will be escape as well. After that, the efficiency of cyclone will be calculated by the ratio of particle reported to underflow to the total injected particle. Repeat the simulation by keeping the oil properties and changing the feed velocity to 3.5, 5, 7.5 and 10 m/s. Record the data and plot the graph of efficiency versus feed velocity to see the effect of velocity to the efficiency.

Once the simulation for first oil properties is done, repeat the exact same step by changing the medium to Basra Medium Crude and Ebok Heavy Crude oil. Change the feed velocity for each oil type. Record the data and plot the graph of efficiency versus velocity, density and viscosity.

3.2 Flowchart



3.3 Gantt Charts and Milestone

Table 3.4: FYP I Project Planning

FYP I														
Week	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
PROJECT PLANS														
Title selection: CFD simulation of Hydrocyclone	■													
Initial study on Hydrocyclone		■	■											
Literature review about hydrocyclone study			■	■	■	■	■							
Identify problem statement & objective (choose crude oil type as control variable)				■										
Generate study methodology				■	■									
Refinement of literature review to the study scope (density & viscosity vs efficiency)					■	■	■	■						
Learn Ansys-FLUENT					■	■	■	■	■	■	■	■	■	
Build hydrocyclone trial model in Ansys-FLUENT					■									
Trial run of simulation (water as feed medium)						■	■							
Interim report preparation							■	■	■	■	■			
Interim report correction & improvement												■	■	
MILESTONE														
Problem statement & objective identified				■										
Methodology for simulation identified					■									
Geometry for hydrocyclone model chosed					■									
Oil properties (density & viscosity) identified					■									
Trial run simulation presentation to SV								■						
Interim draft completed												■		
Interim report finalized													■	

Table 3.5: FYP II Project Planning

FYP II														
Week	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
PROJECT PLANS														
Build hydro-cyclone model in Ansys Fluent	■													
Create meshing of hydro-cyclone model	■													
Meshing quality check	■													
Perform mesh independence study		■												
Determine optimum mesh with several runs with different mesh		■												
Run simulation with 1st oil			■	■										
Run simulation with 2nd oil			■	■										
Run simulation with 3rd oil				■	■									
Collecting result: graphs, contour, etc					■									
Analyse simulation result: amount of particle reported to 2 outlets, separation efficiency, etc					■									
Compare result with other studies					■	■								
Finalize & conclude the study						■	■							
Prepare dissertation report				■	■	■	■	■						
Dissertation correction & improvement									■	■	■			
MILESTONE														
A valid hydro-cyclone model is ready			■											
Suitable with high quality mesh done			■											
Optimum mesh obtained			■											
1st simulation set run complete			■											
2nd simulation set run complete				■										
3rd simulation set run complete					■									
Result finalize								■						
Dissertation report finalize										■				
Dissertation hard bound complete														■

CHAPTER 4

4. RESULTS AND DISCUSSION

4.1 Mesh Quality

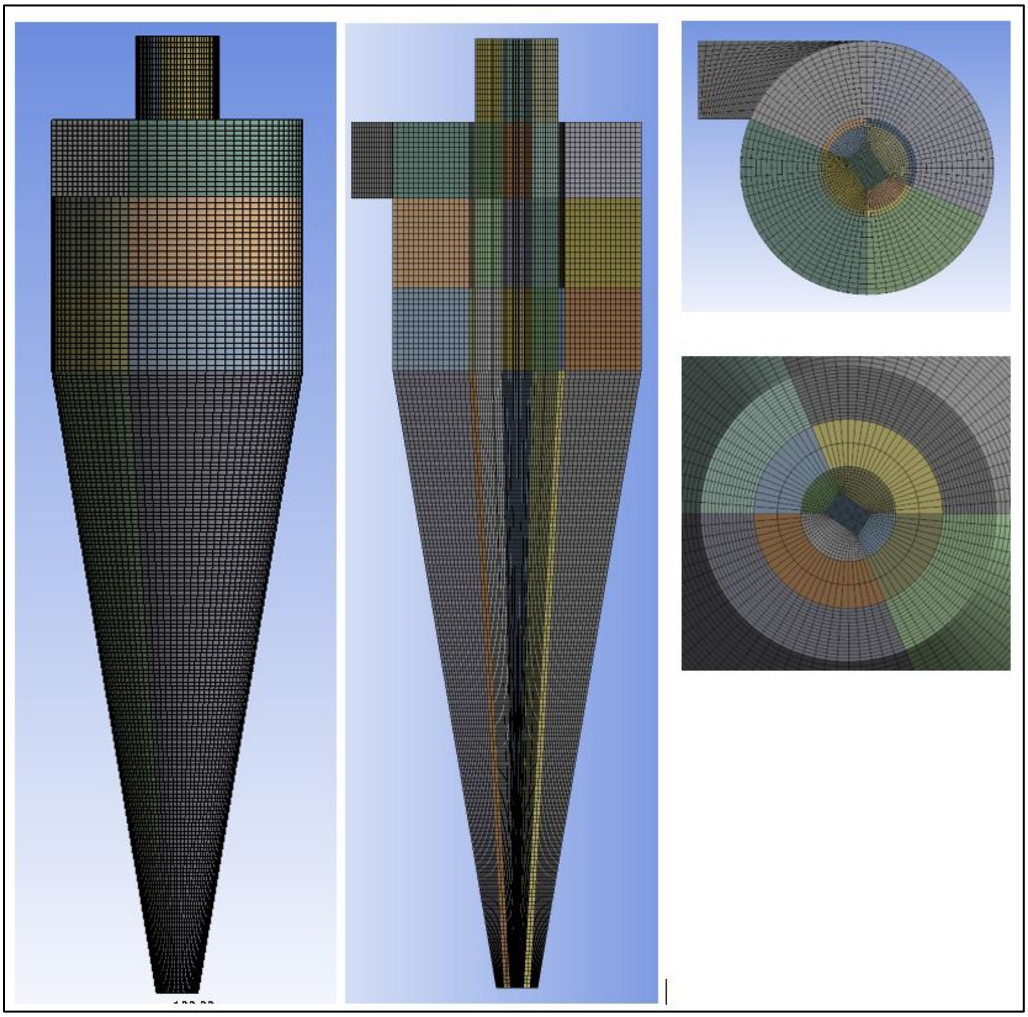


Figure 4.1: Mesh from side view, cross section, top view and bottom view respectively

After several attempt in doing a good quality mesh for the model, the structured mesh as shown in Figure 5 is produced. In overall, the quality of the mesh is satisfied as the skewness and the aspect ratio of the mesh element is within the required value. The element shape of the mesh is being generated to be as structured as possible. The skewness of the critical part mesh especially the cone and cylinder of the cyclone is averagely around 0.1 which is acceptable. However, there is still a little part at the inlet at near the underflow produced huge amount of skewness which is around 0.99 and this in unavoidable. It is still in the acceptable range which is below than 1. Same to the aspect ratio, majority of the critical part have an aspect ratio of less than 10 and only a few small parts that have large value of aspect ratio which is around 31 and it is unavoidable as well.

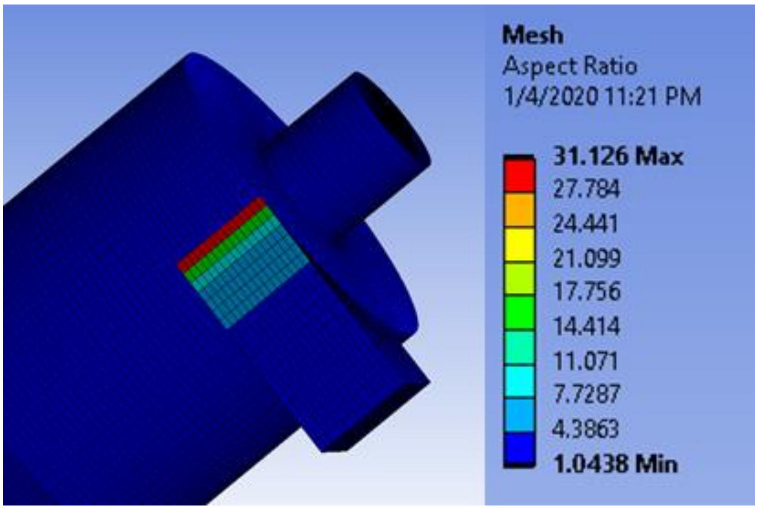


Figure 4.2: Aspect ratio generated mesh

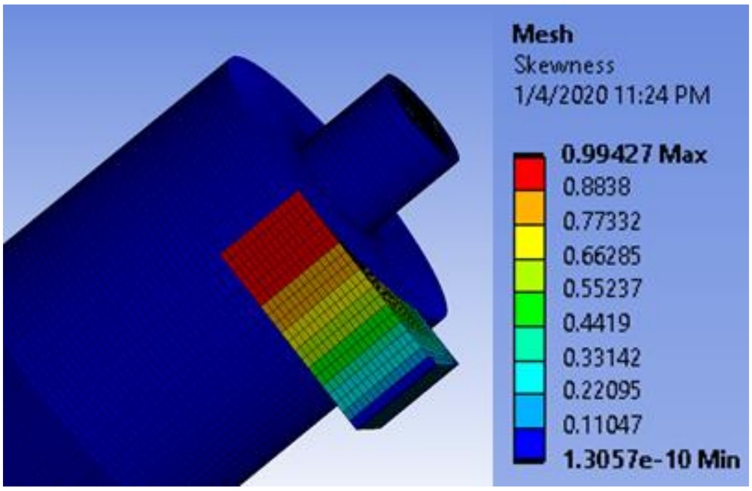


Figure 4.3: Skewness of the generated mesh

The number of mesh element of this model is 511k. Since the software that being used is student version, the maximum mesh element that can be used is only 512k. So, 511k mesh element is the maximum mesh that can be used for the simulation.

4.2 Mesh Independence Study

Figure 4.4: Mesh Independence Study

Table 4.1: Pressure Drop for each Mesh Size

Mesh Element	Pressure Drop, kPa	Different %
11900	7412.20	0
57664	13647.06	84.12
133000	15892.03	16.45
265200	17503.63	10.14
511650	18221.25	4.10

As shown in Figure 6 and Table 4, the independence test on the model has been done in order to get the optimum mesh size for the simulation. The data in the graph and the table shown that the value of pressure drop of mesh size 265200 and 511650 mesh size is almost same with only 4.10 percent of different. Moreover, the mesh size for Ansys Fluent Student Version is only limited to 512000 mesh only and as the graph start to flatten when approaching mesh size of 511650. So, here the optimum mesh size that achieve is 511650.

4.3 Model Validation Test

In numerical study, it is necessary to validate the model before running the simulation for real case problem. In CFD, the model can be validated against the experimental data and the results should be in agreement with measurement. If there is no experiment conducted, the model can be validated against any data from other researchers which has been validated against experiment. In this study, the research papers from previous studies were taken as a reference for the model validation. The model of this study is being validated against the experiment data from the study conducted by Hsieh (1988) study. Figure 9 shown the partition curve of Hsieh (1988) study. The curve shown that the cut size of his study is about 17.74 microns. Cut size means the particle with the size will have 0.5 of possibility to go to underflow or overflow. In this simulation, the sand with size of 17 microns is injected into the cyclone and the separation efficiency is about 52%. So, the predicted cut size obtained is said to be around 17 microns and it is almost same with the value obtained by Hsieh (1988). Same to the pressure drop, the value obtained is 47.5 kPa, where it is almost hit the value obtained by Hsieh (1988). The variation of predicted model and experimental data from Hsieh (1988) is less than 5% which is at acceptable level.

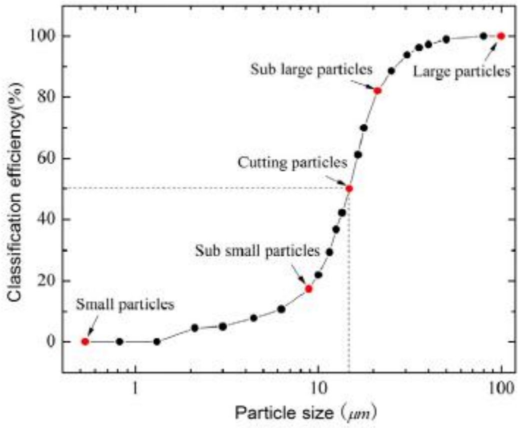


Figure 4.5: Partition curve of Hsieh (1988) study

Table 4.2: Predicted versus experimental results

	Cut size d_{50}, μm	Pressure drop, kPa
Experimental (Hsieh, 1988)	17.74	46.7
Predicted model	17	47.5

However, validation is not the final decider whether the CFD model is correct or not. There is a need to analyse the CFD results by using basic engineering principles. In the case, the expected flow behaviour inside the hydro-cyclone should be in vortex form. As in Figure 10, the particle that has been injected into the cyclone rotating inside the cyclone in vortex form. The flow of the medium inside cyclone behaved like what was expected and made sense in term of engineering principle. So, the model should be in good and valid condition for the further simulation.

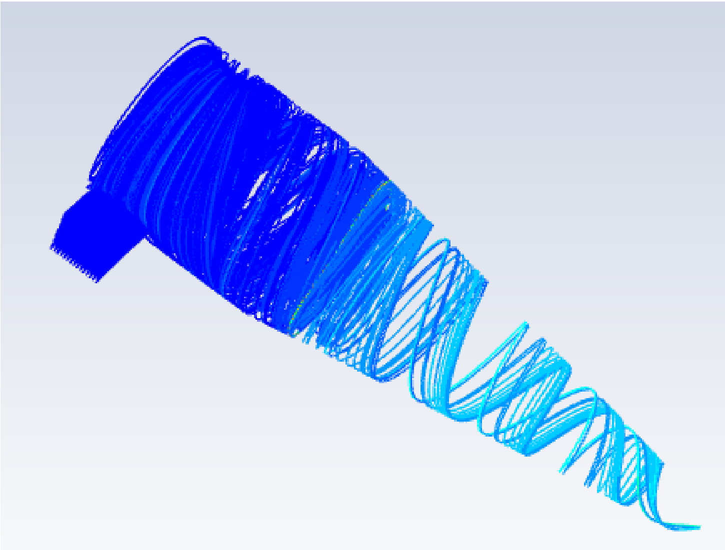


Figure 4.6: The vortex behaviour inside cyclone

4.4 Effect of Feed Velocity and Oil Properties

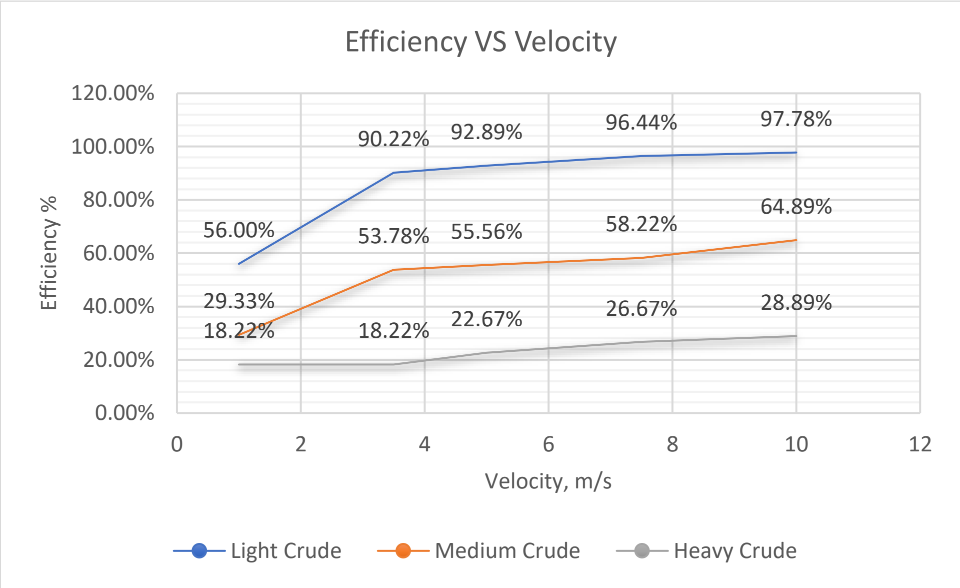


Figure 4.7: Feed velocity VS efficiency graph

As in Figure 11, the relationship of the feed velocity to the separation efficiency for all three type of oil can be seen. The separation efficiency here means the ratio of amount of particle reported to underflow to the total particle injected. The graph shown that the separation efficiency is corresponding proportional to the feed velocity. The efficiency will increase when the feed velocity increase. This outcome agreed with many previous studied conducted. The feed velocity cannot be too high owing to that an unacceptable high-pressure drop will be caused by the further increase in feed flow rate. However, a typical hydro-cyclone showed that the centrifugal forces will got stronger and hence enhanced the separation when the feed velocity or flowrate increased. The feed flowrate can be increased until the feed flow rate reached a minimum stage, where the efficiency will plateaued (Tian et al., 2018). Then, the separation efficiency will stay constant until reach the maximum flowrate and the efficiency will start to drop. The separation performance plateaued due to the balance between increases of centrifugal forces and decreasing in residence time of particle as the flow velocity rise. After that, due to the insufficient of pressure gradient to drive the particle through the vortex finder as the pressure in the cyclone's centre was decreased at high flowrate, the separation efficiency will decrease when the flowrate go beyond maximum limit (Tian et al., 2018).

From the graph above, the effect of fluid density and viscosity can be seen as well. Here, the light oil means the oil have properties of low density and viscosity.

Same go to heavy oil, it means the oil having high density and viscosity. Figure 11 shown that, the heavier the oil, the lower the separation efficiency. The effect of the density itself can be describe in term of feed density difference. Feed density difference is proportional to the separation efficiency. When the density of the medium and particle is high, the centrifugal force acted on the particle will be larger and will push the particle close to the wall and pulled down to the underflow by gravity force.

Moreover, the increasing in viscosity will decrease the separation efficiency as well. When the viscosity increase, the cyclone cut size will increase (Hoffmann, Skorpen, & Chang, 2019). This mean that the smaller particle has very low percentage to be separated out from cyclone at high viscosity. As in the equation below, which is called as “equilibrium model”, the medium viscosity is proportional to the cut size. The overall efficiency will increase with the feed flowrate and decrease with the medium viscosity (Marthinussen, Chang, Balakin, & Hoffmann, 2014).

$$d_{50} = \sqrt{\frac{v_{rCS} 9 \mu D_x}{(\rho_s - \rho_l) v_{\theta CS}^2}}$$

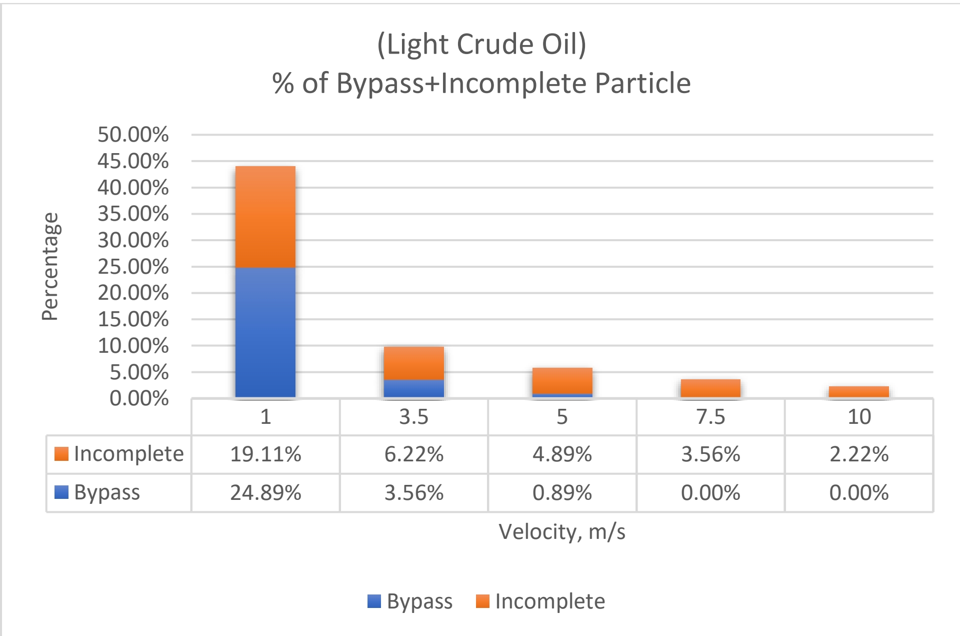


Figure 4.8: Percentage of bypass and incomplete particle VS velocity graph (Light)

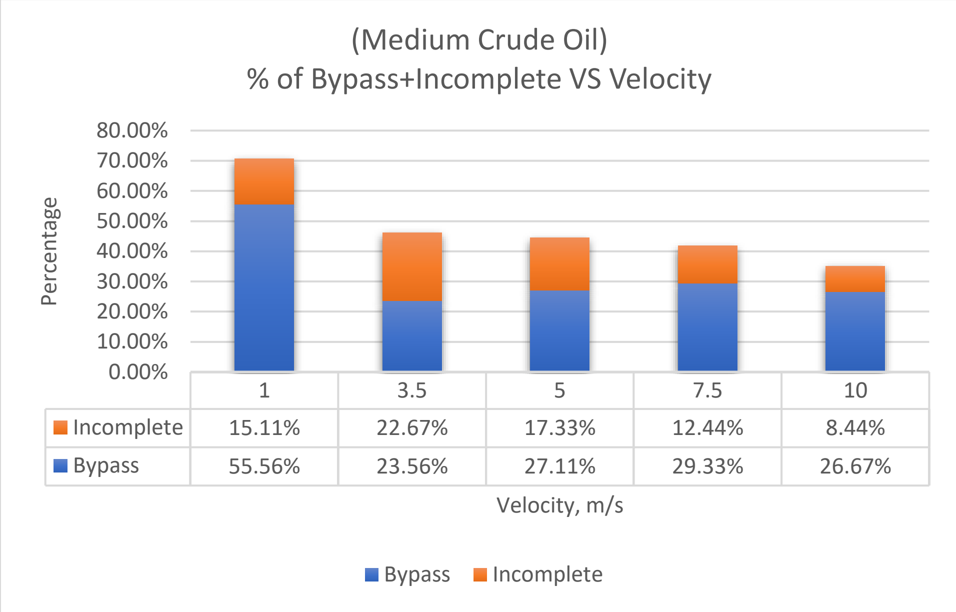


Figure 4.9: Percentage of bypass and incomplete particle VS velocity graph (Medium)

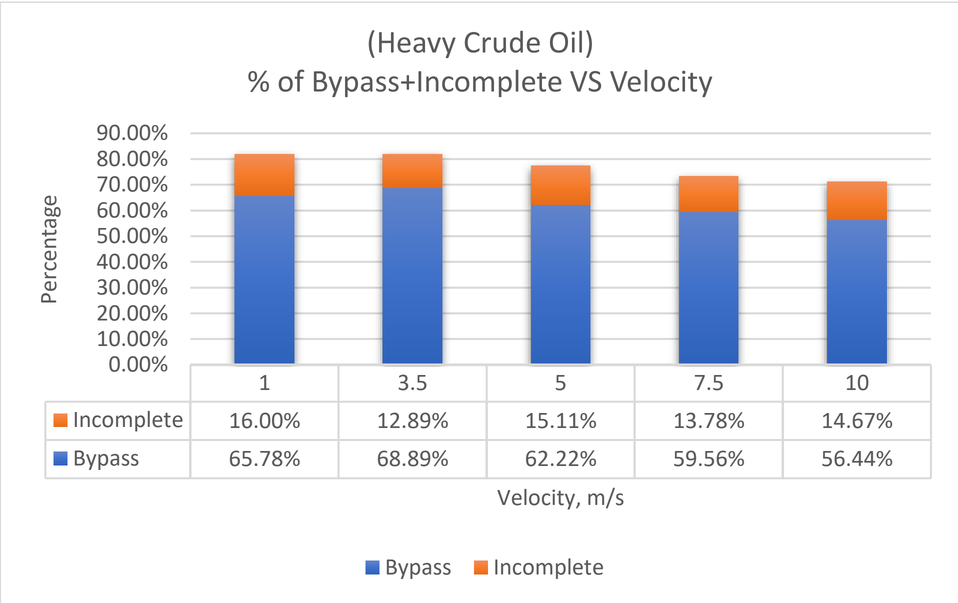


Figure 4.10: Percentage of bypass and incomplete particle VS velocity graph (Heavy)

Figure 12, 13 and 14 show the percentage of the particle that bypass to overflow and incomplete particle that keep rotating inside the cyclone. These particles cause deficiency to the cyclone. Some incomplete particle will cause the erosion to the cyclone wall.

4.6 Effect of Oil Properties and Flow Velocity to The Pressure Drop

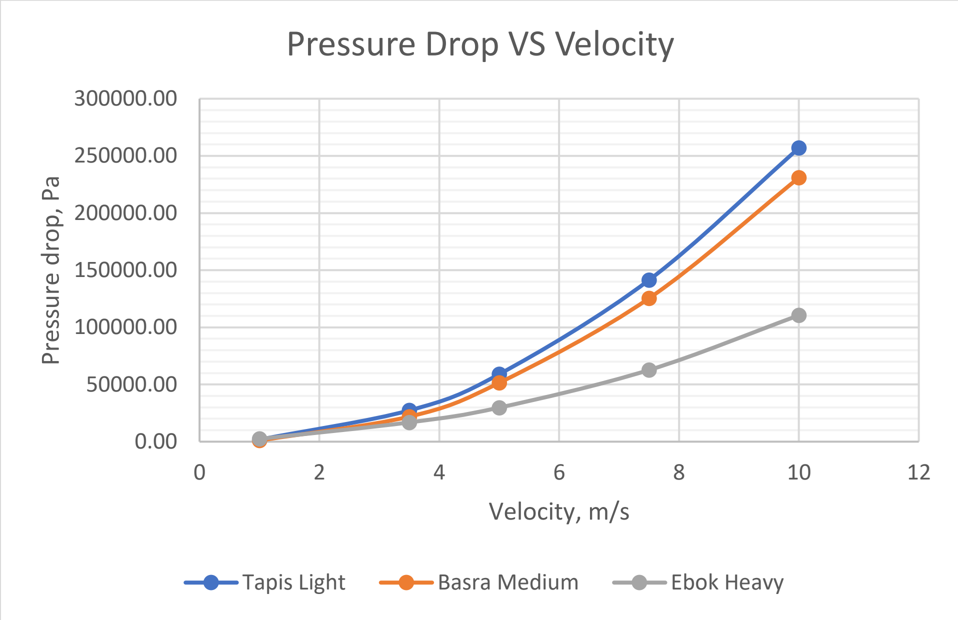


Figure 4.11: Pressure drop graph

Table 4.3: Pressure drop at difference velocity for all oil type

	Pressure drop, Pa				
Oil type	1 m/s	3.5 m/s	5 m/s	7.5 m/s	10 m/s
Tapis	1794.68	27350.33	59026.42	141426.41	256869.62
Basra	1036.21	21902.92	51476.17	125439.39	230945.33
Ebok	2426.39	16873.09	29788.37	62691.96	110521.30

The pressure drop in cyclone is the different of the pressure at the inlet and the underflow and it is important in defining the efficiency of the cyclone. Figure 15 shown that the pressure drop increase as the velocity of inlet flow increase. The pressure drop increase slowly at low flowrate and increase rapidly at high flowrate. Furthermore, the pressure drop for three oil at low velocity is almost the same while the pressure drop decreases as the viscosity of oil increased at high velocity or flowrate. Marthinussen et al (2014) said that the decrease of pressure dropped when the viscosity increase in cyclone may associated with the drop in swirl intensity inside the hydro-cyclone. The drop in swirl intensity will lead to the reduction in the static pressure that will be transformed into dynamic pressure in cyclone body. At higher velocity, an intense vortex can be created in cyclone when the viscosity is high. This means more static pressure will be transferred as dynamic pressure.

CHAPTER 5

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The separation efficiency of the hydro-cyclone is higher at high feed inlet velocity, high density different between medium and particle, and low medium viscosity. At high feed velocity which means high flowrate, the intensity of the swirl flow inside the cyclone will be high and contribute to the higher centrifugal force that will be pushing the particle to the cyclone wall and dragged down to the underflow by gravity. The efficiency of the cyclone is associated with the difference in drag force and centrifugal force that applied on the particle. Any parameter that contribute to the higher centrifugal force will contribute to the high separation efficiency as well. In heavy oil which has larger density and viscosity, the greater drag force will be applied on the particle. However, in light oil with lower viscosity and lower density, more centrifugal force will be acting on the particle and dragged it to the cyclone wall. Therefore, the objectives defined prior to the study is being achieved.

In future, it is recommended to conduct the experimental work to validate this simulation with the exact same operating condition, fluid type and so on. Future experimental work will give more accuracy to result and define more in detail the relationship of the studied parameter.

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APPENDICES

1. Simulation Data collected from Ansys Fluent

Crude	Viscosity, kg/m3	Density, kg/ms	Velocity, m/s	Particle Size, m	Tracked	Escaped	Trapped	Incomplete	Efficiency	Pressure Drop	Bypass %	Incomplete%
Tapis Light Crude Oil	811.2	0.00373	1	0.00005	225	56	126	43	56.00%	1794.68	24.89%	19.11%
			3.5		225	8	203	14	90.22%	27350.33	3.56%	6.22%
			5		225	2	209	11	92.89%	59026.42	0.89%	4.89%
			7.5		225	0	217	8	96.44%	141426.41	0.00%	3.56%
			10		225	0	220	5	97.78%	256869.62	0.00%	2.22%
Basra Medium Crude Oil	876.14	0.01682	1	0.00005	225	125	66	34	29.33%	1036.21	55.56%	15.11%
			3.5		225	53	121	51	53.78%	21902.92	23.56%	22.67%
			5		225	61	125	39	55.56%	51476.17	27.11%	17.33%
			7.5		225	66	131	28	58.22%	125439.39	29.33%	12.44%
			10		225	60	146	19	64.89%	230945.33	26.67%	8.44%
Ebok Heavy Crude Oil	934.05	0.17841	1	0.00005	225	148	41	36	18.22%	2426.39	65.78%	16.00%
			3.5		225	155	41	29	18.22%	16873.09	68.89%	12.89%
			5		225	140	51	34	22.67%	29788.37	62.22%	15.11%
			7.5		225	134	60	31	26.67%	62691.96	59.56%	13.78%
			10		225	127	65	33	28.89%	110521.30	56.44%	14.67%

2. Mesh Detail