RESEARCH OF SCREW EXPELLER ON OIL PALM SEED: A CFD STUDY ON BARREL ZONE

By:

MUHAMMAD AIZUDDIN BIN MOHAMED

(Matric No.: 125027)

Supervisor:

Dr. Inzarul Faisham Bin Abd Rahim

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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This thesis is the result of my own investigations, except where otherwise stated.

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ABBREVIATIONS

KMSK…………………………………….KILANG MINYAK SAWIT KAMUNTING

RPM……………………………………REVOLUTION PER MINUTE

MRF……………………………………MULTIPLE REFERENCE FRAME

CPO…………………………………….CRUDE PALM OIL

PDE…………………………………….PARTIAL DIFFRENTIAL EQUATION

CFD…………………………………….COMPUTATIONAL FLUID DYNAMICS

Abstrak

Kajian kes telah dijalankan di Kilang Minyak Sawit Kamunting Sdn Bhd, Taiping. Projek kajian ini bermatlamat untuk mencari hubungkait diantara tahap kelajuan skrew bersama tahap tekanan di peroleh daripada susunan konfigurasi skrew tidak bersirat. Ia juga bermatlamat untuk mencari hubungan konfigurasi reka bentuk (panjang bebenang yang berbeza panjang) dengan pembangunan tekanan di dalam laras. Penyelidikan ini akan dicapai dengan mensimulasikan zon laras menggunakan perisian ANSYS Fluent. Teknik Rangka Rujukan Pelbagai (MRF) akan digunakan untuk tujuan simulasi. Semakin meningkat kelajuan skru, semakin meningkat pembangunan tekanan di dalam ruang terkurung. Dua skrew model (40 mm dan 50 mm panjang bebenang) telah menghasilkan nilai tekanan yang tinggi; kemudian nilai tekanan ini semakin mengecil jikamana panjang bebenang skrew semakin melebar. Kesepakatan yang baik mendapati bahawa hubungkait kelajuan skru adalah secara langsung dengan tekanan yang terhasil. Peningkatan ini juga menghasilkan peningkatan pada kadar pemprosesan buah rapuh. Dalam pergerakan secara paksi, tekanan dilihat secara beransur-ansur berkurangan bergerak dari saluran masuk ke arah saluran keluar. Hasil campuran dua skrew merupakan faktor yang memberi impak kepada hubungkait antara panjang bebenang dan tekanan terhasil.

Abstract

The case study was carried out at Kilang Minyak Sawit Kamunting Sdn.Bhd, Taiping. The project research has the aims in finding the relationship between the screw speed and pressure development in a non-intermeshing type of screw expeller. It also interest in finding the relationship of design configuration (different screw pitch length) with the pressure development inside the barrel. The research will be achieved by simulating the barrel zone using the ANSYS Fluent software. Multiple Reference Frame (MRF) technique will be used for the purpose of simulation. As increasing the screw speed, it also increases the pressure development inside the confined space. 40mm and 50 mm screw pitch model will have a higher pressure value and eventually as increasing the screw pitch further on; the pressure value inside the barrel is gradually decreasing. Good agreement was found that the screw speed is directly proportional to the pressure and the throughput of fruit mesh will increase along with it. In axial movement of the fruit mesh (fluid flow), the pressure are gradually decreasing as it moves from the inlet towards the discharge outlet. The mixing behaviour of the double screw expeller is the contributing factor that affects the relationship between screw pitch lengths towards the development of pressure.

CHAPTER 1: Introduction

1.1 Research background

Palm oil is produced from the fruit pulp of the oil palm tree (Elaeis guineensis) which the tree is native to the area of West Africa, for which where its scientific name comes from. It is a leading tropical vegetable oil in worldwide scale. It accounts for one-quarter of global consumption and approximately 60% of international trade in vegetable oils, for which it has been estimated that 74% of global palm oil usage is for food products and 24% is for industrial purpose[1]. As one of the world's largest producers and exporters of palm oil and its products, the Malaysian oil palm industry is the pride of the country; the 4th largest contributor to the national economy of Malaysia and one of the major driving forces for the country's agro-industry[2].

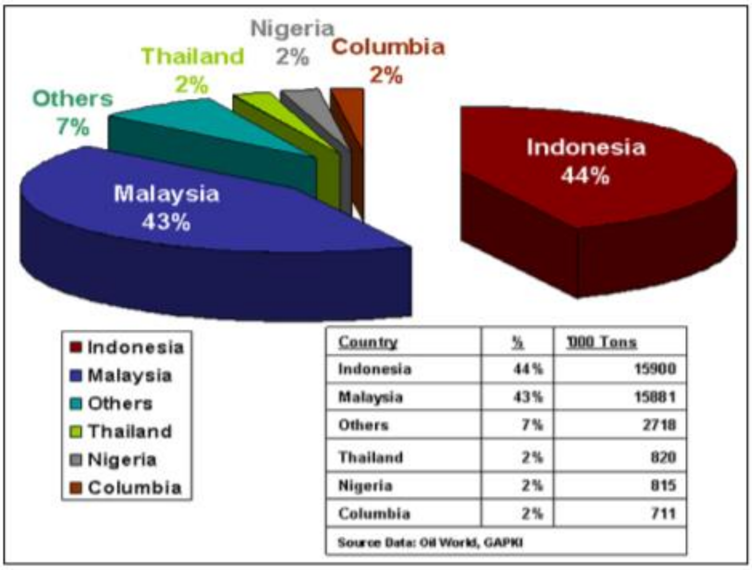


Figure 1.1: Agro-industry of Malaysia.

Generally, there are some processes involve in order to produce crude palm oil and kernels as primary products and biomass as the secondary product. There are up to 6 general process involve which is palm bunches receiving, sterilizer, threshing, mashing and pressing, crude oil clarifying and palm oil kernel recovery. The overview of the process is as shown in the figure.

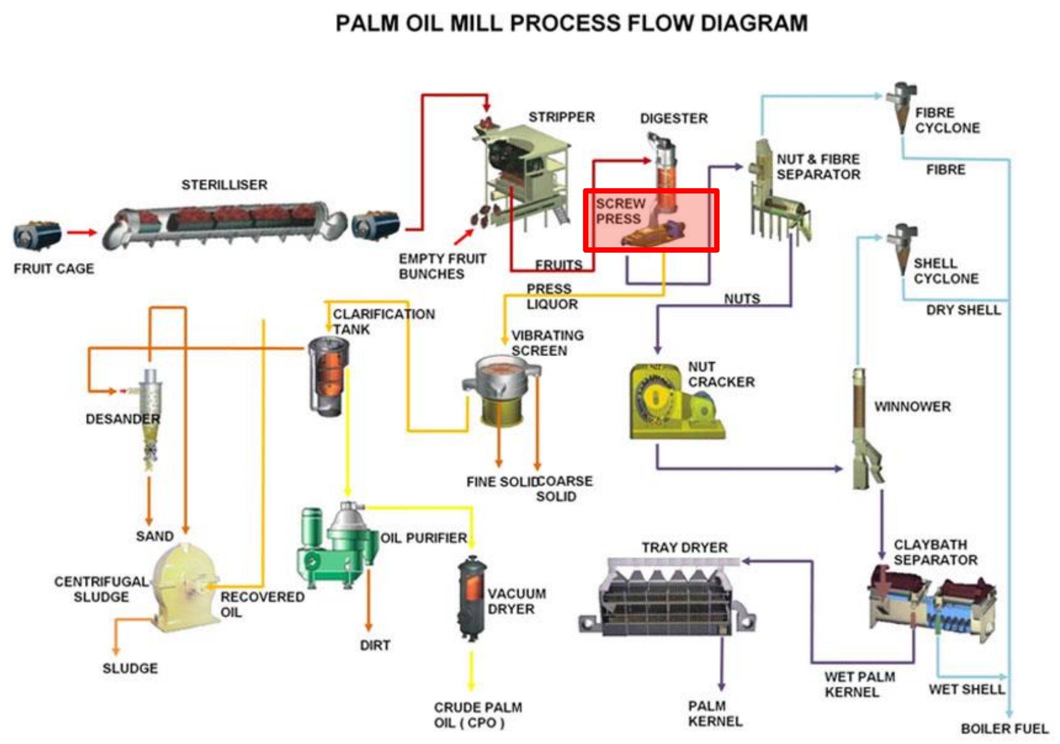


Figure 1.2: Overall process in oil mill industry

Screw press machine is one of the equipment under the palm oil press station that functions to separates palm fruit and kernel (which usually called cakes), and presses fruits which can obtain CPO (crude palm oil) as the byproduct outcome. The continuous process of the screw press can be easily be functional because of cooking, sterilizing, threshing and mashing that undergone through before made the pulp soft and damage to the pulp cell structure, the palm pulp becomes soft and cell is easily broken down.

As it has been seen, the start of the screw press process is right after the fruitlet has gone through the process of digesting. Screw press is known to be the major focus of starting point of the overall process as it gives away two product to process afterwards; the crude oil (for oil clarification) and the nuts & fiber (for separating process). Most of the workers are concentrating towards this process as it has been the deployment of product goods to the other section in the mill. Mainly, the construction of press machine is made up of body, hopper, bed, main shaft, gear, worm and cage gear, bearing, barrel, cone and collar, cutter and tray. The overall components is as shown in the figure

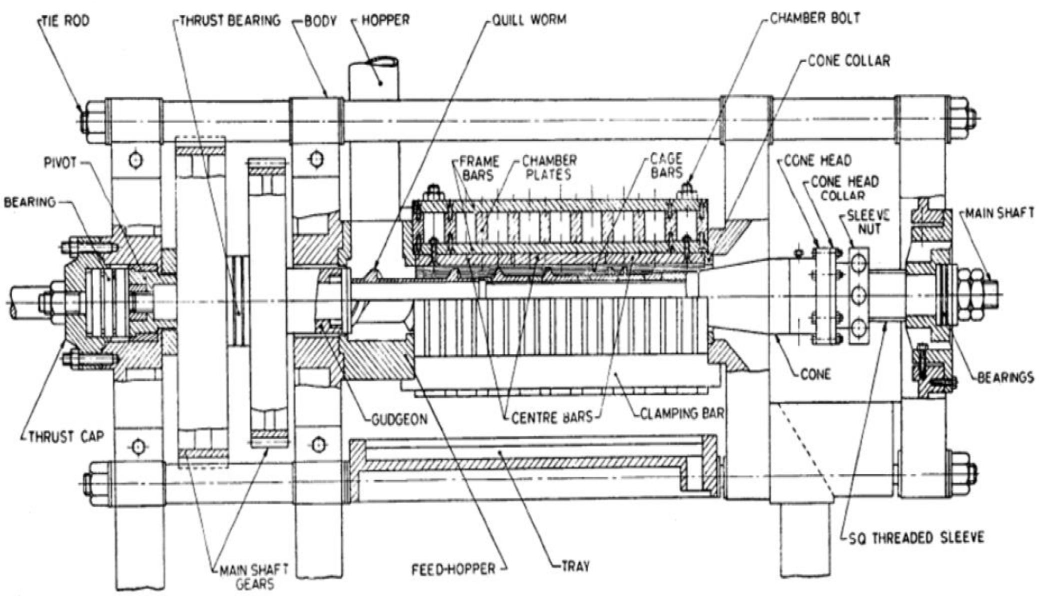


Figure 1.3: Press machine components diagram

Screw press or other called it expellers use a horizontally rotating metal screw, that feeds in oil-bearing seeds (fruitlets) into a barrel shaped outer casing with perforated walls[3]. The continuity of feeding seeds into the expeller, which it grinds, crushed and presses the oil out as it passes through the machine that builds up pressure which ruptures the fruit cells in the product and oil is flowing through the perforations in the casing and is well collected underneath it[3].

The expeller consists of a screw (or worm) which is rotating inside a cylindrical cage (barrel). The configuration of the screw and its shaft are match together led the material to be progressively compressed as it moves on, towards the discharge end of the cylinder. The material that is being fed in between the screw and the barrel are propelled by the rotating screw in a direction parallel to the axis.

In this project, 2 investigation cases are established. The primary case is to investigate the relationship between different pitch lengths of screw towards the pressure development inside the barrel. It is follow by secondary case which will be investigation on the screw speed effect towards the dynamic pressure inside the barrel. These cases are suspected to be affecting the oil extraction in the pressing process.

1.2 Problem Statement

The case study was carried out based on the problem occur in Kilang Minyak Sawit Kamunting Sdn Bhd (KMSK). The associated problem is with the oil extraction of the press machine from the palm oil fruit. From the field work observation, the in-consistent pressure build up inside the barrel is effecting the oil extraction that can be achieve up to only 65% of extraction. There are some residual left in the barrel that is not entirely extracted out from the work. In relation to that, the screw speed and different screw pitch length might affect the extraction process. This assumption need to be investigated and verified. Hence, simulation on the operation of the machine is necessary to verify the claim.

1.3 Objective

1. To investigate different screw design configuration (different pitch length) affect towards the pressure development inside the barrel.

2. To investigate the effect of screw speed on dynamic pressure inside the barrel.

1.4 Scope of work

The field work is carried out at Kilang Minyak Sawit Kamunting Sdn.Bhd, Taiping. The area of focus is on the press machine under the Press Plant Station in Palm Oil Mill. The scope of investigate is specified toward the barrel section of the press machine. Other area section of the press machine will not be discussed in this project. Observation and data gathering is obtained from running simulation of the barrel section. Nevertheless, the simulation will be the key parameter to carry out the all the related investigation cases.

1.5 Thesis Outline

Basically there are five chapters in this thesis which consisted of introduction, literature review, methodology, results and discussion, and conclusion. Each chapter plays an important role in assisting the readers to have better understanding about research which is carried out. The general outline of the palm oil mill processes, the problem statement and the objectives of the work is covered in the introduction. The establishment information of simulation framework of the palm oil is further elaborated in the literature review. In addition to it, it will further discuss about the simulation techniques and types of press machine available. For methodology section, it will be discussing about the simulation procedure to run the press process. Data collection and validation is done after simulation work is finish.

In the section of results and discussion, it shows all the results obtained from the simulation works. Results from simulation works will be validated and compared with other's research findings. The graph of pressure development of press machine will be analysed and discussed. The analysis will be concluded and evaluated in the last chapter by mapping it to the objectives of the thesis.

CHAPTER 2: Literature Review

As a part of the branch in fluid mechanics, computational fluid dynamic (CFD) utilised numerical methods and algorithms in order to solve and analyse problems that involve with fluid flows. Modern tech like computers, performing calculation, CFD simulates the interaction of fluids with surfaces defined by boundary conditions. A set of equations (continuity, momentum and energy) are solved in CFD or most commonly known as partial differential equation (PDE)[4]. These three are the fundamental mathematical statements of physical principles. As CFD have a wide range of application, it allows a detailed analysis of the flow combining the mass, heat, electric, magnetic, and many more to possibly obtain detailed local information on the simulated system. Virtual prototyping is now the standard method to develop new products rather than experiments which are often expensive, time-consuming and some cases are impossible.

A screw press is a press machine that constantly responding (a reactor) which feed is mixed and transported by a screw (auger)[5]. Geometry of the screw (screw flight, restriction size, screw pitch, screw clearance, and other geometrical) will have a direct influence towards the process and the determination of the operational conditions. For example, the factor influencing the mixing of the material in the screw is the clearance and the pitch to diameter ratio (P/D-ratio)[5]. The sort of reactor has some incredible points in application which is utilized as a part of an extensive process, namely conveying, drying, pyrolysis and so on. For a well and deep understanding of the used process, one has to know the exact behaviour of the screw reactor for different parameters. Modelling comes into surface, because it is faster and cheaper than experimenting. It intends to report leading-edge scientific contributions from mathematics, computer science, various sub-disciplines of engineering, management, psychology and cross-cultural communication, all of which focus on the modelling and simulation of human-centred engineering systems. Figure shows an example of a model screw that is simulated using software.

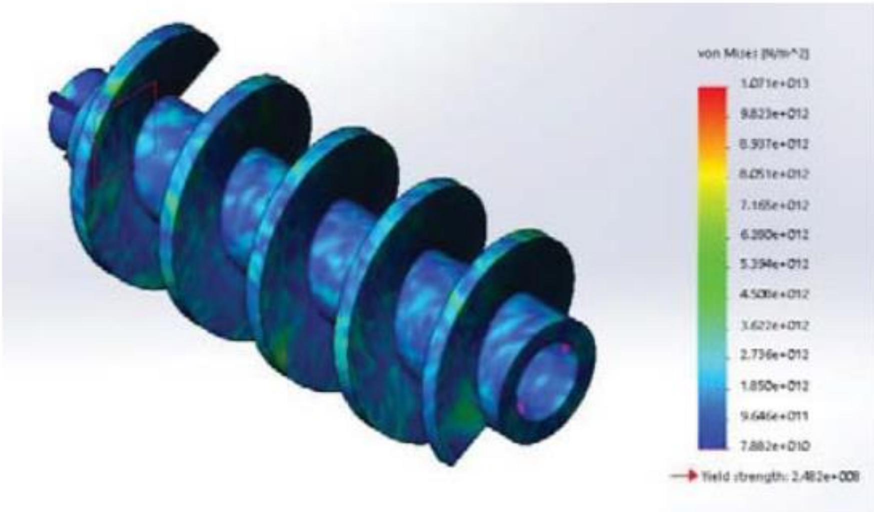


Figure 2.1: Example of simulation of screw press model

It has been recognized that the variables which influencing oil extraction process originates from the screw speed, restriction size, hull content, moisture content, temperature and pressure[6] . Pressure plays a critical part in contributing towards the accomplishment of more prominent yield production of the press machine operation. This contributor needs a further investigation study for the examination of strategies for effective plan control.

2.1 Type of press

Press machine created back in 90's and toward the future it had experienced through some change which basically grow its utilization. There are different sort of screw had been create and the outline relies upon the application (regardless of whether it in small, medium or large scale industry). For small scale oil industry (capacity of 5 tan per hour) utilizes a single screw press to their work. Typically, the oil process industry had experienced through some change by replacing the single screw press with double screw press these days[7]. This is because of the well versatile adaption of the double screw in mill industry helps in producing a higher yield per day compare with a single screw operation. Twin press (double screw) prone to have a better match up with the work environment due to the following:

1. Simplicity and reliability: only few moving parts and compact cross section make the feeding system simpler in construction and more reliable in operation.
2. Good metering characteristic: it is an important feature for a feeder to obtain accurate control of the feeding rate.
3. Wide application: screw flights can be modified to suit different processing requirements, e.g. cut flights, folded flights (or a combination) can be used for pre-breaking of lumps, mixing, blending bulk material.

Certainly screw press also have some disadvantages, such as:

1. Due to the relative rotation of the bulk solid within the screw, mechanical efficiency for transport is low;
2. Because of the existence of the clearance between the flight and the trough a screw feeder may not provide a self-cleaning action;
3. Hard foreign bodies can get into the space between the flight tip

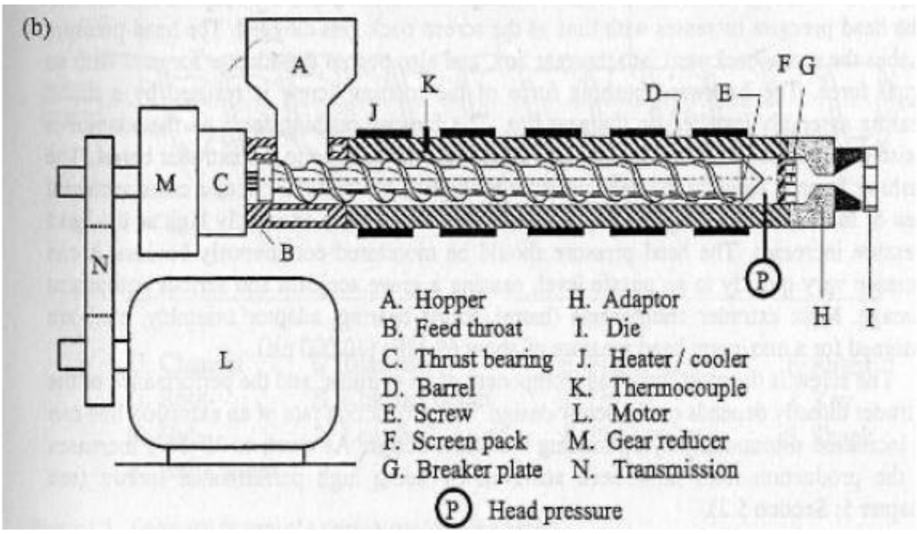


Figure 2.2: Single screw press machine

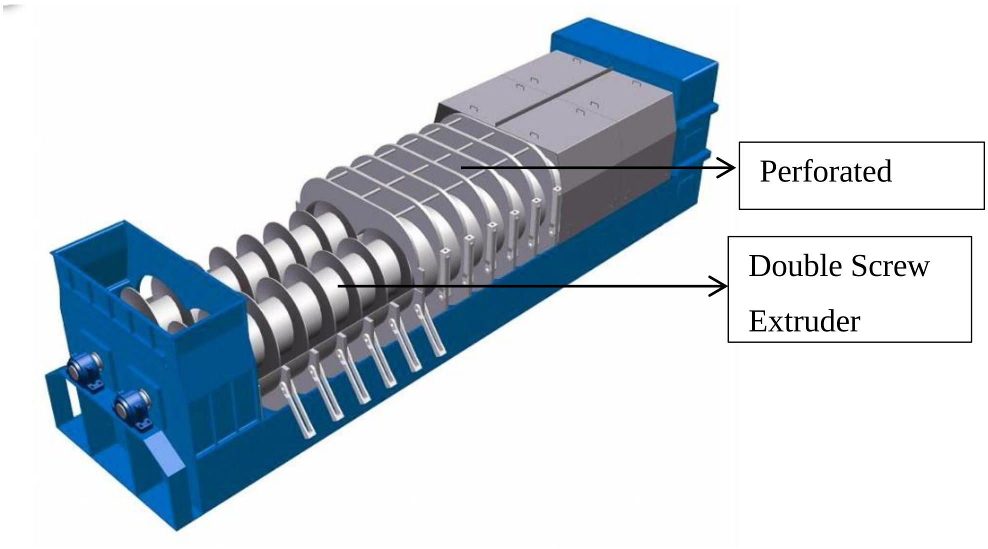


Figure 2.3: Double Screw press Machine

2.2 Associated problem with press machine

The malfunctions of the press machine can be categorized in two categories[7]:

	Construction of the screw press	Auxiliary Parts
Geometry	namely the whole unit, main parts (press cage, screw flight and adjusting cone)	driving motor, gear box, hydraulic module
Problem associated	lifespan of the machine's parts	susceptible to impairment

Due to the relatively intense duty, with the fluctuations in the quality of the oil palm fruit presence, it increases the load factor on the system. Double screw press system experience earlier malfunctions of its parts compare to the single screw press system. It is understandable, as a higher processing capacity does have an unfavourable effect on the lifespan of the machine's parts. In this project, it will be focus on the relationship between the press cage (barrel) and the screw extruder as it has been identified as the problematic ones. Progressively, readers will be exposed to the deep study between these two constructions.

2.3 Orientation of the twin extruder

Twin screw extruders can be grouped by the screw rotation and relative positions of the screws[5]. The classification of twin screw extruders are indicated Figure 2.4. To begin with, the sorts of twin screw extruders can be separated into two gatherings: co-or counter rotating twin screw extruders in terms of screw direction. Second, they can be ordered as non– intermeshing and intermeshing twin screw extruders as per the relative position of the screws. Moreover, the intermeshing type of twin screw extruder is separated into two as completely and partially intermeshing twin screw extruders.

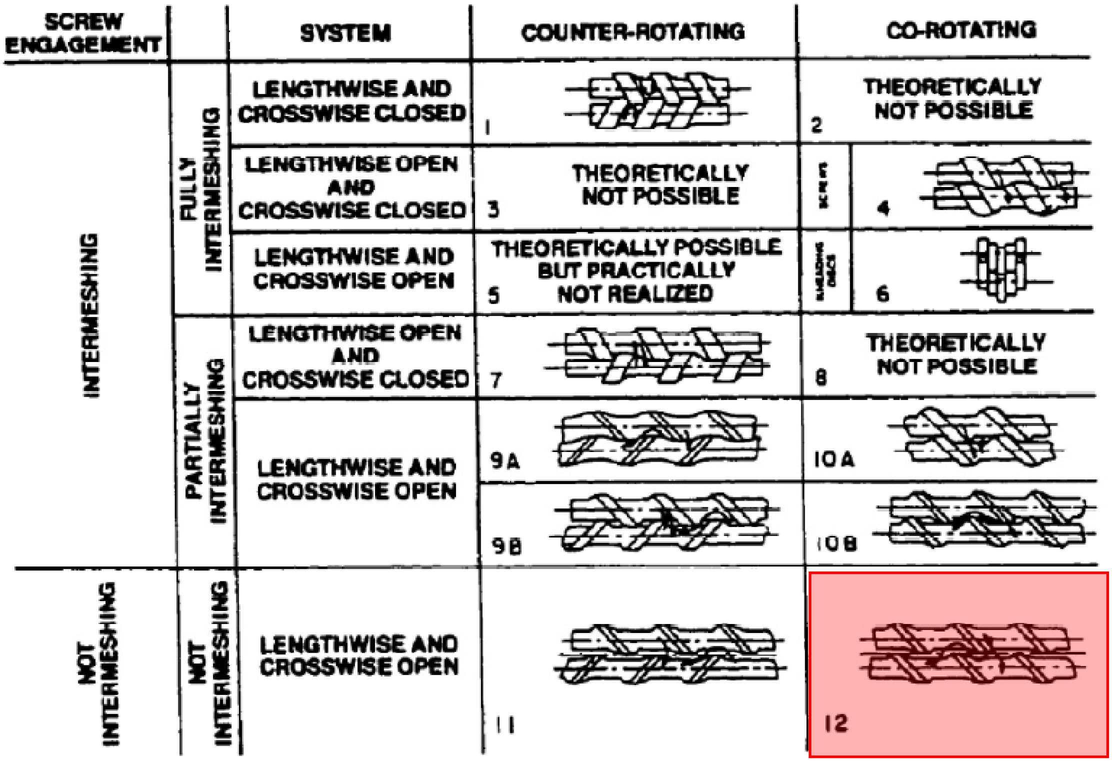


Figure 2.4: Orientation of screw expeller

http://www.industrial-electronics.com/engineering-industrial/process-plant-mach_18b.html

KMSK use the positioning of non-intermeshing with matched type along with co-rotating extruder. The full machine specification is shown in the appendix.

2.4 Techniques of simulation

There are up of 4 simulation techniques can be implement in the simulation work. Each of the technique has their own pro and cons that will be discuss in the table shown:

Table 2.1: Advantages and Disadvantages of Simulation Techniques

Type of Techniques	Concepts	Advantages	Disadvantages
Sliding mesh	As two or more cell zones are used, Each cell zone is bounded by at least one "interface zone" where it meets the opposing cell zone	Simulating flow in multiple moving reference frame	Computationally demanding
Single reference frame	Computational domain to be referred to a single rotating reference frame	Walls can be defined which are non-moving with respect to the stationary coordinate system	Single axis of reference
Multiple reference frame (MRF)	It is a steady state approximation in which individual cell zones move at different rotational speeds.	Appropriate to use when the flow between zones are nearly uniform	-
Dynamic mesh	Mesh motion methods that are available to update the volume mesh in the deforming regions subject to the motion defined at the boundaries	Cell grid changes shape	-

After analysing the techniques, the most appropriate technique to be use in the simulation work is the dynamic mesh. This actually gives most accurate solution involving rotary type of machine. In this undertaking, the dynamic mesh can't be implemented in the project as the ANSYS Software is an understudy version (Student version). In this manner it is consider alright in using the multiple reference frame (MRF) technique for the simulation work.

2.5 Challenges of simulation

Three main difficulties arise when solving the simulation work[8]. The first is that to deal with moving geometries, the screws, in a fixed barrel

Secondly, considering its modular construction, co-rotating twin screw extruders can be easily adapted to work with oil press systems with more strict specifications. However, their geometrical flexibility makes the performance of these machines strongly dependent on the screw configuration. Therefore, the definition of the adequate screw geometry to use in a specific oil press system is an important process requirement which is currently achieved empirically or using a trial-and-error basis. However, regardless of the screw geometry it does not give any disturbance to the current objective of the project.

Lastly, is to deal with a viscosity that is a function of position, shear rate and temperature, and that can change orders of magnitude in the high shear regions. This challenge is the most difficult among the other.

2.6 Simulation strategies

As there are many challenges apprehend in the work there are bound to ease load of the problem by making several assumption. Classical assumptions were made for computing the viscous flow, the assumption is as follows:

i. The flow is transient;
ii. Fully developed and isothermal;
iii. There is no slip at the screw nor at the barrel walls;

There are two type of simulation work can be done[8]. The first the simulation is simulating the overall process. The overall process is made up 3 zones respectively[9]. The first zone is known as feeding zone; this zone is where fruit mash is fed to the screw press, as it will be immediately subjected to a force induced by the screw turning. The second zone is known as compression zone. Toward the start of this stage, oil is streaming out consistently from the fruit let at a little yet steady flow-rate. As more fluid is exit out in this zone, the fluid droplets will coalesce and form bigger ones along the way. Flooding of the fruit mash is bound to happen. Gravity in this case has no significant impact on the fluid dispersion. In the long run, as pressure keeps developing, the flow rate will increment to a maximum value which shows the finish of this stage. The tendency of oil to be absorbed by the fibre is likely to happen. The last zone otherwise called the metering zone. Now, the void between the fruitlets is filled with oil. The applied pressure from both screw extruder and hydraulic compression will be applied for a specific period of holding time. This allows complete extraction process of oil from the fruit mash.

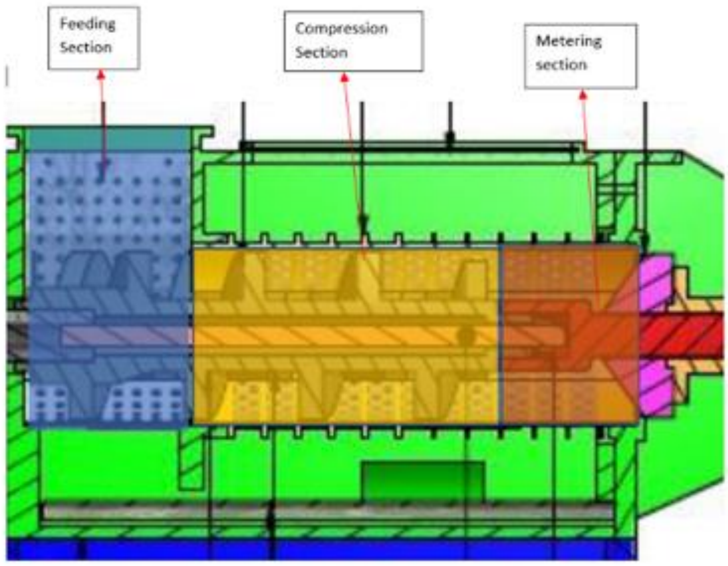


Figure 2.5: Zones in press machine

The second type of simulation is simulation of a particular zone of interest between these three zones. It can also be a combination of two zones (feeding zone and compression zone or metering zone and compression zone). This project interest is only in simulating the barrel section (compression zone). As of today, there is no simulation software that is capable of simulating granular form that will change to form plugs. So as for alternative, simulation as fluid particle as already the default in ANSYS program is simulated for the work. The perforated cells of the barrel in this case can be neglect and it is assume that the oil is flow from inlet to the outlet (axially manner) in a completely confined space. For meshing section, it is chose to use the tetrahedral elements (cells) for the project analysis. It is found that using tetrahedral finite element permitted the most accurate mesh generation for a complex fluid domain[4].

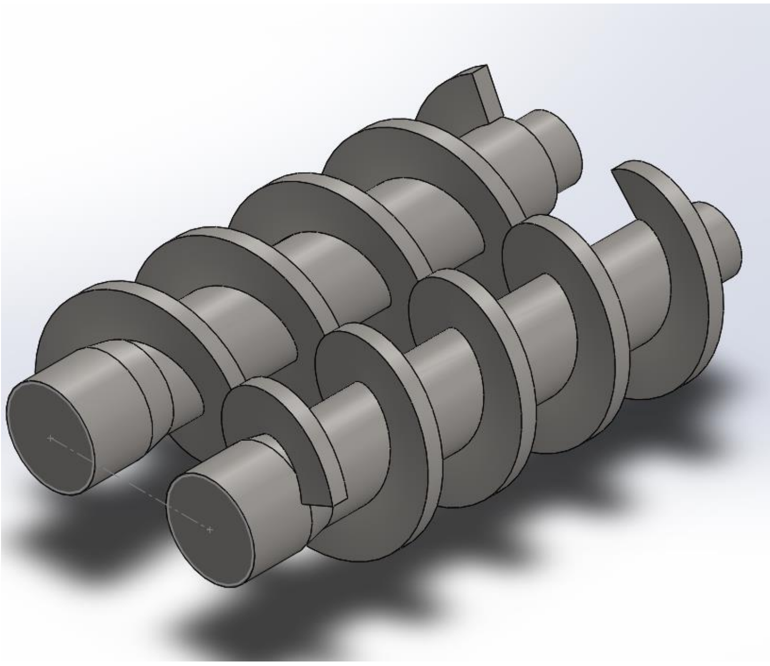
CHAPTER 3: Methodology

3.1 Scale down

In order to run the simulation work, the first step is to create the geometry model of the double screw extruder (see appendix). The best way to do it is by scaling down the dimension of the real press machine. The table shown is the dimension of the model that will be used in the simulation work.

Table 3.1: Dimension of Screw Model

Scale ratio 1:3		
	Machine dimension (mm)	Model dimension (mm)
Length of the screw	1180	393
Diameter of the screw	229.8	76.6
Pitch of the screw	219	73.3
Thickness of the screw	34.7	11.6
Clearance between screw and reactor	0.6	2
Distance screw to screw	375	125



For it to be consider as model, dimensional analysis must been done towards it. The dimensional analysis is powerful tool that retain the scaling law of the physical quantities. Generally, there are 3 criteria that must be achieved for it to be considered as good model. The criteria are as the following:

- Geometrical similarity

- The model and full scale structures must have the same shape

- Kinematic similarity

-Similarities of velocity (Geometrically similar motions in model and full scale)

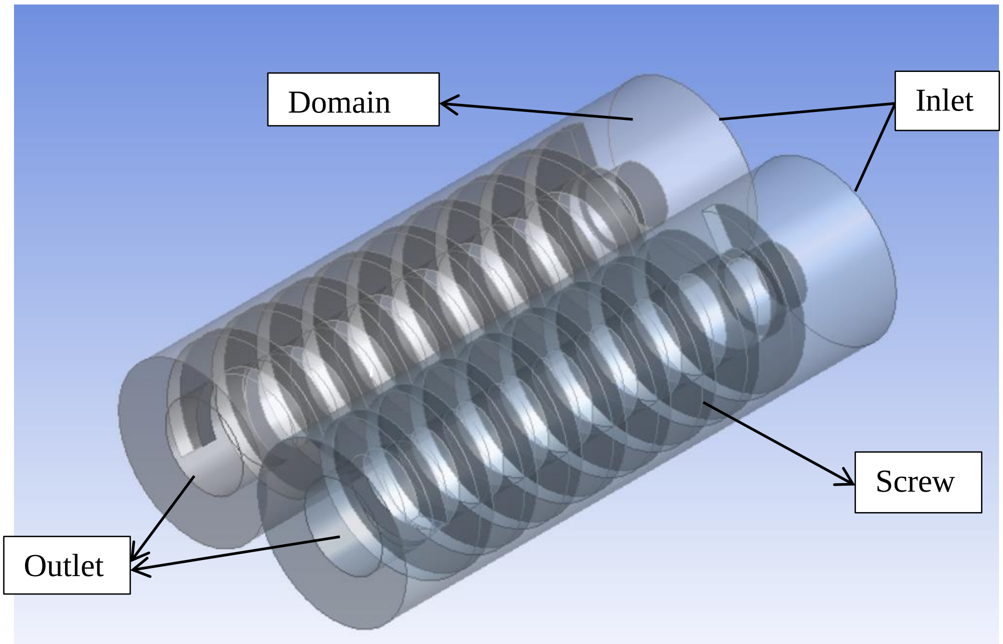
- Dynamic similarity

- Geometric similarity with combination of similarity of forces

Similarity of forces: Ratios between different forces in full scale must be the same in model scale

3.2 Model creation

Using SOLIDWORK 2013 software, the model of screw press expeller is developed (represented in figure). The geometry of the screw press expeller was partitioned into a few zones for grid generation and CFD study purpose. An unstructured grid was generated using ANSYS Meshing. After the process had been done, solution setup was established for FLUENT, and boundary conditions and initial conditions were specified. CFD solution for the domain was determined, and the results were analysed according to the requirements



3.3 Grid generation

The grid generation for CFD analysis of a complex geometry is very high demand job. Unstructured grid modelled the boundary outline very accurately whereas structured grid produce high demanding job of computation involving complex geometry. Because of this reason, unstructured grid is use in the simulation work. Mesh sensitivity test had been done to determine the appropriate mesh size for the simulation work, for it to have a well balance computational cost and time. The result is as follows:

Table 3.2: Result of Maximum pressure using different element size

Size of element (m)	1/ element size (m)	Maximum Pressure (Pa)
0.001	1000	1.86 x 10^1
0.002	500	1.86 x 10^1
0.003	333.33	1.86 x 10^1
0.004	250	1.49 x 10^1
0.006	166.67	1.33 x 10^1

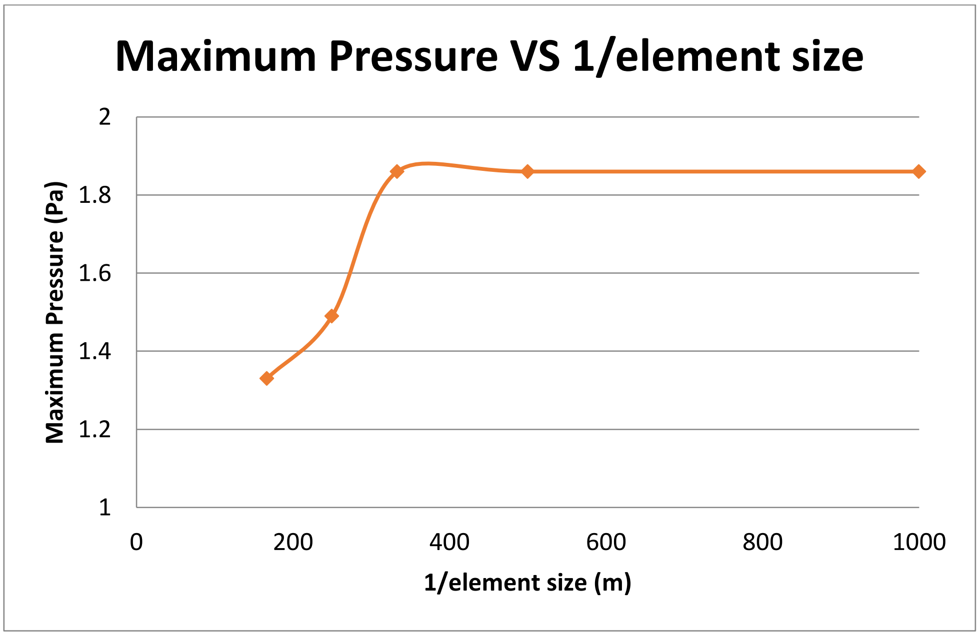


Figure 3.1: Maximum Pressure versus 1/element size

From the graph, it can be concluded that using the mesh size of 0.004 m is the appropriate sizing which is coarsened enough to save the computation time and cost.

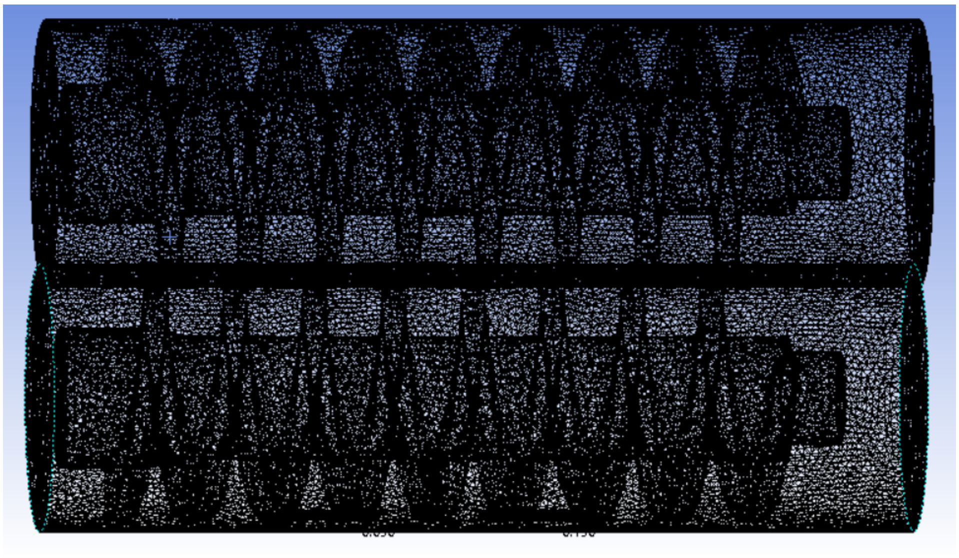


Figure 3.2: Geometry with 0.004 m mesh size

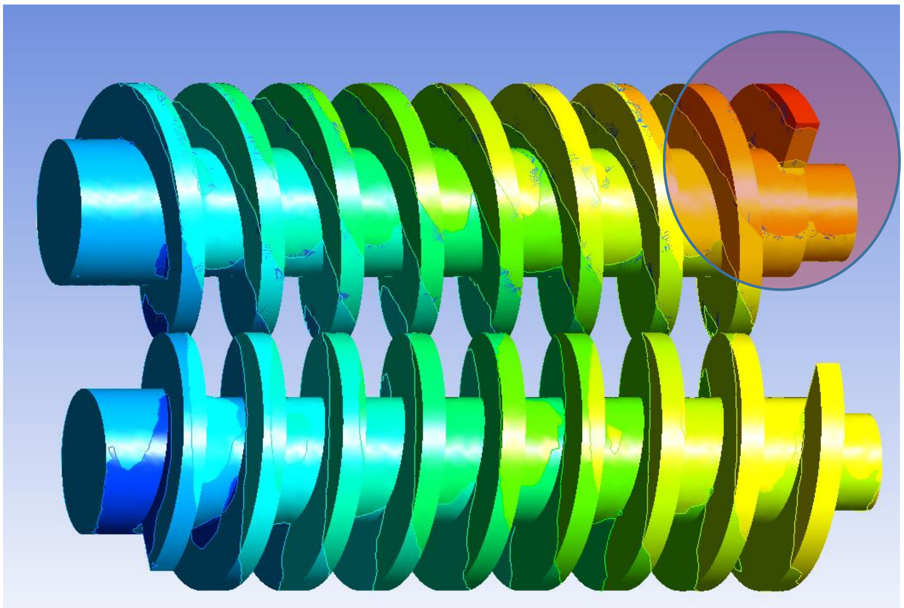


Figure 3.3: Location of interest (Inlet screw number 2)

3.4 ANSYS fluent setup

3.4.1 Physics- Laminar flow

The flow inside the barrel is a laminar flow[4].As mentioned in the chapter 2, it is not possible to simulate granular flow that changes into a plug shape in ANSYS software. As alternative way, fluid flow particle can be representing the granular flow with certain specific properties. There are two important properties one is density and the other is viscosity. The bulk density of biomass is a function of moisture content. The range is around 500 to 900 kg/m³. Viscosity came from the kinetic and frictional models for granular flow that already discuss in [5]. Figure below show the fluid property of palm oil.

TECHNICAL INFORMATION					
PALM OIL PROPERTIES					
Tempdeg. C	ViscositymPas	Heat Capacity KJ/kg-C	Conductivity W/m-C	Density kg/m3	ViscositycST
20	106.8	1.848	0.1726	890.1	119.99
25	77.19	1.861	0.1721	887.5	86.97
30	57.85	1.875	0.1717	885	65.37
35	44.68	1.888	0.1712	882.5	50.63
40	35.41	1.902	0.1708	880	40.24
45	28.68	1.916	0.1704	877.5	32.68
50	23.68	1.93	0.1699	875.1	27.06
55	19.88	1.944	0.1695	872.6	22.78
60	16.93	1.959	0.1691	870.2	19.46
65	14.61	1.973	0.1687	[illegible]	16.84
70	12.75	1.988	0.1683	[illegible]	14.73
75	11.23	2.003	0.1679	[illegible]	13.01
80	9.99	2.018	0.1675	860.7	11.61
85	8.955	2.034	0.1671	858.4	10.43

Properties of the fluid

Figure 3.4: Properties table of palm oil[10]

When the fluid properties are set, the boundary conditions must be defined. The boundary condition is defined as the following:

Table 3.3: Boundary conditions of the domain

	Barrel	Screws	Inlet	Outlet
Velocity (m/s)	No slip	Rotating wall	Fixed value (0.0055m/s)	-
Pressure (Pa)	Gradient	Gradient	Zero gradient	Zero gradient

A mass flow rate of 491.6 kg/h is given at inlet which gives an inlet velocity of 0.0055 m/s (calculation is in the appendix).

3.4.2 Kinetics- Moving & Stationary block

There must be distinctive blocks that are pre-defined for the necessity of computational run. The whole domain was divided into moving and stationary blocks as the moving block contains the fluid which has radial as well as axial velocity components while no-slip configuration applies to the stationary block. The following figures show the block components:

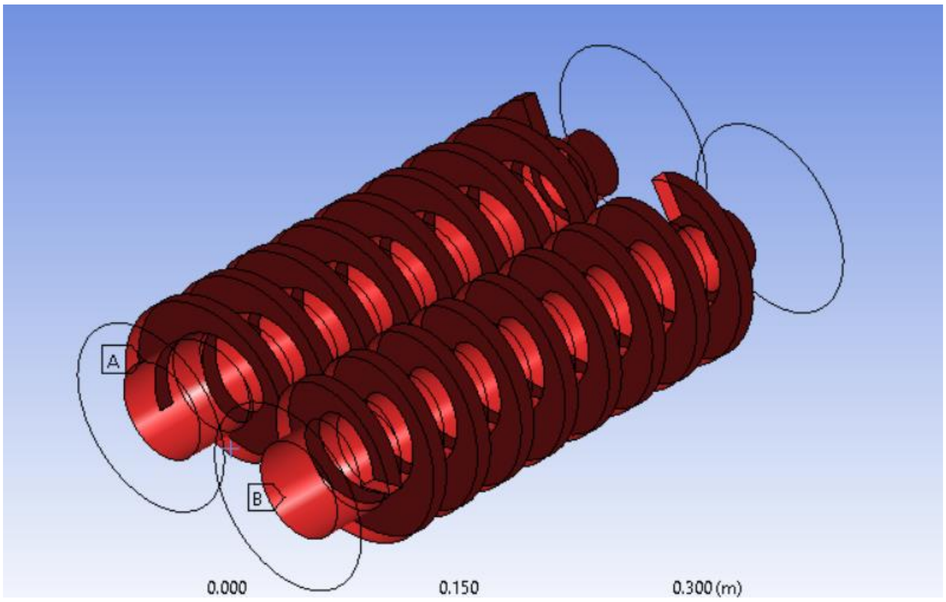


Figure 3.5: Screw 1 and screw 2 as the moving block

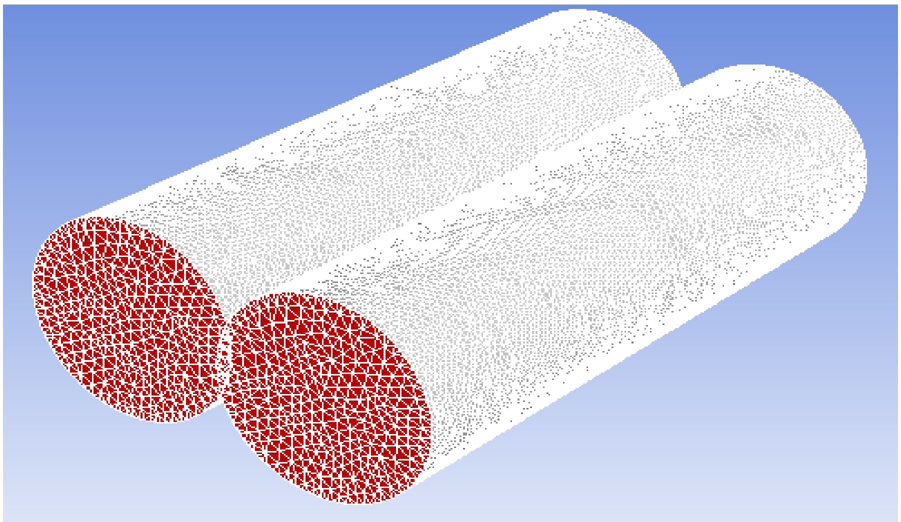


Figure 3.6: Inner domain as the moving block

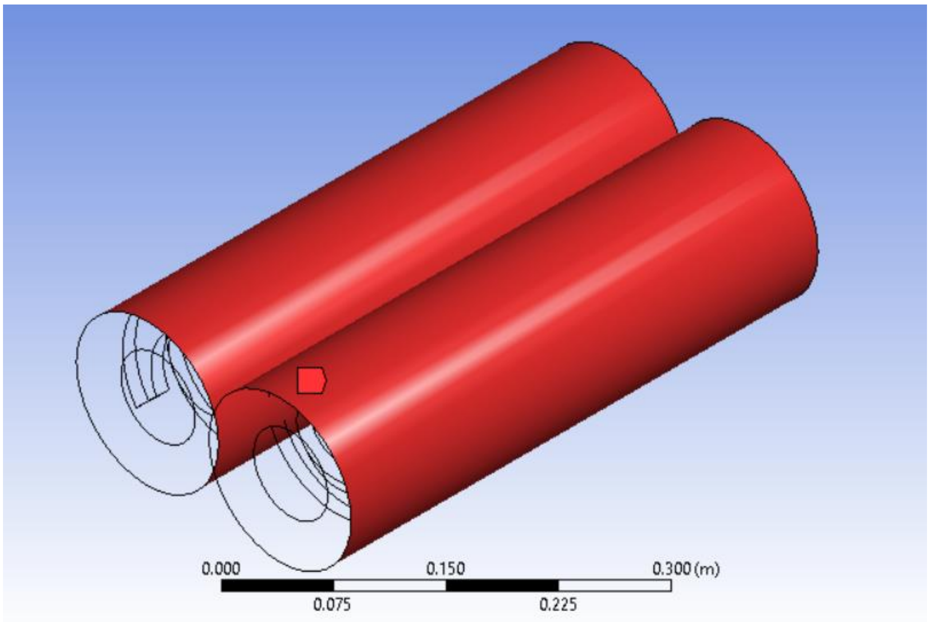


Figure 3.7: Barrel as the stationary block

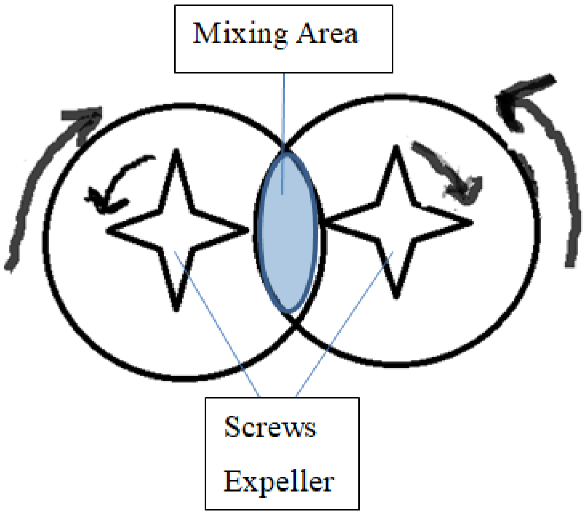


Figure 3.8: Rotating direction both the screw and the domain

3.4.3 CFD solution set-up

Using a multiple reference frame (MRF) technique of FLUENT, an inner zone (moving wall) is rotated at 7 RPM while the outer zone (barrel) is kept stationary. A mass flow rate of 491.6 kg/h is given at inlet which gives an inlet velocity of 0.0055 m/s. A transient simulation of 10s was done while keeping the speed of the both screws at 7 RPM. The key model assumptions are listed in Table below for the screw press expeller simulation. The simulation was repeated using different pitch model (40 mm, 50 mm, 60mm, 70mm, and 80mm) with same rotational speed and using different screw speed configuration (5 RPM, 6RPM, 7RPM, 8RPM, 9 RPM) with constant pitch model.

Table 3.4: Key Model Assumption

Mesh Generating Tool used	ANSYS Meshing
CFD solution tool	Ansys Fluent v.18.0
Grid type	Unstructured grid
Blocks	Stationary block (stationary wall) Moving block (moving wall)
FLUENT CFD techniques	Multiple reference frame technique (MRF)
FLEUNT Solver	Pressure based Steady and Transient Absolute velocity formulation Pressure velocity coupling scheme: SIMPLE Spatial discretization: 95 Gradient: Green-Gause node based Pressure: Second order Momentum: second order upwind Transient formulation: First order implicit
CFD Specifications	Wall Boundary Conditions with Rotational Velocity of the Moving Reference Frame: Wall: Moving wall/stationary wall Motion: Rotational Shear conditions: No slip
Post processing	Contours of pressure

CHAPTER 4: Result & Discussion

A CFD investigation of the screw press expeller was directed for a few reasons, and results were obtained. The CFD investigation of the screw press expeller uncovered the dynamics flow inside the barrel and over the screw, as the simulation procedure was to decide the relationship between different pitch length and speed with the pressure development.

4.1 Raw Data & Interpretation of Data

<u>Contour Pressure Plot of Screw (Different Screw Speed)</u>

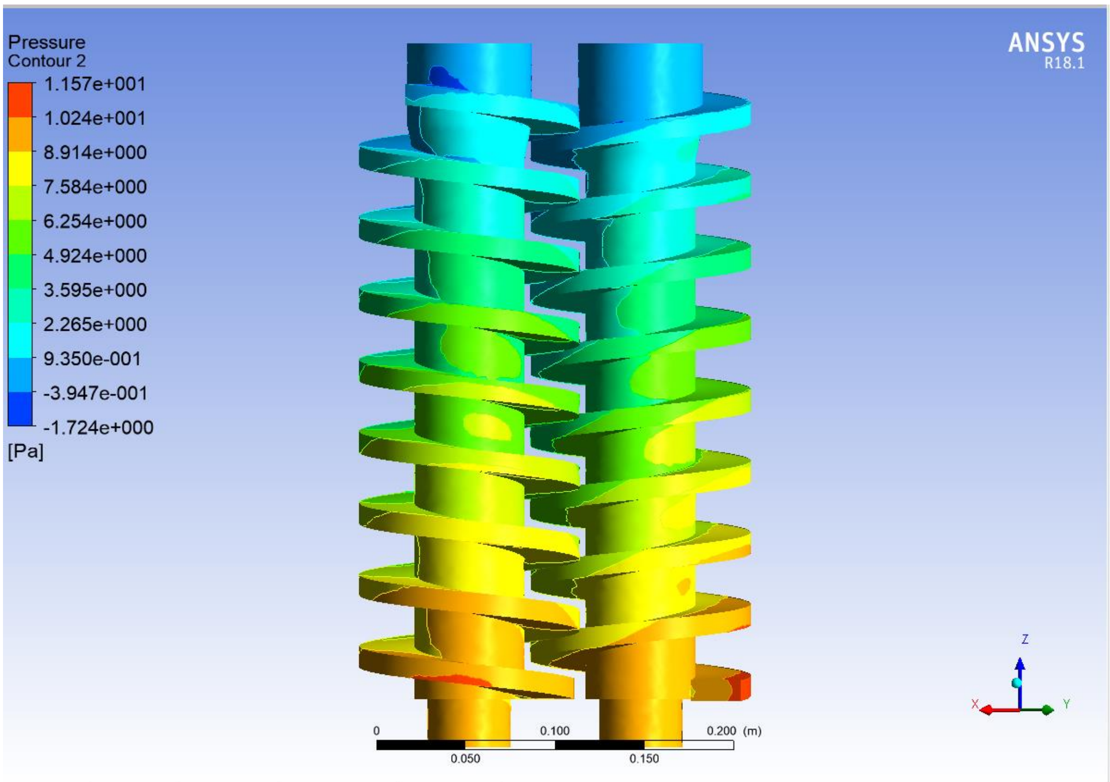


Figure 4.1: Screw Speed of 5 RPM

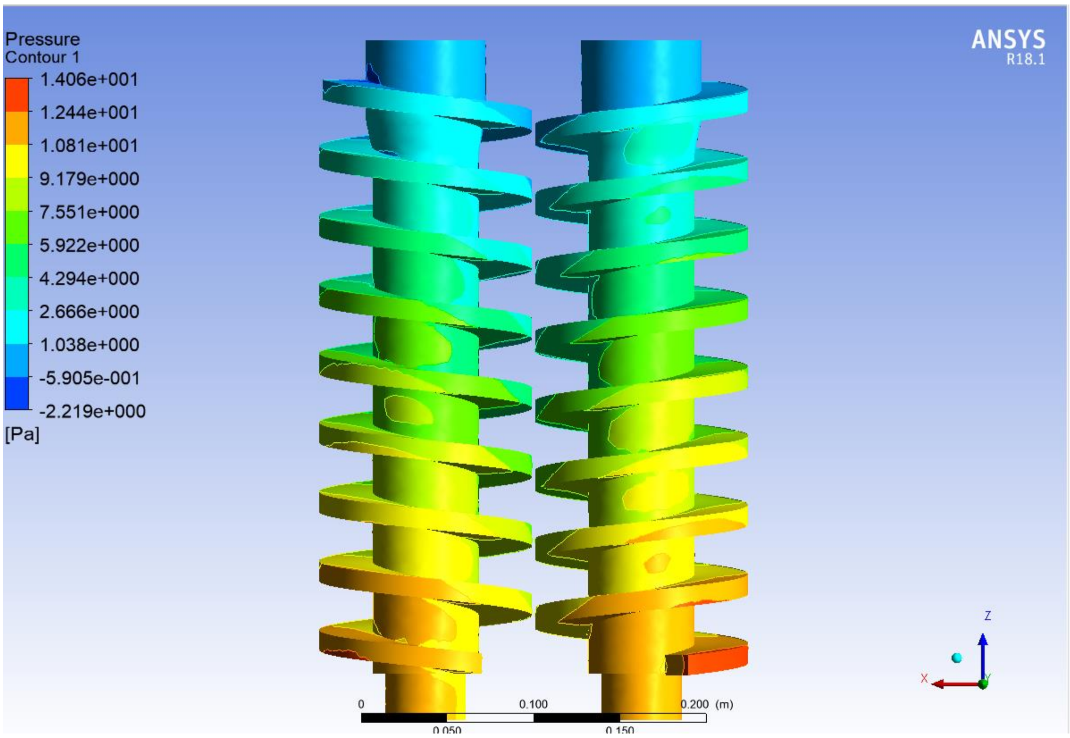


Figure 4.2: Screw Speed of 6 RPM

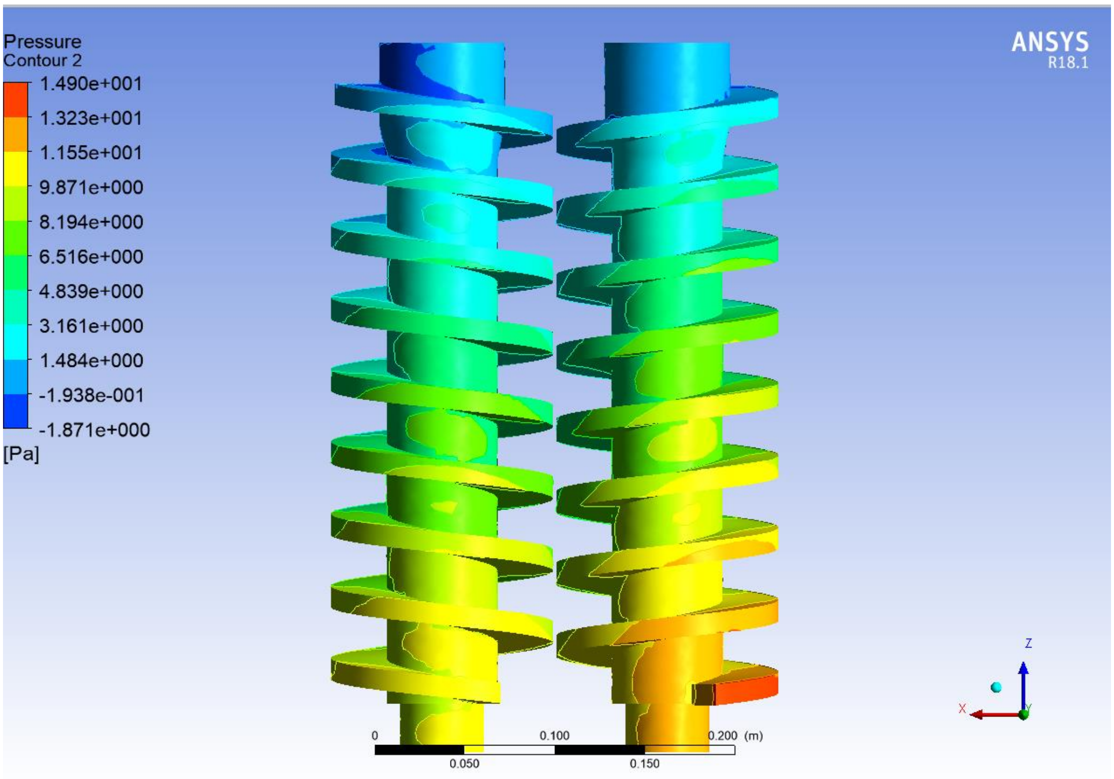


Figure 4.3: Screw Speed of 7 RPM

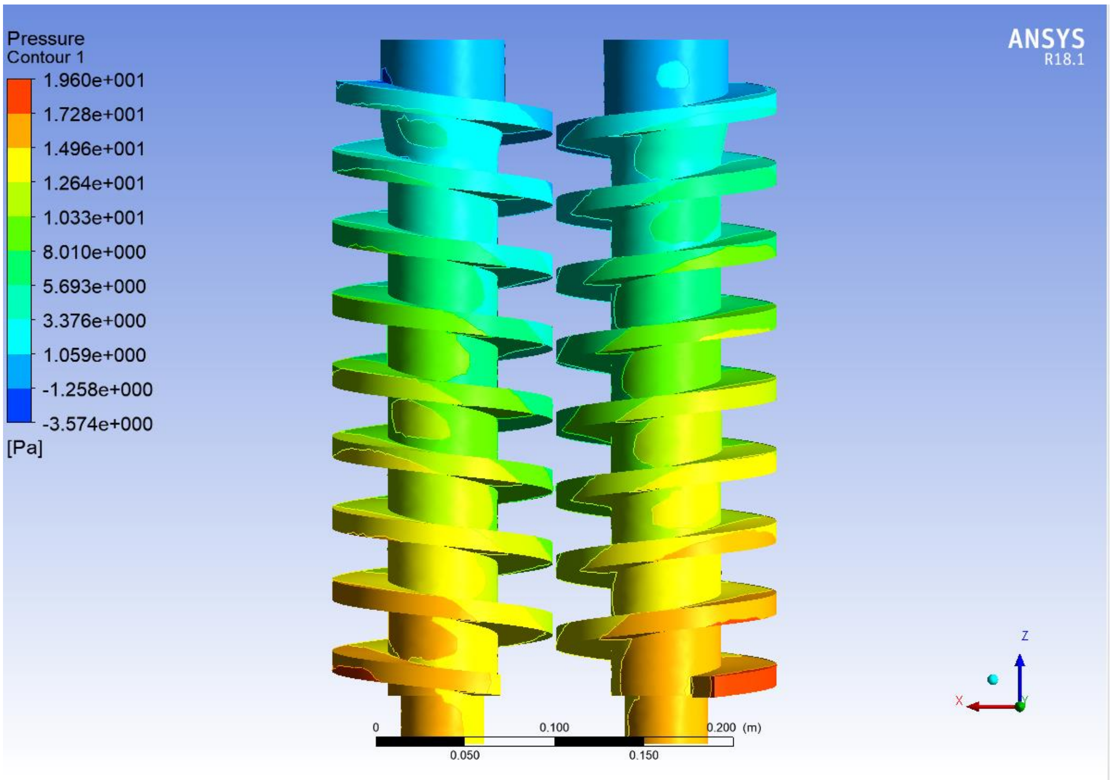


Figure 4.4: Screw Speed of 8 RPM

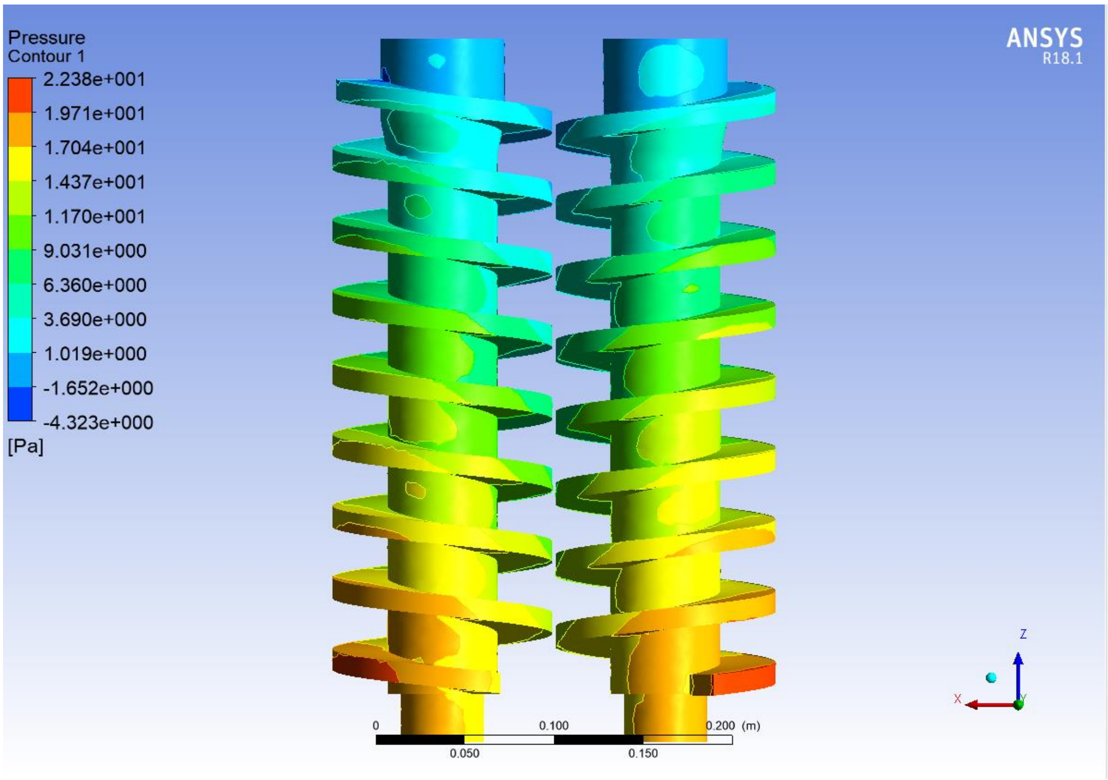


Figure 4.5: Screw Speed of 9 RPM