CFD Based Modeling and Performance Analysis of Single/Twin Extruder

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Dedication

This thesis is dedicated to my beloved parents and siblings for their unlimited support, moral encouragement, and incalculable love

Acknowledgments

All acclaim and eminence be to **"ALLAH''** a definitive creator of this universe, who endowed us with the ability to comprehend and made us curious to investigate this entire universe. Infinite greetings upon the leader of this universe and hereafter **"HOLY PROPHET HAZRAT MUHAMMAD (P.B.U.H)"**: the wellspring of beneficial information and blessings for whole humankind and Uma.

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Abstract

This thesis work is done at the SCME, NUST under MS (Process System Engineering) program. The idea behind this effort is to design and model the Single and Twin-Screw Extruder and determining the local residence time distribution (RTD) by utilizing CFD simulation software FLUENT developed by Workbench Inc. available at the SCME.

The subject work has wide range of applications in process industries such as polymer, food and pharmaceutical in which two immiscible fluids with one have very high viscosity are mixed to get mixture having desired properties. The basic goal in mixing viscous immiscible fluids is to produce a mixture with a desired structure. The structure might be the morphology of a polymer blend or the drop size distribution of an emulsion.

The objective of this work is to model a viscous fluid mixing system using CFD codes. Workbench 21.2 (CFD software) available at SCME is utilized to carry out this work. The major stages involved in this thesis, are creation of geometry of single and twin-screw extruders developed using Design Modeler (component system in workbench) and meshing of the geometry to discretize flow domain. The geometry is exported to FLUENT to simulate the system by solving the CFD equations.

Two immiscible fluids i.e., Ethylene Vinyl Acetate (EVA) and Ethylene Glycol (EG) are selected for mixing. **Ethylene vinyl acetate** (also known as **EVA**) is the copolymer of ethylene and vinyl acetate. The weight percent vinyl acetate usually varies from 10 to 40%, with the remainder being ethylene. It is a polymer that approaches elastomeric materials in softness and flexibility, yet can be processed like other thermoplastics. The material has good clarity and gloss, barrier properties, low-temperature toughness, stress-crack resistance, hot-melt adhesive water proof properties, and resistance to UV radiation. Ethylene glycol is mixed in ethylene vinyl acetate as compatibilizer in cable insulation manufacturing. In this study EVA 28420 is selected because of comparatively low viscosity making the problem simple. The problem is set up in CFD software, FLUENT. Multiphase mixture model is used for transient simulations. The unsteady state of simulation is used because at each time step the meshes move to a new position, coinciding the flow mesh. The fitting boundary conditions of velocity inlet are set for the inlet and by default out-flow is set at the outlet. The screws are rotated 200 rpm for both conveying screws.

As a results total pressure contours, velocity magnitude contours, shear stress contours, volume fractions contours and vorticity magnitude developed in flow domain and mixing index is evaluated. At the end RTD analysis was carried out for both the screws using a tracer injected through inlet into the flow domain and calculating the molar concentration at the outlet.

Key Words: Mixing Index, Single screw extruder, Twin screw extruder, Dispersive Mixing, Distributive Mixing

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Chapter 1

Introduction

Extruders either single screw or twin screw are being widely used in polymer which are being developed since 1840. They are usually good in pressure built-up ability, therefore mainly used for transmission and propelling polymer melts into the molds to manufacture useful shapes. Twin extruders have screws which can counter rotate or co-rotate and are extensively used in polymer manufacturing, in chemical industries and different food industries due to its great mixing ability and self-cleansing properties[1]. In extrusion processing goal is to physio-chemically convert highly viscous polymeric material and make best quality products by regulating processing techniques. A twin-screw has two screws, intermeshing on a shaft inside a barrel. There are a vast range screws and barrel designs available with which numerous screw designs and processes can be established rendering to requirement. The major plus of intermeshing co-rotating twin-screw extruders is that their mixing ability is remarkable, which gives unusual features to extruded product.

1.1Background

In extruders, the material used can be solids (i.e. powder or granular), liquids and slurry etc. Products we get are plastics, modified polymers, edible products and feeds.

Extrusion is a key process, used in making of many food and other products. It is a thermo-mechanical method where mass and heat transfer, change in pressure and shears come together to produce effects for example kneading, cooking, drying, melting, texturizing, conveying, pounding and forming[2]. In extrusion, the process is completed by means of an extruder and a die to get different shaped and size of the products, suggesting the status and likely large spread applications in different industries [2].

Extrusion process can also be carried out in manufacturing cooking food products through extrusion cooking. It is a very adaptable food producing technique, which permits manufacturing food of varying quality. In extruder, different processes take place which are cooking, mixing, shear, cooling and shaping. For the past many years, a lot of changes happened in extruders to new trends and requirements, demand and supply and changes in raw materials. Today, a lot of edible products are made through extrusion cooking process. Due to material variations in extrusion cooking process, process parameters and product quality is very limited. Hit and trial approaches frequently controls product expansion and process expansion on large scale for extrusion process[3].

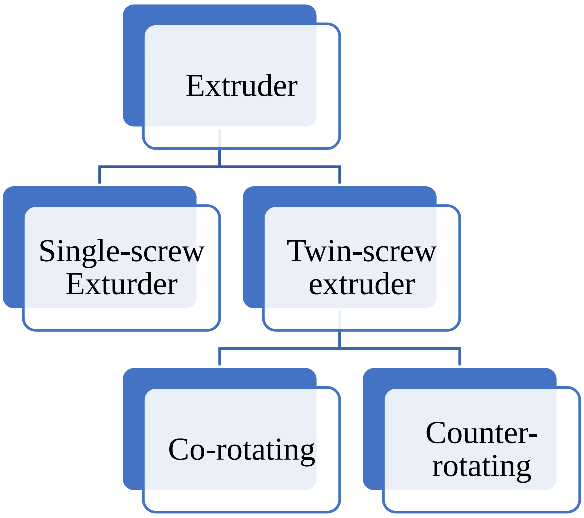

Fig 1: Extruder Types

1.1.1 Single-screw Extruder

Single-screw extruder converts mechanical energy to thermal energy, utilizing to melt polymers. Extruder is fed with feed and is controlled by speed of screw. Screw is made of helical flights with a lead distance (distance covered by screw in complete turn of 360^o) normally equal to the screw diameter. Root diameter of screw should be enough to handle torque. Our area of interest in this project work is the mixing section which acts as pump to drag the material forward. In screw mixer a sufficient pressure is needed to be generated at the inlet to overcome the resistance created in the machine due to presence of die at the exit. Due to this back pressure the material tends to flow back to the inlet. Capacity of an extruder is determined by

$Q = Q_d – Q_p$

Q = Net capacity of the extruder

Q_d =Volumetric forward flow.

Q_p =Volumetric back flow.[4].

1.1.2 Twin-screw Extruder

While single-screw extruder has an advantage of friction between barrel and screw, the twin screw extruder capitalizes on interaction of two screws. They are classified as non-inter-meshing co-rotating, counter-rotating counter rotating and inter-meshing co-rotating and counter-rotating. In non-inter-meshing counter-rotating extruders, flow remains same as single screw extruder, but screws reorient as fluid flows between them. It achieves mixing only when it is full. It is well enough for distributive mixing but gives poor dispersive mixing. Intermeshing counter rotating extruders consists of essentially closed C-shaped chambers. There is milling effect with good elongational flow and good dispersion between flight and channel. These regions have low volume which undergoes high shear and potential over heating there by limiting screw speed and capacity. The most used extruder is co-rotating inter- meshing screws extruder. The inter-meshing counter-rotating twin-screw extruder has areas with low volume experiencing high shear and overheating. Therefore restricting screw speed and capacity of extruder[4].

The co-rotating twin-screw extruders are present in fully inter-meshing manner and are used extensively in polymer processing industry for compounding, blending, reactive processing etc. The flexibility of the machine to some extent rises from the integrated forms of the extruder, subsequently several machinery producers suggest corotating twin screw extruders with inter-changeable barrel and screw segments. Therefore, in the age of flexible engineering, where producers are commended to move from one product to other, using the identical equipment, the multipurpose twin screw extrusion expertise plays an important role. Though, to each time a new screw and barrel arrangement is accumulated, the extruder becomes a new machine[5].

Twin-screw extruders are being widely used in reaction, de-volatizing applications. For reactive extrusion, extruder is used as chemical reactors for polymerization, chain modification in melt form of polymers. But the phenomenon of melt-flow, heat transfer, and other reactions could be multifaceted and inter-linked with each other.

When the alterations in polymer occur in twin screw extruder, it primarily depends upon the residence time, the time that the polymer is in fact going to spend inside extruder. The time, polymer spend inside extruder reflects the quality of the product, reaction efficiency, degradation extant, and mixing quality.

However, residence time distribution in twin-screw extruder is very had to perform due to high viscosity and non-Newtonian behavior of polymer melt[7].

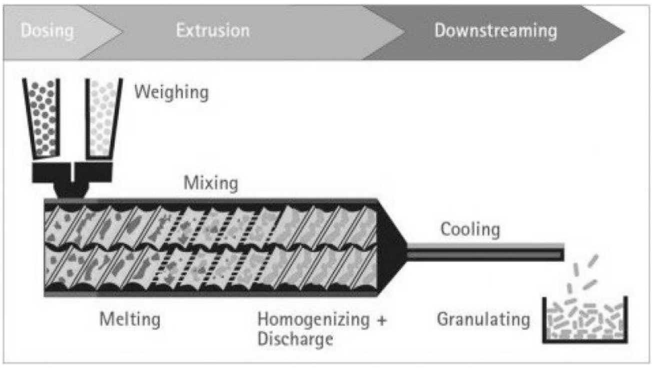

Fig 2: Extrusion Schematic Diagram

The screw is a major part of extruder or extrusion system. Screw pushes the highly viscous feed by increasing pressure from hopper to die, where melt takes the desired shape of the product. An extruder has three zones mainly: feeding zone, plasticization zone, and metering zone[8]. The product quality mainly depends on screw geometry, screw configuration, screw speed and residence time. Different span of time, the melt spends in the extruder its exhibits different properties on to the product. So, screws are the most important part of any extruder as its speed determents how much time the material will spend in the extruder and this time is very crucial for any product. If it remains for long time in the extruder the material may burn out or if it spends less time in there, the material may not cook properly before going into the mold or die[8]. There are various types of extruders as shown in Figure 1.

Polymer extrusion process is used widely for manufacturing tire components, hollow profiles, food industry, and medical equipment. Extrusion molding is low cost and more efficient. Extrusion process uses thermoplastics which undergo repeated melting and hardening. Waste is reused, rather discarded. Raw material is cheaper and disposal cost is low. Extrusion provides flexible products with consistent cross section. The extrusion molding can produce complex shapes. This process is used to produce frames, doors, window etc. in automotive industries and also building and Construction Material[8].

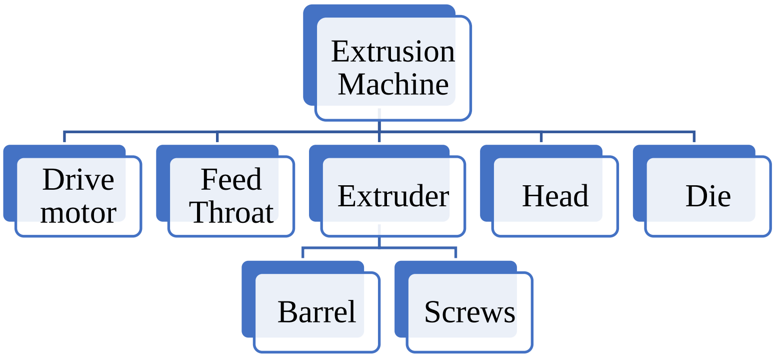

Fig 3: Extruder Sub-parts

Table: 1 Comparison of Single & Twin Screw Extruders

Item	**Single-Screw Extruder**	**Twin-Screw Extruder**
Conveying Element	Conveying through friction	Forced to slide forward
Self-Cleaning Function	Unavailabe	Excellent self cleaning
Running	Stable and occasional Blockage	Stable and reliable
Heat Distribution	Non-Uniform	Uniform
Ingredient Adaptability	Common	Wider
Moisture Content	10%-30%	5%-95%
Product Variety	Limited	Various
Machine Price	Cheap	Expensive
Capacity	Common	High

1.2 Viscous Fluids Mixing

Viscous mixing is used in processes, where the viscosity is adequately high and turbulent mixing is unattainable or high energy dissipation causes high product temperature. Mixers, handling viscous materials, are essential to encourage both linear and transverse motion, when a material or more than one materials are being pulled, sheared, compressed, and kneaded against vessel walls[4].

Mixing is a process in which the non-uniformity of a mixture is being reduced. Mixing, in viscous systems is a difficult task. There is no turbulent flow to distribute the components throughout flow. Diffusion coefficient is very low due to high viscosity[4].

Mixing of viscous systems can be achieved by any mechanical action or by shear and elongational flow. These are termed as dispersive mixing and distributive mixing.

1.2.1 Dispersive mixing

It is defined as breaking, the agglomerates or lumps of dispersed phase to preferred size. Thus, dispersive mixing is basically the result of imposing mechanical stresses on the mixture.

1.2.2 Distributive mixing

It is defined as mixing of two fluids, such that separation is minimized to a level where chemical reactions or diffusion occurs. Basically, viscous mixing is a blend of dispersive and distributive mixing; dispersive mixing is used to break down the agglomerates, and distributive mixing spreads the broken phase throughout the mixture[4].

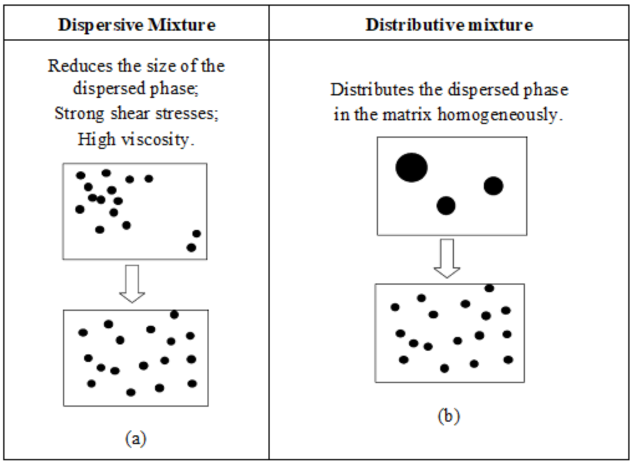

Fig 4: Morphology of dispersive and distributive mixing [4]

1.3 General Principles:

In any process industry such as polymer, pharmaceutical and food processing mixing is very significant unit operation. It is used to produce products of requisite specifications. Mixing reduces non-homogeneity in any blend or a mixture of different components. Homogeneity occurs in concentration, phases, and temperature. Mass transfer, reaction rate, and product quality also play an important role. In a mixing process, materials undergo continuous changing because of shear rate which varies from location to location. High viscous fluids mixing is much complex than less viscous fluids because of the absence turbulent eddies in the mixing domain to effect diffusion. Other difficulties associated with viscous fluids mixing are that many of them are non-Newtonian (means viscosity varies quickly with shear stress.) and temperature builds up during mixing due to viscous energy dissipation. Viscous mixing requires both dispersive and distributive mixing for better mixing. Mixing of fluids can be miscible or immiscible[4].

1.3.1 Miscible Fluids Mixing:

Miscible fluids have no inter-facial forces between them. Dispersed phase experience elongating, compacting to very thin layers until complete diffusion occurs, though it is low in matrix phase. Phenomenon is shown in Fig 5

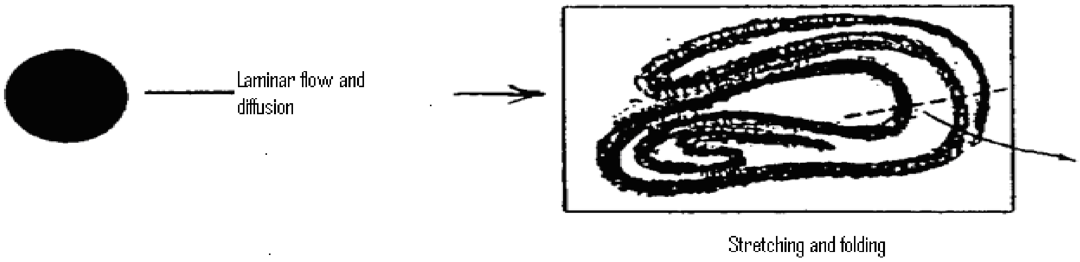

Fig 5: Mixing and diffusion in miscible fluids

1.3.2 Immiscible Fluids Mixing:

When two immiscible fluids are mixed, one fluid turns into dispersed phase as precipitations in the second fluid, forming a continuous phase. Liquid-liquid mixing is an example of immiscible fluids. Both the fluids meet a solvent that dissolves one of the fluids. Continuous stirring causes one fluid to disperse in second fluid and if particle size is small, an interface is formed for inter-phase mass transfer. When stirring is brought to a still, separation of phases may occur but if the particles are too small then a stable diffusion layer may form in spite of an interface, preventing the separation. Examples of immiscible fluids mixing are stable emulsions in food, brewing, and pharmaceutical applications.

First of all, mixing of immiscible fluids is done by folding of blobs and then by stretching, breakup, and coalescence of each particle. At first dispersed phase is embedding in continuous phase. As the time lapses, large agglomerates break into smaller particles. Due to this breakup morphology of particles is determined[9]. The phenomenon is shown in the figure 6.

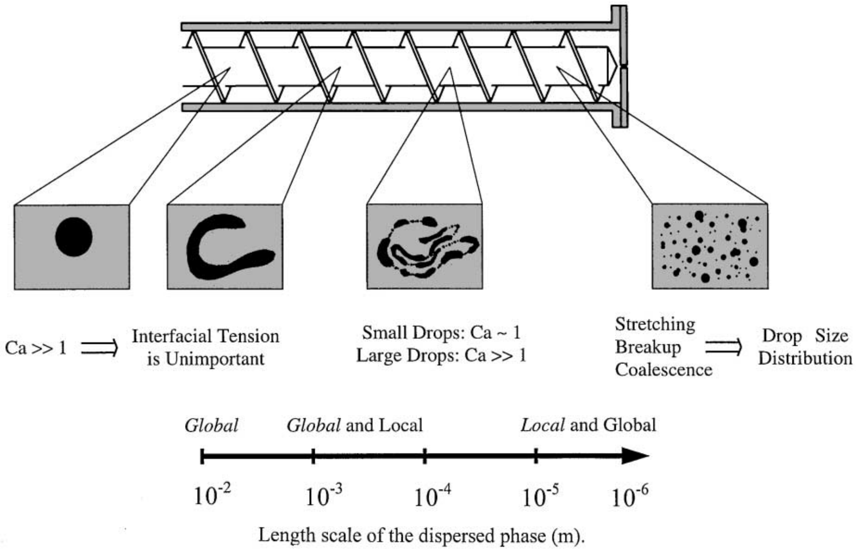

Fig 6: Mixing of immiscible liquids

At inlet of a full flight single screw extruder the Ca number is high which means viscous forces are much larger than interfacial forces and dispersed phase is present in the shape of large blob. The material is subjected to shear stress and stretching by the action of screw movement and large blob of dispersed phase is stretch into long thread and interfacial forces between phases increase and at certain stress the dispersed phase is broken into small drops. A process of extrusion continuous small neighboring drops coalesce to form large drop. This process of breaking and coalescence compete to effect mixing of dispersed phase in the continuous phase.

1.4 Viscous Fluid mixing Equipment:

Mixing of high viscosity fluids cannot be mixed with the help of conventional impellers such as turbine or propeller stirrer. High viscosity is linked with low-mixing Reynolds number ($Re = \rho D^2 N/\mu$) may be less than 100. The requirement for highly viscous fluids mixing is to development of deformation in the fluids. This deformation can be brought by shear stress in the fluids but simply shear is insufficient. Additional complexity of the system must be sufficiently incorporated for improving mixing. When the feed passed through narrow pathways, pressure drops and dispersion occurs[4].

Viscous fluids mixing equipment must have narrow clearance between screw and barrel wall, low screw speed, small volume, and high power. There are two major classes of mixers for the viscous fluid.

- Batch mixers
- Continuous mixers

1.4.1 Batch Mixers

Batch mixers enable mixing fluids and have two centrifugal pumps to deliver fluids to other units. Batch mixers can hold large volumes of fluids. These are single stirrer mixers which may be of anchor blades or helical ribbons. The latter is preferred as they give axial mixing and consumes less power than anchor blade mixers. For high viscosity fluids which are mostly Non Newtonian too anchor blade mixers are not recommended because their central motion do not produce agitation at the vessel wall[4].

1.4.2 Continuous Mixers

Recently mixers are used extensively in mixing operation replacing batch mixers because of low power requirement, less material hold up in the machine and continuous product attainment. But mixing efficiency can be reduced due to broad residence time distribution. So very accurate metering is required in continuous mixers[4].

Screw extruders are most used continuous mixer which has two major classes.

- Single-screw extruder
- Twin-screw extruder

1.5 Residence Time Distribution (RTD)

1.5.1 RTD Definition

When any material in liquid state or viscous state passes through a reactor in steady state, numerous segments of fluid does not pass through the outlet at the same time rather at different times which reflects that there is a distribution of residence time of reactor. This is called residence time distribution[10]. Residence time distribution is of importance for any unit operation.

There should be a control on reaction rate, catalyst activation, heat transfer, and mass transfer for better mixing and residence time inside reactor. That’s why residence time distribution data helps us understanding the fluid dynamics. This data is critical for reactor’s design, expansion, operation, and optimization[11].

Residence time distribution, as we know in solids, poses certain problems. Residence time distribution in solids depends on concentration and velocity. Finding best tracer materials and detection methods is very problematic in solids. In order to measure residence time distribution, there are certain requirements which needs to be fulfilled[12].

- Measurement sensitivity should be high i.e., using small amount of tracer is beneficial.
- Reproducible measurement in a certain time period.
- No assumptions for ideal conditions.
- Any detection device or method used, should not affect the internal flow pattern.
- Residence time distribution is measured in steady state.
- Detection method of residence time distribution should be fast.

Tracing method which is basically an experimental determination of RTD is implemented in vast range of industries and laboratories[13].

1.5.2 Functions for residence time distribution E (t)

Residence time distribution is typically measured, by injecting a tracer in feed stream at time t=0 and then measuring the concentration of tracer in exit stream as function of time[14]. Tracer has the properties like the bulk feed and is chemically inert but completely soluble in bulk. The tracer does not get adsorb on reactor surface.

Common and simpler tracer injecting methods are pulse, and step input[15].

1.5.3 Pulse Input

Tracer is injected rapidly in a small interval of time inside a reactor. Concentration of tracer is measured a function of time at outlet. An illustration of step input and output and pulse input and output is given in fig.8. Pulse input is much challenging to perform experimentally than step input.

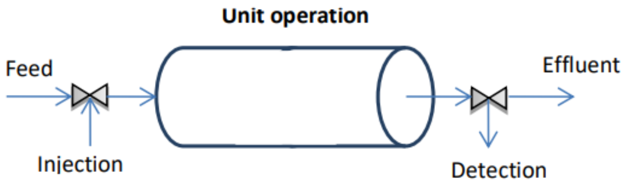

Figure 7: Experimental set up to determine E(t).

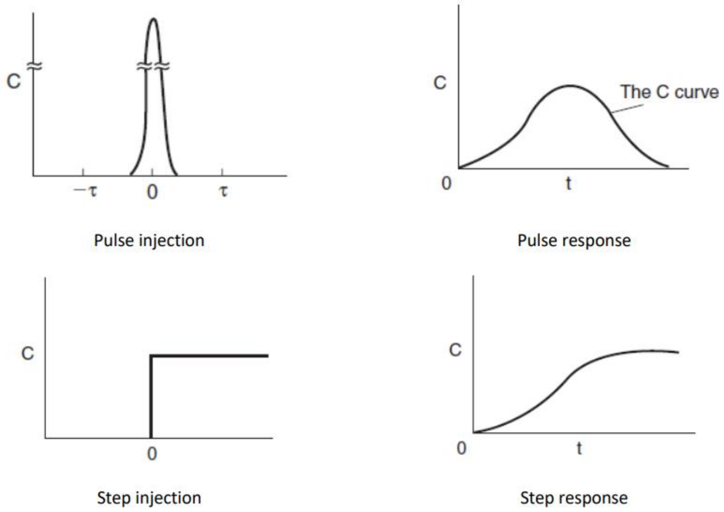

Fig 8: Typical concentration curves for a step and pulse inputs

1.5.4 Step Input

Large amount of tracer is required in feed stream. Tracer amount in feed stream is known over the experimental time. It is mandatory to maintain the tracer concentration in feed stream. Results obtained in step input gives large errors[14].

Chapter 2

Literature Review

P. Cassagnau et.al studied that mixing of viscous fluids is very vital process, which is being carried out in process industry, but its mixing efficiency measurement is quite a difficult task. They introduced a UV tracer (Hydroxymethyl anthracene) for EVA. A colored batch was made with 1% tracer in the molten EVA. EG tracer was also physically prepared distinctly. The resulted RTD for each phase in the mixer is found by using a UV fluorescence device at the outlet. They took a dual screw extruder whose diameter was 34 mm and had L/D ratio of 35. EVA is introduced as molten state at a temperature of 140^{o} C. Experiments were carried out on three different geometries with slight differences to enhance mixing. Residence time distribution of EG was calculated at different speeds and at different flow rates of EG. It was resulted as that at higher flow rates, the lubrication effect plays vital role and increased residence time is witnessed. Shear effect will be enhanced at higher speeds and way more dispersion is projected. They concluded that high screw speed and higher flow rates increases the RTD and hence mixing will get better[19].

L. Yerramilli et.al using an equipment called **Laser Doppler Anemometry** inspected the velocity distribution in the translational region of self-wiping twin-screw co-rotating extruder. Experimentation was done using Newtonian fluids to evaluate mixing efficiency of kneading section of the machine and velocity distributions to know about the flow field. Screw pitch effects of the screw geometry can also be observed in flow field. Mixing index was determined. Results concluded that if screw pitch and screw speeds are increased then that have a significant leakage flow as well which increases the mixing efficiency. Finally they concluded that in translational region of extruder, dispersive mixing is more than distributive mixing[20].

P. DeRousselet.al solved numerically the Stokes equations to model the initial mixing for two phases. Different methods had been used for this purpose which are, Volume of Fluid (VOF) method, moving mesh methods, the marker and cell technique. Mapping methods had been developed so it was possible to use that methodology to multiphase systems as well. All those methods worked well for the mixing and each one had its own advantage, according to the problem[9].

Robin K. Connelly et.al used 2D finite-element-method (FEM) simulation with particle tracking for the study of mixing capability of both single and twin-screw extruders. For a dough mixer, they used poly-flow (CFD code) using Carreau's fluid model to develop both velocity distributions and particle trajectories. The FEM simulation used a rotating reference of frame in single-screw extruder and the mesh superposition technique (MST) in twin-screw extruder. Results for difference in velocity profiles were concluded. Distributive-mixing was assessed visually and by the segregation scale and cluster distribution index. Stretching was gauged using length of stretch. Mixing efficiency and dispersive mixing were estimated using mixing index and shear stress[21].

B. Alsteens et.al varied geometric parameters like stagger angle and disc width and studied mixing efficiency of kneading section of a twin-screw extruder. Poly-flow (CFD code) and finite element model (FEM) of governing equations discretization is used. The mixing effectiveness is calculated in parallel with the residence time (RTD) and by launching virtual particles in the flow domain they assessed the total shear[22].

A. Shah et.al used Flow Network Analysis (FAN) technique to study the effects of elongational viscosity on a flow, using power law model in twin-screw extruder for a 3-D simulation. For this purpose, twin screw geometry was developed with screw tip diameter of 29.6 mm and screw root diameter of 21mm and screw lead of 30mm. Only fluid domain was simulated with three different viscosity models. Simulation results concluded that, axial component of velocity in inter-meshing region of extruder is max. When elongational viscosity increased, axial component of velocity decreased. Pressure decreased from high positive value on outlet to a negative value on inlet of the extruder. When they kept rotating speed at constant, pressure increased and elongational viscosity of polymer increased[23].

Ivan Gajdos et.al aimed to introduce a new design for the construction of single-screw extruder. A rotational-barrel segment which considerably changed kinematics of single-screw extruder's movement, was yet not been evaluated using numerical method or at laboratory level. Using ANSYS Poly-flow, a 3-D FEM model of rotational barrel segment in single-screw extruder was built, adopting the Mesh Superposition Technique. To numerically simulate the problem, behavior of melt flow in the rotational barrel segment was evaluated. Simulation gave results that integrating a RBS for an extruder is a correct idea.[17].

Dapeng Sun et.al used ANSYS Poly-flow and gave a correlation among the flow, mixing and reactions in preparing PP/TiO2 in co-rotating twin screw extruder (TSE). Effects of speed of the rotating screws, flow rate and initial temperature on the mixing efficiency and reaction process were examined. Results revealed that operative and geometric parameters, determining the mixing efficiency, residence time distribution, and temperature, affects the species concentration and reaction rate, having influence on conversion rate. Results showed that when rotational speed or inlet flow rate were increased then mixing efficiency has decreased, not advantageous for thorough reaction. Increasing the stagger angle had an opposite effect. Initial barrel temperature greatly affected the conversion rate[6].

Prashanth S Ra et.al reported that in plasma reactors for the pellet production, an intermeshing counter-rotating twin-screw extruder was more consistent among the different extrusion techniques. CFD modeling was effectively carried out in POLYFLOW, using Mesh-Superposition Technique. Using Herschel-Bulkley equation, the shear rate of solid hydrogen was modeled. Neglecting inertia and gravity simulated flow in the extruder, involving flow through the calendar, tetrahedron, flight and side gaps. Flow in die was simulated separately and super-imposed with the extruder at the operating point. It was resulted that, change was smaller when mechanical clearances were made smaller. The study revealed, when pitch-length was increased or gaps were decreased, resulted in lesser viscous dissipation[18].

Giorgia Tagliaviniet et.al compared viscosity values which were attained by different theoretical models, of starch-based dough. Firstly, a 2D simulation was performed to validate the comparison. In second phase, a 3D simulation of the feeding zone of the twin-screw extruder was carried out. Objective was to find an appropriate model, and the operating conditions of a co-rotating intermeshing twin screw extruder. Once model was designed, several operational conditions and different screws geometries predicted development of the product rheological properties[8].

Shichang Chen et.al through numerical simulations and experimentation of a gravity driven falling film of highly viscous polymer studied thickness of film and residence time. When the film thickness was large, flow of viscous fluids observed, stable. Experimentation and simulated results showed great similarity and were in full agreement with one another. Residence time of viscous fluids agreed with experimental results. This provided the understanding to how to assess and improve flow of polymer fluid[24].

Ali Nurrakhmad Siregar et.al studied in detail a single-screw extruder. A single-screw extruder was modeled, examined using Finite Element Method (FEM). Three altered screw sizes of extruder were developed and then examined with ANSYS POLYFLOW, to analyze the flow domain and the performance of dough in single-screw extruder. Power-law model was used to simulate the velocity profile and shear rate. Results achieved shown important areas for modeling a single-screw extruder were gap-area, chamber-area and root-area[25].

Ram Yamsaengsung et.al designed a single screw extruder for starch-based products with 3D Finite Element Modeling in Poly-flow to mimic the flow of rice flour dough in an extruder. The generalized Newtonian model was used to describe the material that might suitably blend and transfer the material to outlet. [26].

Kumar M. Dhanasekharan et.al using 3D non-isothermal numerical simulations obtained an up gradation for mixing and heat transfer in single screw. They performed numerical simulations in metering section of the extruder using viscosity model for little to intermediary moisture wheat dough for flow and heat transfer. Residence time distribution (RTD) and specific mechanical energy (SME) were selected as the model parameters for the up gradation of mixing and heat transfer respectively. By changing screw geometry such as helix angle, channel depth, screw diameter to channel depth ratio, screw length to screw diameter ratio, and the clearance between the screw flights and barrel, numerical simulations were conducted. Through numerical simulations SME and RTD curves vs. the screw parameters were developed. Using this modeling technique couple of different sized extruders were developed which had same RTD and SME based on throughput[27].

G. Karrenberg et.al developed an alternate concept to conventional extrusion technique by developing a High-Speed-S-Truder. This method used a cardinal plasticization jacket with hundreds of bores around the screw to isolate the melt from solids in the flow. CFD simulations were used to examine and improve the difficult fluid flow during the procedure. Simulating the flow and plasticization was not yet carried out in CFD based software. Therefore, a 3D simulation was developed for melting polymeric materials in S-Truder. A new design enabled to differentiate among solid phase and liquid phase depending on temperature in just one account. Therefore, it was possible that without any assumption of melting mechanism to simulate melting in a single fluid domain. This resulted that the model was totally valid and could be used for the simulation of usual extrusion procedures at high speed settings along with the study of melting mechanism in High-Speed-S-Truder and further improvements[28].

ZHOU Ke et.al proposed that propellant based single screw extrusion process was cause of numerous calamities, complex rheological restrictions and tough measurement of real-time situations, but these all problems can be reduced, and detailed process can be reproduced by using numerical simulation suitably and instinctively. A simulation platform, POLYFLOW (CFD code) was used to design and investigate extrusion method for propellant, using Finite Element Analysis (FEA). Pressure distribution, temperature distribution and different other factors along with change in viscosity during extrusion process distributions and changes of viscosity were the starting point for the study. The simulations showed that the due to sever mixing and plasticizing procedure at screw edge was hazardous. Parametric study was also done for different screw speeds which provided harmony among safety and low-cost making[29].

Philip R. Onffroy et.al modified a twin screw extruder on the bases of solid-state shear pulverization (SSSP) in an uninterrupted polymer extrusion. They used low barrel temperatures and machine chemistry for the development of a wide array of polymers. The multifaceted relationship between processing and structure in SSSP was explained with different cohesive, co-variants which captured interaction among various extrusion parameters. RTD and specific mechanical energy (SME) were assessed using polypropylene (PP) as case study, comprising design, speed of screw and output constraints. Particularly an improved residence curve was attained using lower screws speed as well as higher output settings, which led towards higher level of mixing of material and shear[30].

M. Seker modeled single-screw extruder for starch with sodium tri-meta-phosphate and sodium hydroxide. Moisture content in starch effected residence time, residence time distribution and flow pattern for different speeds. When screw speed was increased, residence time decreased. Increase in moisture content had no considerable effect on residence time. Couple of different models was used to characterize the flow pattern. Non-linear regression set on the constraints for every model. Flow models fitted with the data.[31].

Krzysztof Wilczynski et.al modeled single-screw and twin-screw extruders for polymer extrusion. They modeled discrete models for every segment of the screw. They used an innovative continuous model, DEM (Discrete Element Method) for computation[32].

Y.Li et.al developed single-screw extruder giving critical solution for an isothermal, Newtonian flow. They presented velocity distributions, in three-dimensional plots. Properties like, velocity, screw’s physical characteristics and boundary settings projected in the study were verified using experimental data, available[33].

Objective

The objective of this thesis is to design single-screw and twin-screw extruder for a profile extrusion machine in order to perform the analysis for local residence time in twin-screw extruder. Performance analysis of single and twin-screw extruders. The performance of designed screw is also compared with already existing model to validate the results.

The basic objective of this project is to study the mixing of viscous fluids. Single and twin-screw extruders are selected machines. CFD software Ansys Fluent 19.2 is utilized for modeling. To fulfill these objectives single and twin-screw extruder geometries are developed in compatible software Design-Modeler and after proper meshing these are simulated in Fluent. The system selected for the mixing is based on experimental data available in literature. Study of dispersive and distributive mixing is done by studying pressure, shear stress, strain rate, velocity and vorticity contours developed after convergence.

Chapter 3

Computational Fluid Dynamics (CFD)

3.1 Computational Fluid Dynamics (CFD)

As this project relates with the computational study utilizing CFD, It is worth a while to present the preliminary information concerning CFD. CFD is the procedure of solving precisely the physics of any flowing fluid and answering it mathematically by the computational proficiency. As there is upsurge in computers and advancement in their computational supremacy, use of CFD has become a frequent useful tool for creating solutions for flows with or without solid interface. In CFD, the analysis of fluid flow is in accord with its physical properties for instance viscosity, pressure, velocity, temperature and density. Essentially to answer precise solution for fluid flow these properties must be considered all together.

Numerical models and mathematical methods, both are used in any CFD tool to examine the fluid flow. The Navier-Stokes (N-S) equations are considered as the mathematical model for any physical scenario. This defines variations in all the physical properties of both fluid flow and heat transfer. A mathematical model changes with every problem being considered such as, physical change, chemical change and any kind of transfer either heat or mass etc. Furthermore, the uniformity of a CFD study is very much subject to the complete structure of the method. For any problem the authentication of the mathematical model is enormously vital.

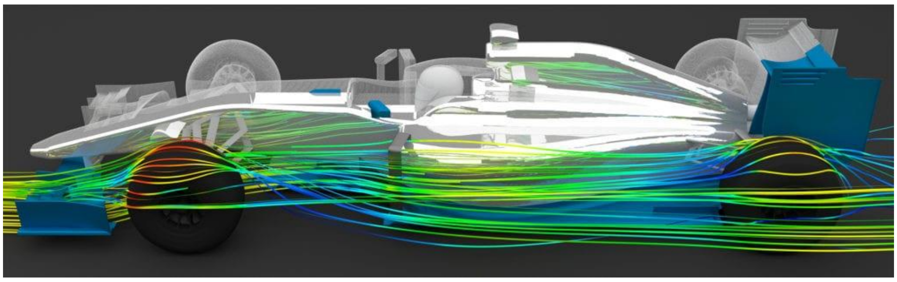

Fig. 9: Streamlines showing airflow around the F1 car obtained using N-S equations

3.2 Governing Equations

Structure of thermo-fluids depends upon the governing equations that are built based on conservation of mass, momentum and energy. These equations are

- Conservation of Mass: Continuity Equation
- Conservation of Momentum: Newton’s Second Law
- Conservation of Energy: First Law of Thermodynamics or Energy Equation

These three laws states that mass, momentum and energy remain stable within a system and no loss occurs.

Any fluid which undergoes a thermal change, the change depends on its physical properties. These equations give very important unknown variables, which are velocity, temperature and pressure. Pressure and temperature are the variables which are independent in thermodynamics. These equations govern four other variables which are density, enthalpy, viscosity and thermal conductivity. Viscosity and thermal conduction give transport properties as well. These all properties depend on mainly pressure and temperature.

Analysis of fluid flow gives vector velocity, pressure and temperature in the whole fluid regime. These properties are very crucial for modeling any fluid flow product. Kinematic properties play an important role in fluid flow. Fluid flow can be inspected by either Lagrangian or Eulerian methodologies.

Lagrangian method is used when particles of fluid are very large so that’s, properties can be detected. It examines the initial coordinates of a particle at a time zero and then detects at another time t of the same particle

Eulerian method does not follow a singular particle in the flow, but the whole velocity profile of the fluid field is studied as a function of time.[34].

Conservation of mass is given by the following equation.

$$\frac{\mathrm{D}_{\rho}}{\mathrm{D}_{t}} + \boldsymbol{\rho}\,(\nabla.\boldsymbol{\upsilon}) = \mathbf{0} \qquad \mathbf{(1)}$$

Density is given by “ρ”, “υ” gives velocity vector and “∇" is gradient operator. If we keep the density at constant, flow becomes incompressible, and the equation reduces

$$\frac{\mathrm{D}_{\rho}}{\mathrm{D}_{t}} = \mathbf{0} \qquad \mathbf{(2)}$$

Navior-Stokes equation which represents conservation of momentum is given as:

$$\frac{\partial}{\partial t}(\rho\upsilon) + \nabla . (\rho\upsilon\upsilon) = - \nabla p + \nabla . (\tau) + \rho\vec{g}$$

(3)

Here “p” is static pressure, “τ” stress-tensor and “$\rho\vec{g}$” is the gravitational force per unit volume. The viscosity coefficient remains constant if fluid is incompressible with constant viscosity and Navier-Stokes equation reduces to[34]

$$\rho \frac{D\upsilon}{Dt} = - \nabla p + \mu\nabla^2\upsilon + \rho\vec{g}$$

(4)

3.3 The CFD Methodology

Fluid flow problems can be solved by CFD codes which are built around numerical algorithms. CFD consists of following structures[34];

- Pre-Processor
- Physical Modeling/Solver
- Post-processor

3.3.1 Pre-Processor

- In a pre-processor geometry is made and meshing is done on the geometry and then physical constraints for the problem are defined. Usually, geometry is designed in any CAD software. Geometry volume or fluid domain is then extracted from it.
- Extracted volume is then divided into distinct cells, which is called mesh. The mesh can be either uniformed or non-uniformed. It can be well structured or unstructured. Mesh is usually made of a blend of hexahedral, tetrahedral, prismatic or polyhedral entities. [35].

3.3.2 Physical Modeling/Solver

- Equations for fluid motion are defined in the solver. Equations for enthalpy, radiation and species transport.
- Then boundary conditions are defined, how fluid is behaving and implying boundary parameters on the boundary surfaces of domain.

- Simulation can be steady state or transient. If the problem is time dependent, then the initial condition is also defined.
- Initialization of the problem is carried out and then run the simulation for certain iteration until solution is converged.
- Physical modeling is done to produce suitable results for a certain problem of flow.

3.3.3 Post-processor

Results or the solution of the problem are visualized in post-processor and then further analysis is carried out on them. Most of the available CFD programs have technologically advanced graphical tools, through which we visualize the required results with the help of graphics, such as

- Contour plots
- Vector representation for velocity.
- Path-lines tracks the particle went through.
- Animations.
- View manipulation (translation, rotation, scaling etc.)

3.4 Discretization Technique

Discretization is usually done numerically instead of analytically for linear problems. For solutions which are dis-continuous, discretization is done very carefully. Discretization techniques which are being used are[35]:

- Finite Volume Method (FVM).
- Finite Element Method (FEM).
- Finite Difference Method (FDM).
- Spectral Element Method (SEM).
- Lattice-Boltzmann Method (LBM).
- Boundary Element Method (BEM).

3.4.1 Finite Volume Method

Finite volume method is most common technique used for CFD, as it is fast in solution speed and advantageous in memory usage for complex problems, with turbulent flow having high Reynolds number and combustion.[35].

In FVM, the required partial difference equations for instance, Navier-Stokes equation, mass and energy conservation equations and turbulence equation are all reorganized in their conservative form and then these equations are solved over every distinct control volume. Conservation of fluxes through a certain control volume is also assured. Following equation shows governing finite volume equation in the form,

$$\frac{\partial}{\partial t}\iiint Q dV + \iint F dA = 0$$

(5)

Here “***Q”***, the vector of conserved variables, “***F”***, vector of fluxes, “***V”,*** volume of control element and “***A***”, surface area of control volume.

3.4.2 Finite element method

Finite element method is used usually for structural analysis for solids, but is also valid for fluid flow. To ensure conservation of solution FEM requires precautions. FEM is being used for fluid dynamics as well for governing equations. FEM is more stable than FVM but special care should be taken for formulation.[36].

FEM requires more memory space and has slow solution time than that of FVM.[37].

FVM governing equation is formed as:

$$R_i = \iiint W_i \quad Q \quad d \quad V^{e}$$

(6)

Here “R_i”, the equation residual at element vertex “i”, “Q”, conservation equation stated on element basis, “W_i”, weight factor, and “V^e”, volume of element.

3.5 Multi-phase Flow

In multiphase flow two are more materials flow having different thermodynamic phases simultaneously. Mainly all the processing technologies involve some sort of mutiphase flow from turbines to construction industry. Therefore multiphase flow remains relavent in many natural phenomenon[38].

Multiphases consists of similar chemical components e.g. water in liquid or water in vapours, or it can be consist of chemically two or more different components e.g. water and oil[39].

Phases can be continous or dispersed. A continuous phase is in which materials are connected to one another in a region. Continuous phase can be of either gas or liquid.

A dispersed phase is one in which phases are disconnected in a region. Dispersed phase can be solid liquid or gas[40].

In FLUENT the subject project deals mixing of two immiscible fluids making two phase system. The problem can be modeled utilizing multiphase model. There are diverse methods for modeling a multiphase flow, Euler-Langrange approach and Euler-Euler approach. A brief introduction to both approaches is given in next paragraphs. [41].

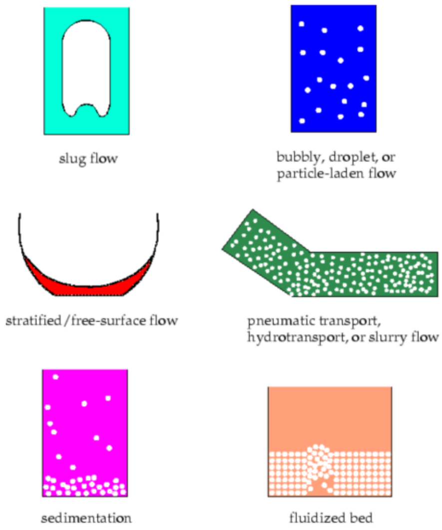

Fig. 10: Multiphase Flow Regimes

3.5.1 Euler-Lagrange Approach

In Eular-Langrange approach, flow is considered to be of particles in discrete phase in a space, carrying a particular sort of computational info. The lagrangian approach treats a phase as continous phase and solves time-average Navier-Stokes equations. Dispersed phase is usually solved by tracing large particles present in throughout the flow field. Dispersed phase by exchanging the heat, mass, momoentum and energy, interacts with the fluid. The appraoch tracks the trajectories of particles at specific time periods in the fluid phase during calculations[42]. These all makes this approach an ideal for the flow problems which involve spray dryers, coal-liquid fuel combustion etc. In this approach, dispersed phase is considered to be second phase have a low volume fraction, which makes it inappropriate to use for liquid-liquid mixtures or where second phase can not be neglected. Lagrangian approach possess only one model that is

- The Lagrangian Discrete Model

3.5.2 The Euler-Euler Approach

This approach treats different phases as continuous interpeneterating with themselves. I this model every phase has their own volume fraction and that cannot be occupied by other phase. Overall volume fraction of all the phases is unity in each cell and are in continuous manner of space and time. On the basis of Euler-Euler approach there are three further different models available. These models will be discussed further in brief and their limitations will be studied, on the basis of which we will select which model to use. The models are

- Volume of Fluid Model (VOF)
- Mixture Model
- Eulerian Model

3.5.3 Volume of Fluid Model (VoF)

The Vof model is used for meshes which are fixed Eulerian meshes and it is a surface-tracking model. This model is used where the position of interface between two interacting immiscible fluids is of importance. Volume fraction of each fluid is tracked every cell through out the flow domain and equation of momentum is same for each fluid. Application of VoF model includes stratified flows, filling, motion of large bubbles, motion of liquid in dam break, jet breakup, liquid-gas interfacing and free surface[43].

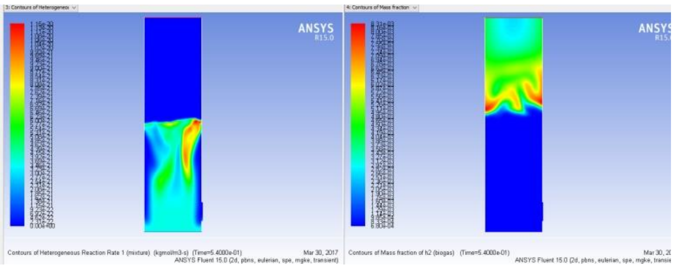

Fig.11: Visualization of VOF Model

Limitations of Volume Of Fluid Model

- Only segregated solver can be employed.
- Flow control volume is filled with one fluid or other or combination of both .There is no void region in the flow domain.
- Not all the phases can be identified as compressible ideal gas rather only one phase is defined as compressible gas. Compressible liquids can be used with no limitation using UDFs.
- LES turbulence model is not suitable to be used with VOF model.
- VoF model is not used in second-order implicit time step designs.

3.6 Mixture Model

In mixture model two or more phases are used, one of which is fluid and other can be in particles form. In mixture model momentum equations are solved for the complete mixture and relative velocities are given to define the dispersed phase. Mixture model is used in bubbly flows, cyclone separators and sedimentations etc. for homogeneous multiphase flow relative velocities of dispersed phase can be ignored.

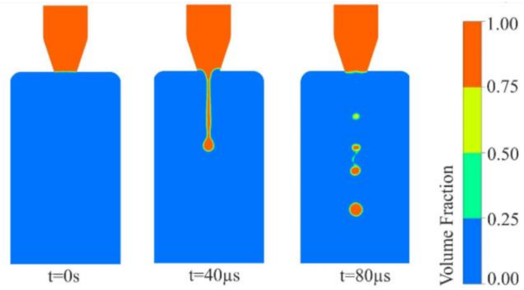

Fig.12: Visuals of a Mixture Model

Limitations of Mixture Model

- Mixture model can not use density-based models and is only available with pressure-based solvers.
- Stream-wise periodic flows with specific mass flow can not be modeled alongwith mixture model.
- Mixture model is not compatible for solidification and melting of materials.
- Do not use relative formulation in combination with mixture model.

- Non-viscous flows can not be modeled with mixture model.
- Mixture model cannot be used with shell-conduction model

Advantage of using mixture model is that it can solve energy, momentum and continuity equations of all the phases in the mixture. It can solve volume fraction equaion of secondary phase and relative velocity, if the velocities are different for different phases[44].

3.6.1 Eulerian Model

Eulerian model is used for modeling separate phases which are interacting with one another. There is no exception as all the states of matter can be used as phases in any combination. Eulerian model is used for each phase. Memory requirement and convergence criteria plays a big role in Eulerian model. Eulerian model is different to mixture model in the sense that there is no difference in liquid fluid flow or solid fluid flow in Eulerian model[44]. Solid fluid flow is the one where atleast one phase is considered as granular phase. Solution of Eulerian model is based on some assumptions that are

- All the phases are at same pressure.
- Equation of momentum and continuity are solved for each phase separately.
- Drag-coefficient function between phases, suitable for different multiphase systems is available in Eulerian model.

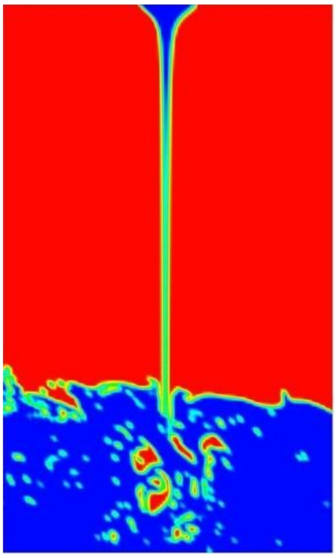

Fig.13: Visual of a Eulerian Model

Limitations of Eulerian Model

- Reynolds turbulence model does not exist for every phase.
- Particle tracking works only with primary phase.
- When using Eulerian model, stream-wise flow with specific mass flow rate does not work.
- Inviscid flow is not permissible.
- Melting and solidification are not allowed.

3.7 Selecting from General Multiphase Models

Selecting a model from either mixture model or Eulerian model, one have to reflect following instructions before selecting the appropriate model.

To use mixture model following instructions should be kept in mind, if the particle size varies and larger particles are difficult to separate from fluid phase mixture model is preffered. If inter-phase drag laws for non-granular particles are unknown then one can use mixture model. Mixture model can be used for simpler problems, where computational effort is required less.

To use Eulerian model following instructions should be kept in mind, if particles are concentrated in domain we use Eulerian model. If drag laws between phases are applicable then Eulerian model gives better results. Eulerian model gives more accurate results but due to difficult computstional methods it is less stable than mixture model.

3.8 Selection of Mixture Model:

Our problem relates with mixing of immiscible high viscosity copolymer Ethylene vinyl acetate(EVA) with low viscosity Ethylene glycol. Ratio of viscosity of continuous phase to dispersed phase is in range of $5.095e^{03}$,so system may be treated as dispersed phase of ethylene glycol embedded in continuous phase of ethylene vinyl acetate(EVA). On this basis discrete phase model, mixture model and Eulerian model can be selected. As volume fraction of dispersed phase i.e ethylene glycol is more than 10%, so discrete phase model is rejected. Mixture model and Eulerian model can be selected. Due to time constraint mixture model is selected because of simplicity and requirement of less computational effort. Due to more complexity of Eulerian model, it is less stable than mixture model.

3.9 Selection of Fluid System

Literature has been surveyed for the selection of fluids system for our problem. For the purpose mixing of immiscible fluids (Ethylene vinyl acetate EVA) and ethylene glycol is selected. We take this system for single screw extruder conveying element. High viscosity co-polymer is taken in molten state while ethylene glycol is low viscosity liquid. The ratio of zero shears viscosities i.e. μ (EG) to μ (EVA) is in the range of 10e-8. Due to different viscosity value and phase ratio, interfacial tension will break stretched regions into segments. When viscosity is high, Reynolds number is less than 100. In our case its value is 0.0056. In such cases, mixing occurs only due to viscous forces and turbulence would have no effect. In our case the matrix phase i.e., EVA possess very high viscosity as compared to dispersed phase i.e., ethylene glycol, so very high shear stress and elongational stretching is required to affect mixing in the system. Study is conducted on the same screw geometry at different screw speed to record effect on mixing efficiency.

Chapter 4

Problem Modeling Approach

This chapter describes the steps involved in modeling of system selected. Starting from basic concepts and tutorials of software Ansys Workbench (Design-modeler) were solved to learn the creation of geometries for different equipment's in 2D and 3D. Tutorials of Ansys Workbench (Meshing) were also carried out to get familiar with the meshing process as it is a critical part of the simulation. Different Tutorials were solved repeatedly to get the knowhow of the software Ansys Fluent these tutorials helped a lot in setting up the solver and use of required models for the simulation. With all these practices I was able to build the geometry of both the single and twin-screw extruder as it was a complex geometry and was a time taking process. Then this geometry file was imported into Ansys Meshing for discretization of the mesh. The name selection of required boundaries is done in Ansys Meshing and then we generate the mesh. The generated mesh is then imported into Ansys Fluent a Fluid flow module in Ansys Workbench which deals with the physics and analyzes variety of fluid phenomenon. Comprehensive details of geometry, meshing and solver are coming in next few paragraphs. Due to time constraint and some complications in solving CFD codes following simplifications are incorporated.

- Only modeling of conventional single screw conveying element section is done.
- No mixing enhancer is included in the geometry.
- Separate mixing head and die are not incorporated, at inlet and outlet of the mixing element respectively.
- Fluids are Newtonian as flow rates in the system are low.

4.1 Geometry/Mesh Creation

Geometry creation was the first step in this thesis work. At SCME Ansys workbench 19.2 was available and I used a module in this software named design modeler. I used this software for the creation of my required geometries of both single and twin extruders with a proper flow domain extracted. As the geometries for both the extruders are of complex nature, I spent a lot of time and put in great effort in making these geometries. After a lot hit and trial method and a lot of literature survey, I was able to create both single and twin-screw extruders conveying element geometries. The dimensions of both single screw extruders are as follows:

Table: 2 Dimensions for Single & Twin Screw Extruders

Dimension	Value
External Diameter	30.0 mm
Internal Diameter	29.2 mm
Clearance	0.8 mm
Pitch	30.0 mm
Center Line distance	26.0 mm

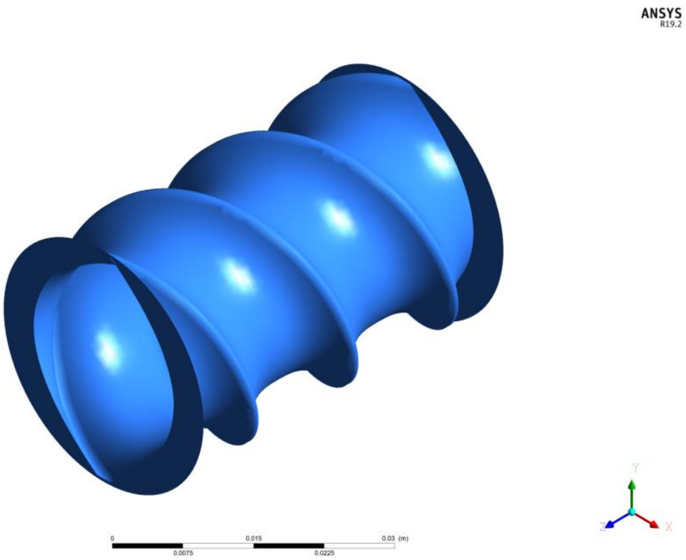

Fig. 14: Single Screw Geometry

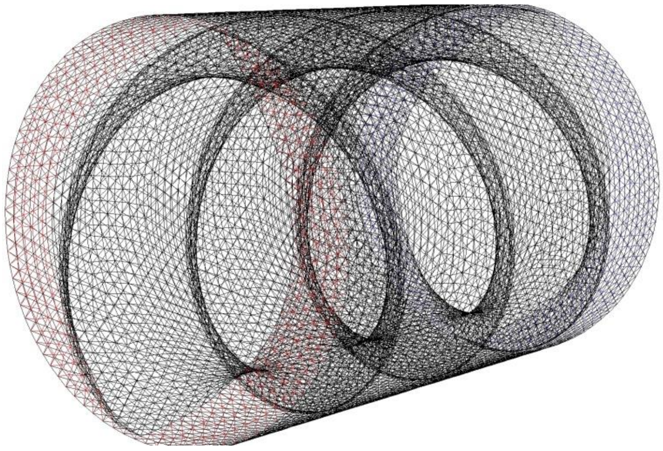

Fig. 15: Single Screw Extruder Mesh

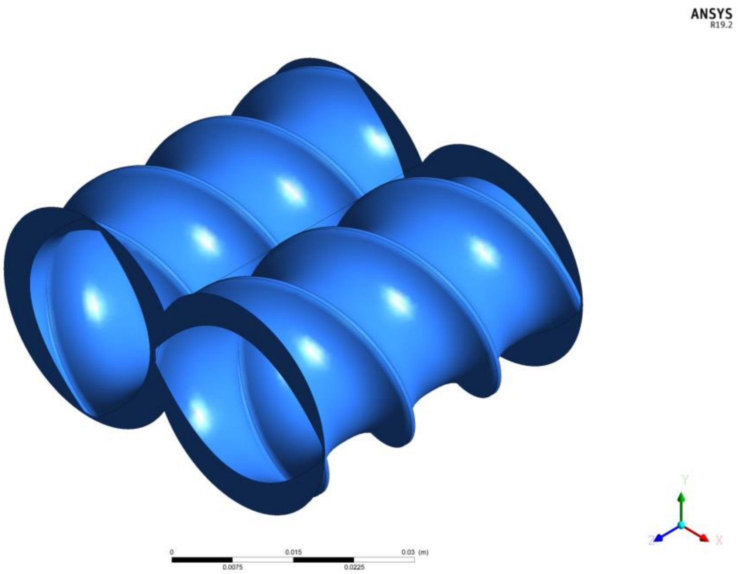

Fig. 16: Twin Screw Geometry

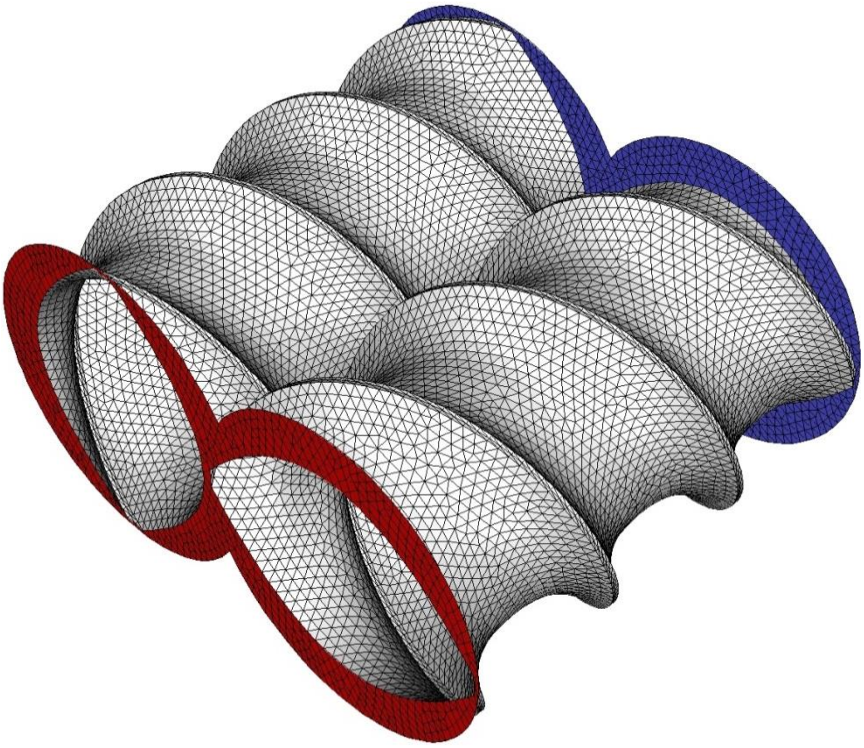

Fig. 17: Twin Screw Mesh

Flow domain is extracted and discretized with tetrahedral mesh elements with 0.001 mesh spacing. The information of nodes, elements and faces generated of conveying element is as follows

Table: 3 Mesh Specification for Single & Twin Screw Extruders

Type	Number of Nodes	Number of Elements	Tetrahedron
Single Screw Extruder	21498	96366	96366
Twin Screw Extruder	36042	156088	156088

4.2 Simulation Approach

Our system consists of two phases' i.e., Ethylene vinyl chloride (EVA28420) and Ethylene glycol (EG). The properties of interest are tabulated below.

Table: 4 Materials Specification

Property	EVA28420	EG
μ (zero shear stress viscosity) at 140 deg. C	80 Pa. s	0.0015 Pa. s
ρ Density	930 Kg/m3	1111 Kg/m3
Volume fraction	0.7	0.3

The primary phase **EVA** is highly viscous was taken as continuous phase while **EG** is less viscous phase was taken as dispersed phase.

Multiphase mixture model is selected because of higher volume fraction, of dispersed phase and because of simplicity and less computational effort requirement.

Unsteady, segregated solver is selected because of very low Reynolds Number ($Re = \rho D^2 N/\mu$) i.e. 0.0056 so laminar flow is assumed. Another assumption is that fluid is considered as Newtonian. (Viscosity does not change with high shear stresses). Only mixing section is selected for the problem solution

Boundary Conditions

Inlet is velocity inlet. The screw tip velocity comes out to be 0.38 m/sec for both phases. Volume fraction, of dispersed phase is kept 0.3 at the inlet.

Outlet is set as Outflow having mixture rating of 1 Kg/hr. with both phases coming out with zero EG backflow volume fraction.

Screw speed is 200 rpm for both screws.

Convergence criteria for the residuals drop on continuity, and velocities were set at $10e^{-3}$.

Transient simulation having a time step size of 0.001 was carried out and convergence was obtained at about 2500 iterations.

Pressure, velocity, shear stress, shear rate and velocity vectors contours and mixing index are studied to observe mixing efficiencies in both geometries. Difference in both results is also studied.

Chapter 5

Results and Discussion

Two separate simulations were run on geometries of single-screw and twin-screw extruders. Screw speed was set at 200 rpm which gave screw velocity at inlet of 0.38 m/sec. outlet was set as pressure outlet and screw and barrel surfaces were represented as rotating and stationary walls respectively. Velocity magnitude increased from inlet to outlet indicating the increase in elongational stretching along the flow domain and indicating dispersive mixing.

5.1 Velocity Distribution

Contours of velocity magnitude at 200 rpm with velocity in range of 0 to 1.02 m/sec. Velocity of screw element increases from inlet to outlet and maximum velocity, seen at the middle of flow domain indicating flow is in the forward direction and elongational flow enhances the stretching in the fluid. The velocity increase is due to the energy provided by the rotating screw to the fluid which is converted into kinetic energy. The combination shear stress and elongational stretching due to velocity gradient causes dispersive mixing in the machine.

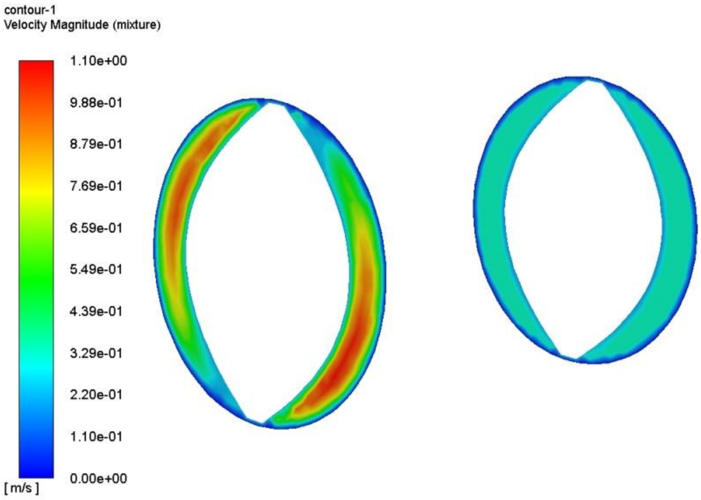

Fig. 18: Single Screw Velocity Contour

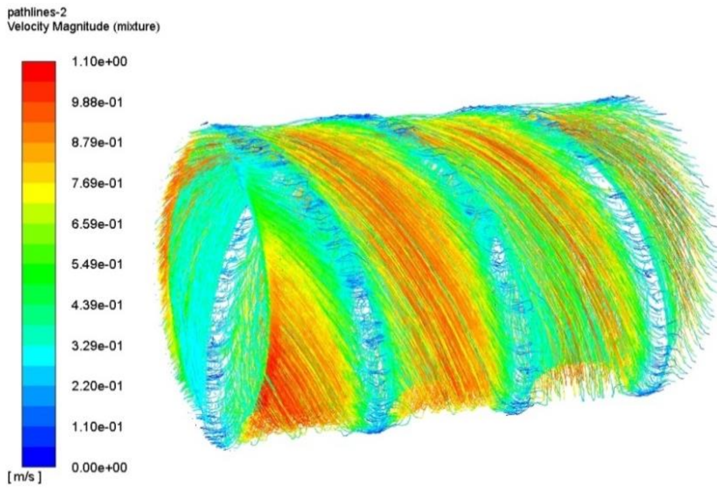

Fig. 19: Single Screw Velocity Path lines

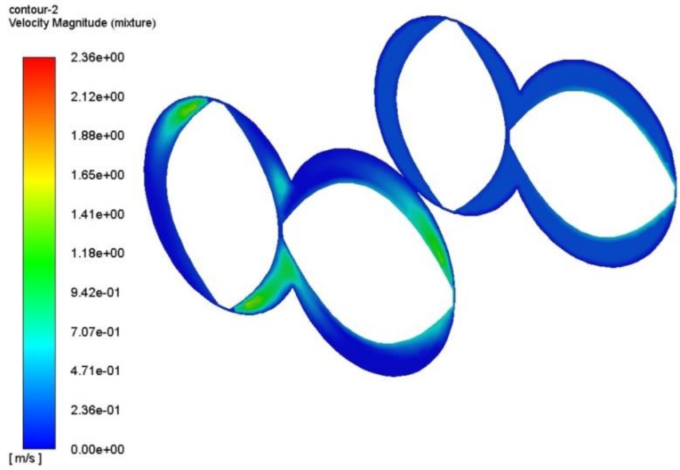

Fig. 20: Twin Screw Velocity Contour

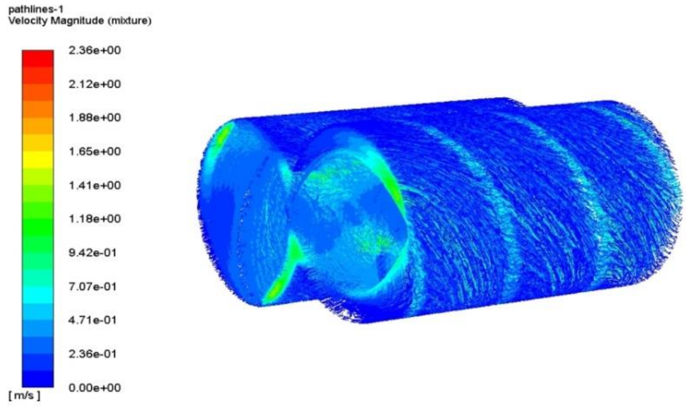

Fig. 21: Twin Screw Velocity Path lines

5.2 Pressure Distribution

The pressure distribution generated indicated that pressure is decreased from very high value of about M Pa at the inlet to very high negative value at the exit. The screw drags the fluid into the mixing section causing high pressure at the inlet but as fluid moves along the screw in the extruder the pressure energy is converted into kinetic energy produced by the movement of screw. This high value of dynamic pressure at the exit indicates elongational stretching in the mixing section contributed to dispersive mixing. The pressure distribution contours of conveying element and kneading element are shown in fig and respectively.

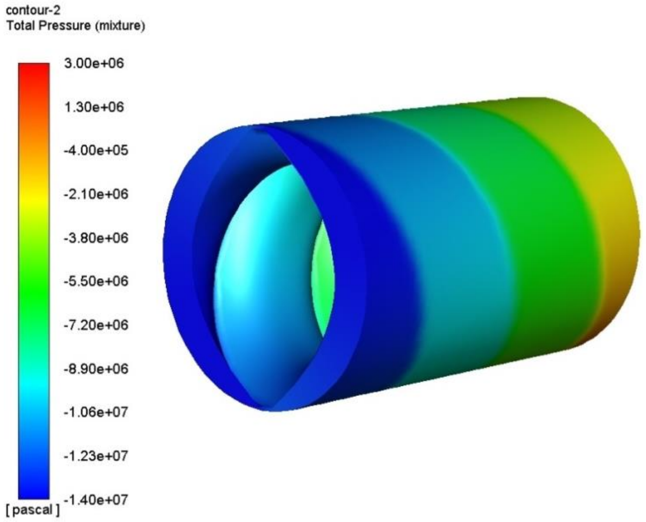

Fig. 22: Single Screw Pressure Contour

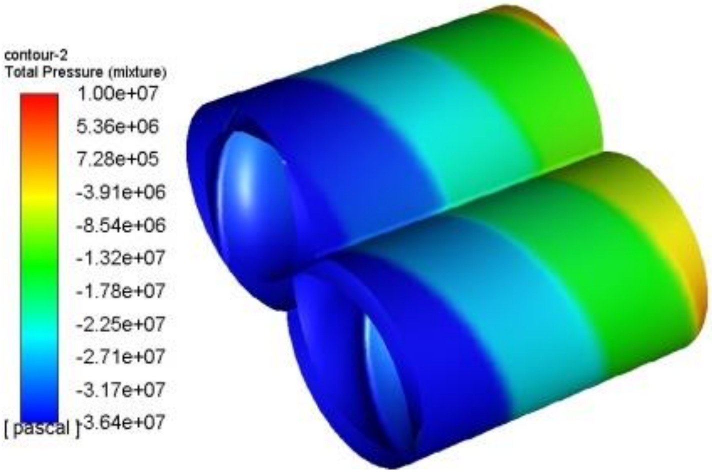

Fig. 23: Twin Screw Pressure Contour

5.3 Wall Shear Stress Distribution

The selected system is highly viscous and very high magnitude of shear stresses is required to disperse the phases mutually. Stresses play an important role in dispersive mixing. Dispersive mixing is done by driving the material through small gaps between barrel and screw tip repeatedly. Stresses are applied on the material. This causes the agglomerates to break down and material size reduces. Wall shear stress distribution contours of both geometries are shown below

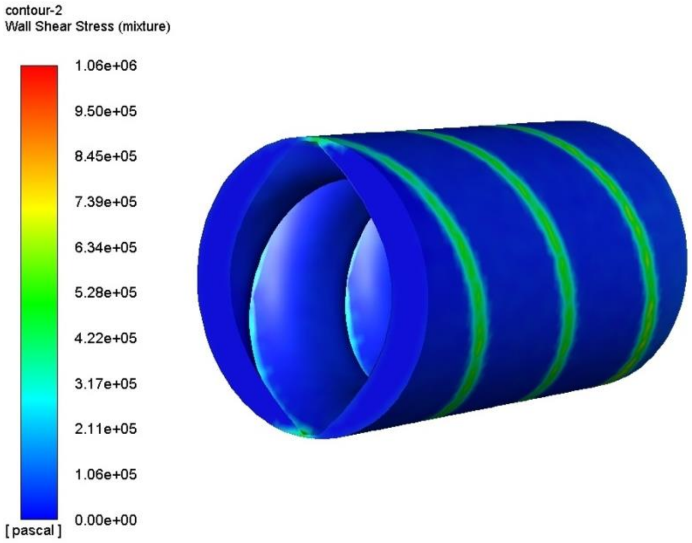

Fig. 24: Single Screw Wall Shear Contour

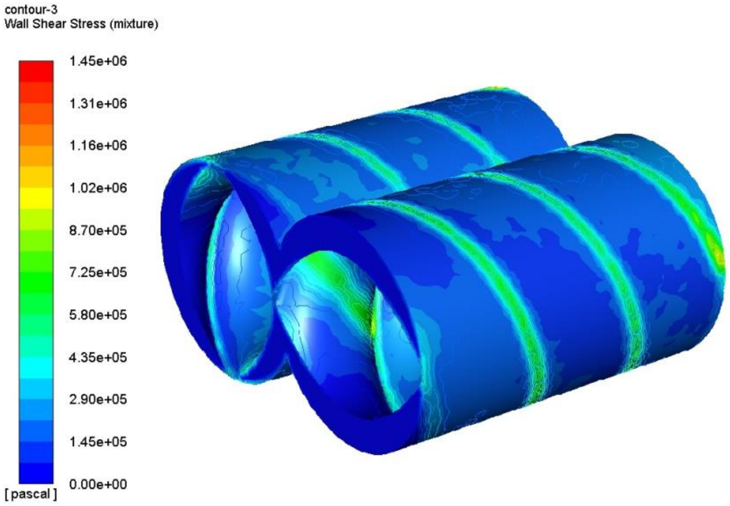

Fig. 25: Twin Screw Wall Shear Contour

The wall shear stresses of conveying screw and kneading element are up to the magnitude of 9.56e05 and 8.91e05 respectively. The strong stress gradient is also seen from the barrel wall to the extruder screw channel indicating dispersive mixing. Conveying element section generates slightly more wall shear stresses than kneading disc element.

5.4 Strain Rate Distribution

Mixing in machine depends upon strain rate developed because it describes deformation of fluid. Fluid is dispersed in regions with high strain rate. The data collected from the simulations results will be utilized to evaluate mixing index. The contours of strain rate are shown in figure.

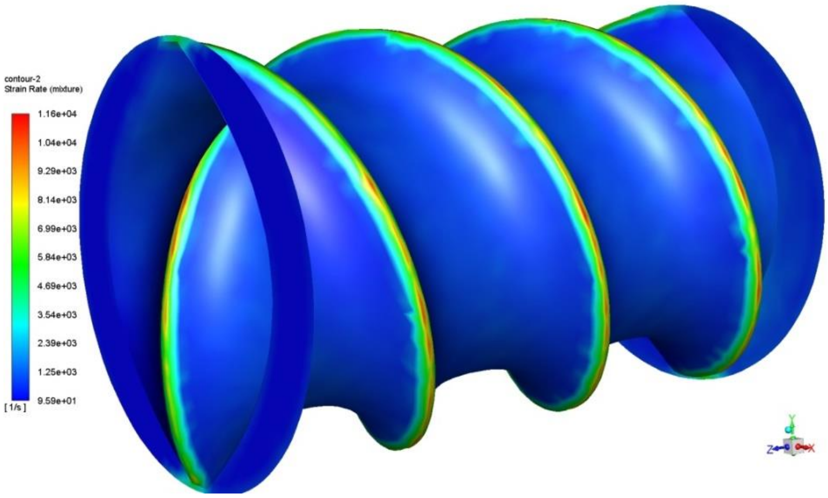

Fig. 26: Single Screw Strain Rate Contour

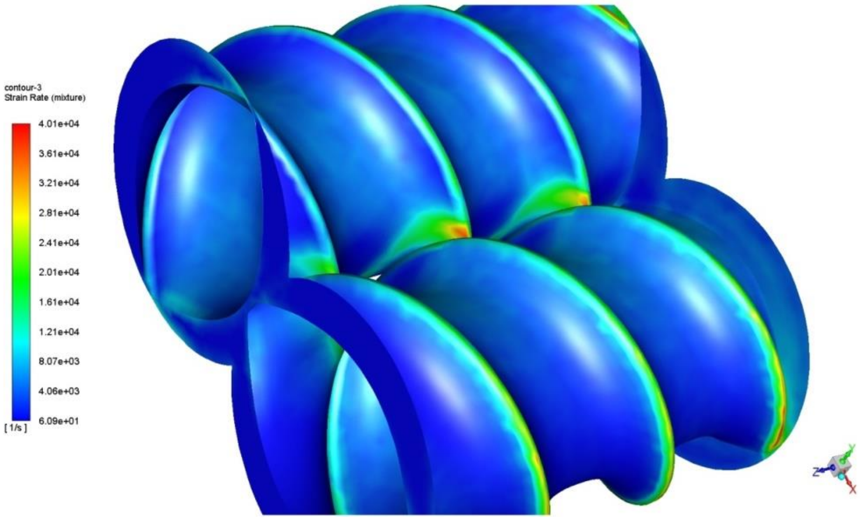

Fig. 27: Twin Screw Strain Rate Contour

The mixing is directly proportional to the strain rate, so twin screw shows better mixing than single screw.

5.5 Vorticity Magnitude

It is defined as measure of rotation of fluid in extruder. In our case of 3D simulation, the plot of vorticity magnitude is used to calculate mixing index. The contours of vorticity magnitude are show in figure.

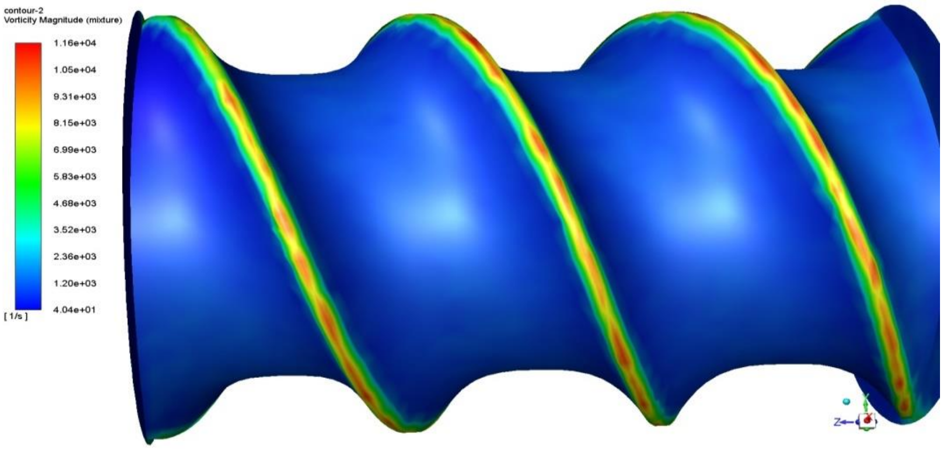

Fig. 28: Single Screw Vorticity Magnitude Contour

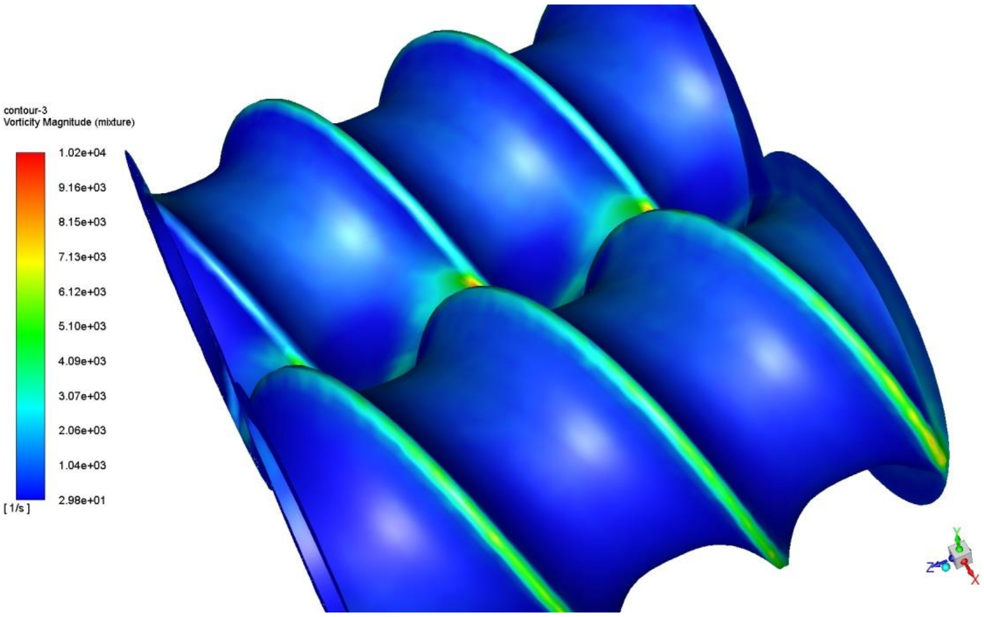

Fig. 29: Twin Screw Vorticity Magnitude Contour

Vorticity magnitude distribution from screw flight of conveying element. The range is 16/sec from screw root to 11300/sec at screw tip.

5.6 Velocity Vectors

Velocity vectors plots are also one of the post processor simulation results which gives magnitude and direction of flow inside the domain. In our simulation results, velocity vectors are directed from inlet to outlet of the flow domain. As vectors are not diverging, shows that our work is in right direction. The velocity vectors contours for the conveying element is shown in Fig

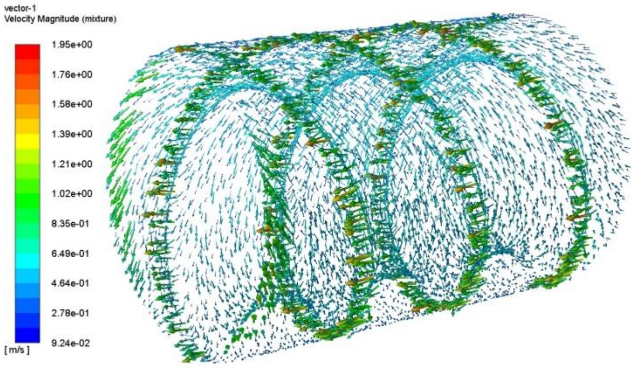

Fig. 30: Single Screw Velocity Vectors

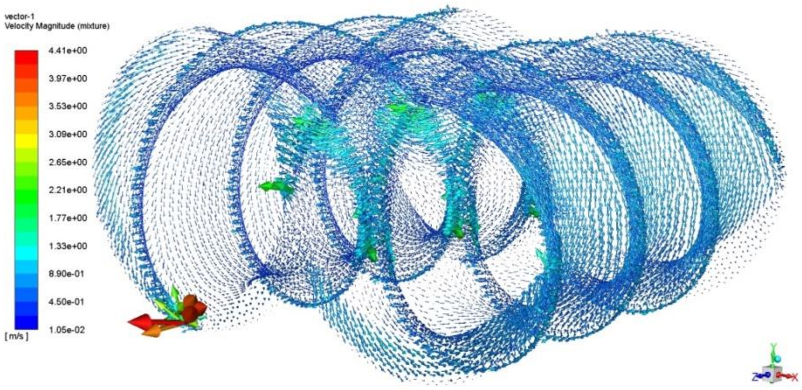

Fig. 31: Twin Screw Velocity Vectors

5.7 Mixing Index

Mixing Index (λ) Evaluation From the vorticity magnitude and shear rate distribution results after simulations of single and twin-screw geometries, mixing index (λ) or flow number is calculated and given in tables below. The values of both parameters for calculations are taken from the screw tip to screw channel.

Table: 5 Mixing Index for Single Screw Extruder

Sr. No	**Vorticity Magnitude (Ω)** S^{-1}	**Strain Rate (Υ)** S^{-1}	**Mixing Index** $(\lambda)=(\Upsilon)/(\Omega)+(\Upsilon)$
1	10200	11600	0.532
2	9160	10400	0.531
3	6990	8140	0.538
4	5100	5840	0.533
5	2360	3540	0.612
6	29.9	60.9	0.670

Table: 6 Mixing Index for Twin Screw Extruder

Sr. No	**Vorticity Magnitude (Ω)** S^{-1}	**Strain Rate (Υ)** S^{-1}	**Mixing Index** $(\lambda)=(\Upsilon)/(\Omega)+(\Upsilon)$
1	10200	16100	0.612
2	9160	10500	0.534
3	6120	8070	0.568
4	4090	6890	0.627
5	1040	2060	0.664
6	40.4	96	0.714

Conclusion

ANSYS Workbench 2021is utilized for the modeling of mixing of two immiscible fluids i.e. Ethylene Vinyl acetate (EVA) and Ethylene Glycol (EG). EVA of type EVA28420 (28% Ethylene and melt index of 420gm/10 minutes) is selected at its melting temperature of 140 0C .The zero shear stress viscosity of EVA is 80 Pa. s while EG possess viscosity of 0.0157 Pa.s. Study is conducted on mixing section of single and twin screw extruder. The viscosity ratio between continuous phases to dispersed phase i.e., EVA and EG is in the range of 5.095e-03 requiring very high shear stresses and shear rate for the breaking of dispersed phase droplets. The results are indicative of that concept. High shear stresses and shear rates are observed close to the barrel and falls to minimum at the center of the channel due to presence of large volume of fluid. This shear stress and strain rate gradients are indications of deformation in the fluid necessary for the dispersive mixing. More elongational stretching is observed in twin screw extruder due to high axial velocity in the intermeshing (nip) region. Mixing index range varies 62 from 0~1.0 with 0.5 being pure shear flow and 1.0 is elongational flow. Mixing index from 0.6~0.7 indicates very good dispersive mixing. The mixing index in single screw extruder varies from 0.51~0.64 showing very good shear and elongational stretching, a very good indication of dispersive mixing. Mixing index in twin screw extruder ranges from 0.55~0.61 indicating more elongational stretching hence better dispersive mixing.

Future Recommendation

Residence time distribution analysis of single and twin screw extruder is an important feature to be considered in modeling of an extruder as it will tell how much a material will spend time inside the extruder on the basis of which the material will be cooked. As viscosity changes is an important issue to be considered for the polymers mixing. So, Non-Newtonian models can also be included in the simulation model to study the effect of viscosity changes during the mixing.

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