NUMERICAL INVESTIGATION OF FLOW BEHAVIOUR AND WALL SHEAR STRESS IN CONTINUOUS CASTING TUNDISH

A DISSERTATION

Submitted in partial fulfilment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY
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MECHANICAL ENGINEERING

(With Specialization in Production and Industrial Systems Engineering)

By

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CANDIDATE'S DECLARATION

I hereby declare that work carried out in this dissertation entitled, "**Numerical Investigation of Flow Behaviour and Wall Shear Stress in Continuous Casting Tundish",** is presented on behalf of partial fulfilment of requirement for the award of degree of Master of Technology with specialization in Production and Industrial Systems Engineering, submitted to the **Department of Mechanical and Industrial Engineering**, Indian Institute of Technology Roorkee (India), is an authentic record of my project work carried out under the guidance of **Dr. Pradeep Kumar Jha**, Associate Professor**,** Department of Mechanical And Industrial Engineering, IIT Roorkee. I confirm that I have not submitted the matter embodied in this report for the award of any other degree or diploma.

June 2019 **Nitin Singh Solanki**

CERTIFICATE

This is to certify that the above statement made by candidate is correct to my knowledge and belief.

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ABSTRACT

Continuous casting process has nowadays used for 95% of world's steel production. Experimental analysis of continuous casting was tedious due to having many complex phenomena and high temperature so we analyze this process with the help of many computational models like fluid flow model, heat transfer model, solidification model etc. Due to flow inside the tundish, shear stress was developed on the walls and Standard k- ε turbulence model used for wall shear stress analysis. Initially simple boat shape tundish with change in outlet positions with velocity were simulated and contours of wall shear stress of tundish were plotted. Bottom wall of tundish has maximum wall shear stress for respective geometry at given velocity. While front wall which was near to outlets along + z direction has more wall shear than back wall in all the cases of outlets positions, which was opposite to front wall except the symmetric geometry case of outlet positions.

Effect of inclinations in simple boat shape walls on fluid flow and wall shear stress were analyzed. The results obtained by changing the wall inclinations were also compared with T shape tundish. After that effect of shroud depth was studied on boat shape and T shape tundish. Shroud inclination effect on wall shear were also analyzed on boat shape and T shape tundish. Wall shear stress and velocity contours were plotted for all the different possible cases discussed above and results were compared with each other.

It was observed that simple boat shape case has more wall shear stress on bottom and back wall, while T shape has maximum wall shear on front wall and minimum on back wall. Bottom wall shear decreases with shroud depth but back wall stress first increases then decreases for boat shapes but continue to decrease for T shape.

Keywords: Continuous Casting, Tundish, Wall shear stress, Shroud.

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CHAPTER 1

INTRODUCTION

Continuous casting process is very useful process for the steel manufacturing nowadays and used as one of the process as it does not require any secondary process for getting final product that has to be manufactured. This process is coming to existence with the help of the idea given by **Sir Henry Bessemer** in 1846 which was used for nonferrous metals that possess low melting points. In 1887 **R. M. Daelen** suggested some improvements in the process with the idea of solidification of molten metal with help of water-cooled molds. In later 1960 continuous casting became used for steel production, having low thermal conductivity of heat and low melting point relative to nonferrous ones gives to solve the many problems that were going to hamper the process due to the properties like thermal conductivity and melting point. After 1950 onwards technology interventions were made for making process efficient. Initially only 5 % steel production is done with the help of continuous casting but in today's world with so much inventions and technology development it gives around 95% of worlds steel production and named as the mother process for steel production.

1.1 Continuous Casting Process

Continuous casting is a process used for manufacturing of steel in form of slabs, blooms, billets etc. As we said in previous section around 95% of today's steel is manufactured[1] with the help of this process. In this process it has mainly three components Tundish, submerged entry nozzle and molds. Discussion of all three will be done in detail after brief introduction of whole process. Liquid molten metal is poured into the Tundish that will serve as a reservoir[2] for molten metal with the help of ladle in which liquid metal is taken from furnace and poured into the Tundish inlet. Ladle is made of non-ferrous and refractory material because of high temperature of liquid metal against it has to withstand. Its capacity of accommodation of steel ranges from 20 kg to 300 tons according to the plant capacity. The ladle is connected to inlet of tundish with the help of shroud that is also made of ceramics so that it pours liquid metal safely and interaction with environment is avoided .From inlet it goes inside tundish vessel which acts a reservoir because once the ladle is poured there is some time duration required to poured another ladle but due to molten metal storage in tundish it supplies continuously molten metal into the mold and the process goes on. Tundish not only acts as a reservoir but also helps liquid molten metal for smooth out flow[3]. There are many types of tundishes present according to their shapes and number of outlets. From inlet the molten metal passes through tundish inside it many flow modifiers like dams, weirs, baffles are applied to change the flow inside tundish to improve quality of steel since if the flow inside tundish changes it affects the whole process of continuous casting enormously. Many researchers[4], [5] analyses the changes in dam height and its position inside the tundish and gives best possible dam height and its position. After from tundish liquid molten steel passes through outlets and goes into the mold through submerged entry nozzle (SEN). Schematic of simple continuous casting process with important parts are shown below in Figure 1.

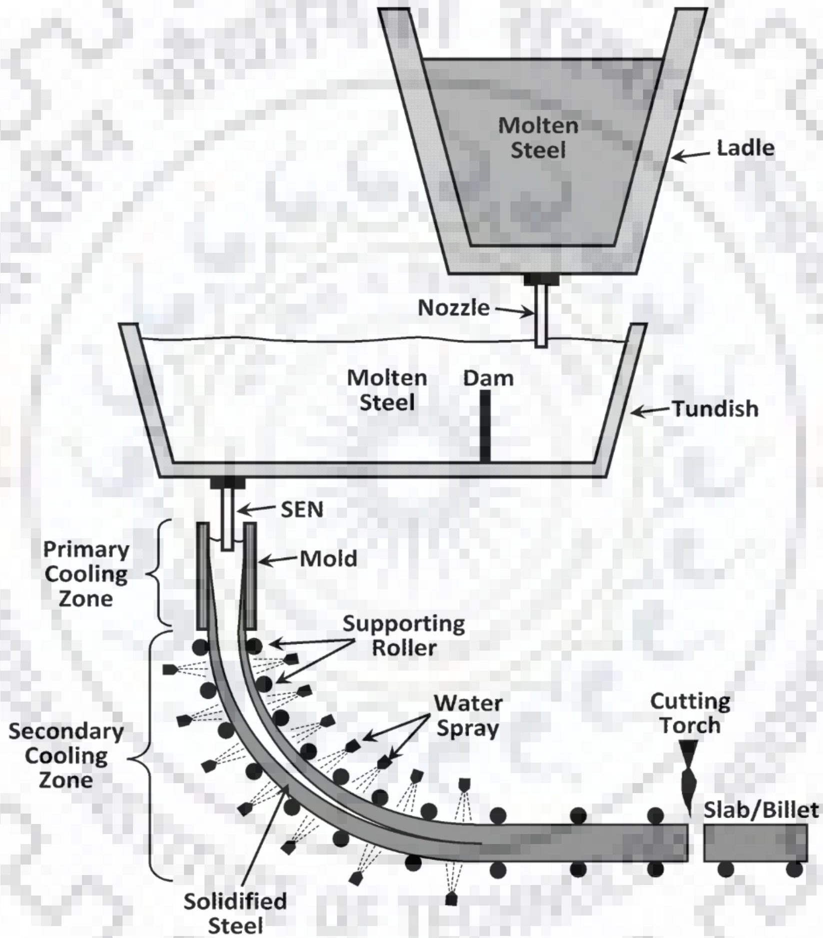


Figure 1 : Schematic of continuous casting process[1]

We required very high production rate and good quality for maximizing the profit but for high production rate we have to use high casting speed but with high casting speed we risk of defects like breakouts, shell thinning [6]and inclusions were increased[7] because these are influenced by fluid flow of that liquid steel especially inside mold. The influence of turbulent flow in mold is characterized by submerged entry nozzle with changing in port designs and its submergence depth. Submerged entry nozzles are of different types. Submerged entry nozzles can also be changed with make changes in their ports and flow pattern altered inside mold[8] like shape of port circular, rectangular, oval and square port[9], [10]. SEN also have single port type or double port type i.e. bifurcated or multiport. Also, size of SEN like its opening size, bore diameter, its thickness etc. By changing the angle of port flow is also altered and affect the flow inside mold. The depth up to which it is gone inside mold are also altered and up to some depth it also affects the fluid flow and product of continuous casting process. Many researchers investigated the role of submerged entry nozzle like changes in port angles from 0 to 45 degree and submergence depth up to 400 mm inside mold.

Inside mold the liquid molten steel enters through SEN and the flow inside it decides the quality of steel because chances of defects are many in during that process during mold oscillations[11] there is chances of scratches and many other defects due to mold oscillations. After SEN molten though mold or may be many molds as per the required thickness of the casting. First heat transfer or we can say primary cooling of liquid molten is done in mold through mold walls and first solidification starts, many researches gives different heat transfer models[7], [12], [13] for that phenomenon. Most preferred molds were copper molds due to having their properties that were desired for this process good refractory properties due to high temperature range but also have good conductor to start solidification. After that there are series of water sprays that helps to speed up solidification process and to support shell that forms during solidification is supported by support rollers. Mold flow leads to many defects so proper parameters required to produce defect free product, that why some called mold as a heart of this process. Molds are of many types and were used as per need like tubular or plate molds and according to need of caster they may be straight or curved. As discussed earlier most preferred molds are of cu, so to avoid its erosion they are coated with hard materials like chromium and others. Flux powders are used for minimizing defects during mold flow and oscillation marks on shell due to oscillation of molds during process.[14]

When it continuously solidified a sufficient thickness of shell is made which will support's the liquid molten pool and helps in avoiding surface cracks due to extra Ferro static pressures[1], [15]. Many researchers examines[6], [12] effect of velocity and superheat on shell thickness to analyses and give suggestions to produce defect free product. Since shell thickness plays an important role in producing surface crack[16] free products. In recent advancements some were applying magnetic forces to alter the flow inside mold[17] and trying to produce good quality products as per the need.

1.2 Modelling of Continuous Casting Process

Modelling of continuous casting process is required due to complications of physics phenomenon involved in this process and working conditions like very high temperatures due to these limitations process it is very difficult to perform experiments so models are made with help of physical models in mainly water models and experiments are done and results of that models are used for validations of results that were developed with the help of numerical and computational models[1], [2], [4], [18], [19] Different numerical models are developed using classical FDM or FV most commonly with CFD software and mainly ANSYS FLUENT during the course of time and some of them are fluid flow models for tundish and mold, heat transfer models, solidification models, models involving combination electromagnetic forces with flow models in mold[14].

Develop mathematical model as per need of physical phenomenon

Develop geometry in any software

Develop meshes of case framed in geometry

Apply boundary conditions and simulate with the help of fluent

Plot results and compare with experimental results obtained through physical model

The most commonly used for flow analysis is steady and single flow using RANS combined with turbulence models like standard k-ε model, the k-ε SST [20]which is used frequently for discuss the effect of turbulence with transport phenomenon. For study of inclusions and slag entrapment we can also use these basic models, For transient flow LES were utilized with finer meshes and smaller time step .For heat transfer inside different models developed to study heat transfer phenomenon because heat transfer leads to solidification in which most commonly used was enthalpy porosity technique to analyze shell thickness with different variations. Some analyzed effect on flow and solidification inside mold of EMS[17], [21]some models were developed to study crack, residual distortion and creep with the help of combination of thermal mechanical model[17]. Some modelling related to defects are also one for this process like for shell thinning, superheat transport and breakouts. Flow chart of modelling is shown below.

1.3 Tundish and its Role

As we discussed in section 1.1 tundish acts as a reservoir for this process due to continuous supply of liquid steel with very low velocity from outlets to mold through SEN .Due to further research and up gradation of technology it was made a refining vessel[7], [22], [23] rather than only reservoir and it is also acts as controller because it decides the composition and temperature inside it which further decides quality of steel since speed of liquid metal inside tundish has a significant role in inclusion which was a serious defect in deteriorate steel quality .Heat transfer and superheat also has a significant role in steel quality. Heat transfer decides solidification and solidification decides shell thickness and shell thickness decides quality of steel. We have to slow down the speed for proper solidification and have to give time for heat transfer otherwise shell is not much thick due to which it does not withstand against Ferro-static pressure and leads to bulging and surface cracks.

If there is very large heat transfer in tundish then for overcome that loss we have to supply extra energy in the form of superheat before inlet to tundish and due to that heat is uniformly heated gives good mixed flow and produce large turbulence and helps to reduce inclusion and also superheat helps in proper solidification. Tundish has refractory lining on the walls to withstand high temperatures and argon gases are also supplied to prevent oxidation of metals. The walls of tundish undergoes different wears like mechanical, chemical due to many complex reactions, thermal shocks, wear due to high temperature and erosion of walls [24]–[26]due to turbulent flow inside it. Due to having important as discussed in this section main focus is to improve its sequence life[27] which is that we have to change the lining of tundish by stopping the process and again made it fit for working which became economically loss to the industries. These relining greatly influenced by flow inside turbulence due to that wall shear stress induced since flow pattern inside it is turbulence due to that refractory wear rate and high velocity can create serious erosion of refractory, our objective is to minimize the skull that was formed due to erosion of lining of tundish. The schematic of erosion of lining is shown below in Figure 2.

Life cycle of refractory is influenced due to erosion of walls due to flow and impact on walls. Very few were analyzed wear due to wall shear[24], [25] inside it so it became area and to explore and study how we can minimize wall shear by considering and analyzing different cases. Main focus was of researches are mostly on flow behavior inside tundish using different flow modifiers, different geometries, different variations with shroud angles and by changings wall angles and width of tundishes. Tundishes are of many types and some are of different shapes and some are having different combinations of strands i.e. number of outlets are single, double, four strand, six strands.

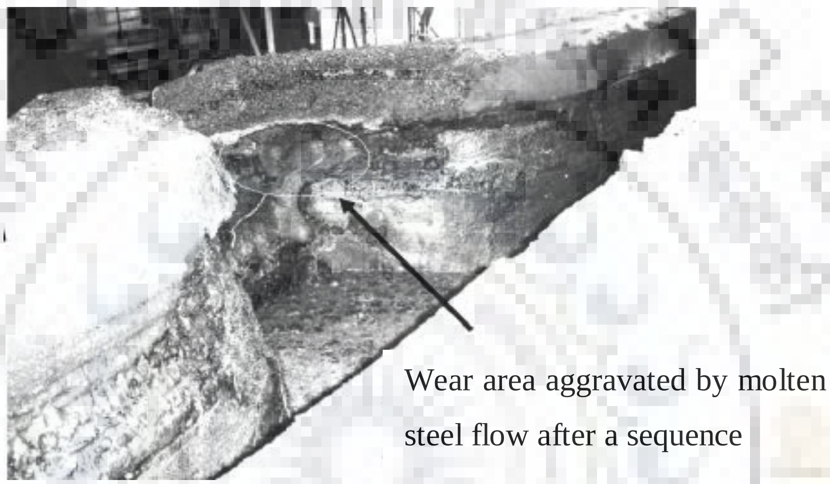


Figure 2 : Erosion of tundish due to wear[24]

Some of the important parts of tundish are shroud, impact pad, stopper rod other than refractory linings and flow modifiers like dams, weirs, baffles. Shroud used for delivering the liquid molted steel from ladle to inside the tundish through inlet and we can say shroud as a gateway of molten metal to tundish. Impact pad placed just below inlet at bottom to reduce the high velocity impact on bottom wall so that turbulence intensity of fluid can reduced and damages and wear should minimize and good quality of steel can be manufactured. Stopper rod acts as a controlling device of flow of liquid molten metal to the mold inlet through SEN as per the need of process. Generally, production rate ranges are from 1 Ton per minute to 2-3 Ton per minute and 5-7 Ton per minute and accordingly geometry of tundish process parameters are selected for the process.

1.4 Comparison of Continuous Casting with Ingot Casting Process

A brief comparison between two processes was made with the help of flow diagram of their method of steps involved in them and that gives an idea that there is no need of secondary process as finishing process after continuous casting that tells the importance and advantages of process over ingot casting.

As seen from flow chart of route we can say due to advancement in technology and research we can get better quality and high yield product in comparison with ingot and the energy and capital investment in ingot is higher than comparison with continuous casting.

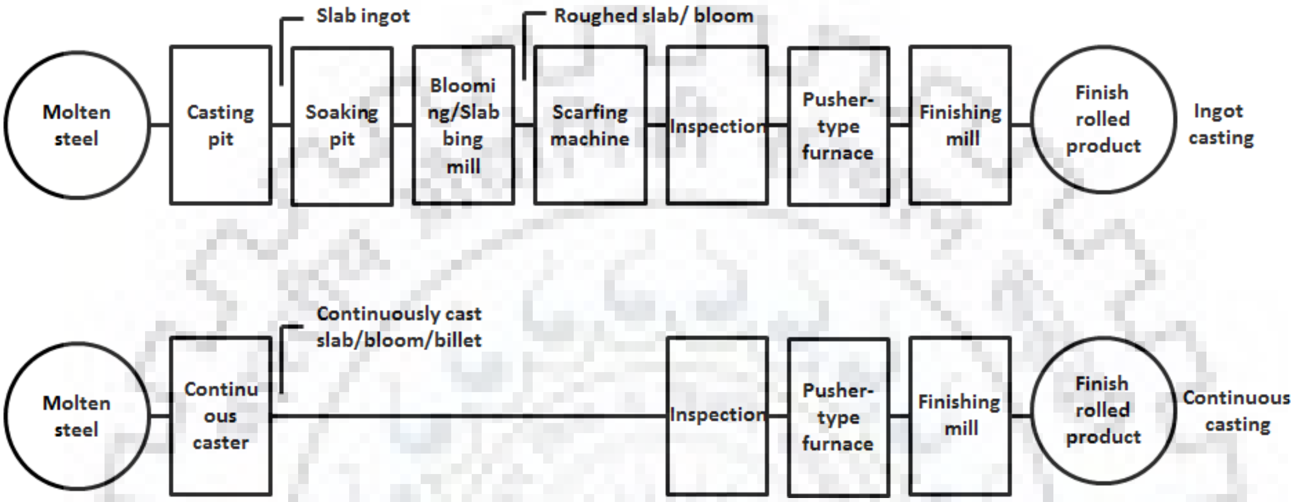


Figure 3 : Comparison of continuous casting with ingot casting.[3]

1.5 Organization of Dissertation

The dissertation is organized in five chapters in which the details of each chapters are discussed below

Chapter 1 has a brief introduction of continuous casting process and its modelling and mostly focus on tundish.

Chapter 2 is all about literature review of continuous casting in which it tells about research done in continuous casting over a decade of period.

Chapter 3 has brief of mathematical equations used for flow and heat transfer and specifications of geometries that were used for simulation of process

Chapter 4 has results of contours of wall shear stress and velocity vectors that were plotted for different cases discussed in chapter 3 and discussion was done to verify results that were obtained.

Chapter 5 have conclusions that can be drawn from the results and brief idea about future scope that can be done further in future.

CHAPTER 2

LITERATURE REVIEW

Over a last period of decade, research is going rapidly in continuous casting process because for steel production it is used more than 95% worldwide. Mostly author analysis it by using mathematical modelling either with help of flow model or heat transfer or solidification model, now days since good quality is of steel is required so authors are focusing towards modelling of defects in continuous casting process.

Thomas et al.[1]reviewed the work that was done till now in modelling of continuous casting process, Significant progress has been made in the ability of computational models to accurately predict fundamental phenomena in the continuous casting process (nozzle, mold, and strand), including temperature, solidified shell growth, turbulent fluid flow together with multiphase phenomena, electromagnetic effects and particle transport, microstructure and grain structure, thermal-mechanical behaviour, distortion, and stress. Indeed, basic heat transfer models are being used as part of model-based online control systems, for the control of spray water flow rates and breakout-detection warning systems in the commercial process. Significant inroads are being made toward predictions under transient conditions, which are often when defects form. However, the accurate prediction of real defects that affect the cast product is still in its infancy. Model predictions of clogging, inclusion entrapment, segregation, and cracks need much further validation and testing. Finally, the coupling together of the different phenomena into Multiphysics models, including the vastly different length and time scales of interest will remain a challenge.

Thomas et al.[2]discussed present past and future of modelling of continuous casting process. First he tells about what continuous casting is .After that in past he discuss how to calculate shell thickness with the help of casting speed and then discusses different models that were used in continuous casting like shell solidification model, mold thermal distortion and taper, stress due to thermal and crack occurrence that is how formation of internal cracks is avoided this is one of important challenge while producing steel, crack formed internally depends on the stresses how mechanical and thermal shocks is subjected to the shell. While in present fluid flow in mold and solidification in thin slab and billet caster is analyzed for breakouts below mold.

Mazumdar et al.[4]numerical and experimental studies are carried out on both aqueous and industrial tundish unit with different shapes like boat, rectangular, C, T, curved shaped with single and multi-strands using flow modifiers like dam's weirs and baffles etc. to investigate performance

Jha *et al.*[5] analyzed six strand tundish for mean residence time and ratio of v_c and v_d and firstly values were analyzed for all three outlets at zero immersion depth but height of advanced pouring box were changed and results were plotted after that ratio of v_c and v_d are plotted for different outlets separately with changes in APB height with shroud immersion depths and optimization of outlets position with APB height, shroud immersion is established with all possible positions

Maurya et al.[6]developed a model for continuous casting to investigate the effects like degree of superheat and casting speed with help of mathematical models available for it like solidification which uses enthalpy porosity technique which treated molten liquid as a mushy zone and heat transfer model which determines the solidification. Results shows that effect of superheat has not significant effect on solid shell thickness and temperature distribution while casting speed affects significantly both solid shell thickness and temperature distribution. With high casting speed less time available for heat transfer, no proper solidification takes place due to that solid shell thickness decreases and thus originates problems related to steel quality

Zhang et al.[7]used 4 strand tundish for investigation of flow and inclusion i.e. first investigated with the help of SEM after that proper mathematical model used for inclusion and fluid flow and then velocity vectors are plotted for different combinations of outlets openings with considering and without considering effect of gravity after that inclusions of different size that were taken for analyses were plotted. Superheat drop and values are also plotted and found that larger diameter inclusions were in very less amount of fraction at outlets for different combinations.

Calderon et al.[8]studied flow pattern of rectangular plot different type of geometries like square, rectangle and with changes their submergence depth .Effect of submergence depth was plotted for pressure change with casting method, turbulent kinetic energy with more pressure and turbulent intensities.

Calderon et al.[9]investigated fluid flow for different SEN design like with square port, circular port and rectangular plot and the intensity of turbulence is characterized with the parameters of SEN like bore diameter, angle .Mathematical model is developed and flow pattern were matched with dye for all three different shaped SEN with duration of time. After that flow vectors were plotted for different ports.

Conclusion was made that SEN with rectangular port were worse as far as flow and its intensity is concerned and SEN S is better. Due to that flow heat transfer and solidification is affected and creates problems like shell thinning, breaking, cracks formation due to the reason that not having enough strength of shell to withstand liquid pool.

Thomas et al.[15]discussed modelling of continuous casting related to defects presented to investigate the formation of several different types of defects related to flow phenomena. The amount of gas injection into the tundish nozzle to avoid air aspiration is quantified by modelling. Computational model calculations of superheat transport and surface level fluctuations are presented. Meniscus defects, such as subsurface hooks and their associated inclusions, may form if the superheat contained in the steel is too low, or if top-surface level fluctuations are too large. A thermal stress model has been used to compute the distortion of the meniscus during a level fluctuation. Gas bubbles and inclusion particles may enter the mold with the steel flowing through the submerged nozzle. In addition, mold slag may be entrained from the top surface.

Thomas et al.[18]used physical modelling of continuous casting process with water for simulating liquid molten steel for understanding the flow behaviour of the process. Different models are generated for different analysis. For heat transfer and solidification analysis a separate model is used with uses enthalpy porosity technique to solve solidification problem which includes pull velocity which is the velocity of a solidified shell by which it is pulled out with constant speed. For flow modelling in mold and tundish standard k-ε model is used which uses continuity equation, momentum equation and turbulent dissipation energy equation. While for superheat dissipation the transport and removal of superheat is modelled by solving transient heat conduction equation and flow model equations

Thomas et al.[19]discussed about fluid flow in continuous casting process. Firstly he talks about fluid flow modelling in continuous casting, thereafter discusses fluid flow in nozzles, fluid flow in mold, transport of second phase particles likes air bubble and inclusion and after that brief idea about multiphase flow models.

Jha et al.[20]investigated the tracer dispersion concentration with 9 different turbulent models and make comparison in their results with experimental results. standard k-ε model, the k-ε Chen-Kim (ck) and the standard k-ε with Yap correction (k-ε Yap) are models used and standard k-ε model does not gives better results during circuital flow so that that's the reason for comparing other models with each other models and these mentioned models are used for high Reynolds numbers and some models like LB,CK were used for low Reynolds number and compared these models with LES model by plotting dimensionless concentration with dimensionless time for different models.

Chattopadhyay et al.[23]reviewd the all research that was done during decade of 1999 to 2009 regarding mathematical and physical modelling of tundish operations .During this decade mostly focus was on different RTD curves and dimension less parameters used for tundish with different geometries and different models .Some of them analyzed the effect of various flow modifiers like dams, weirs ,baffles, advanced pouring boxes and their effects on flow behavior and some had analyzed effect of shroud and submerged entry nozzle on flow behavior while some had make their focus on inclusion separation while and focus is to make tundish as a refining vessel rather than just a reservoir vessel and very less attention made around slag entrapment.

Singh et al.[24]change in lining of tundish walls happens due to various wears which defined the sequence life of tundish i.e. after how much time we have to do relining of tundish i.e. we have to stop the process. Due to flow of molten steel wear of walls happens due to flow induced wall shear on the walls that wall shear is studies on the curved strand tundish shape with the help of 3D model i.e. The flow-induced shear stress on the wall of a six-strand curved type billet caster tundish has been computed by a 3D mathematical model. Effects of changes in walls inclination, tundish width, and curvature radius are studied for the wall shear values on different walls of tundish. With use of pouring chamber which modifies the flow, wall shear was also studied which shows significant role of pouring chamber and the peak values of wall shear that were observed were decreased with use of pouring chamber.

Siddiqui et al.[25]investigated numerical wall shear stresses induced on the tundish walls of three different shapes like boat shape, T shape and make comparisons to make decisions on selection on shape of it for a particular operation and make appropriate actions to reduce the wall shear and consequently erosion of wall reduces. Bottom wall of each tundish experienced maximum shear stress and T shape experienced maximum shear stress than other shaped except for back wall of T shape tundish and these results were verified with the help of velocity vectors and turbulent kinetic energy values with the help of contours.

Smirnov et al.[27]proposed a design with help of mathematical and physical simulation of tundish to improve the life of tundish and also gives an idea about ladle design for development inclusions by using calcium and additives in melt, A bucket shaped tundish with dosing nozzles were proposed because due to bucket shape it reduces turbulence inside turbulence. Liquid surface and flow motions were shown in for different time period.

Launder et al.[28]described work on the development of a particular turbulence model in which two differential equations were solved, the dependent variables of which are the turbulence energy k and the dissipation rate of turbulence energy E. Emphasis is given to aspects of the model having importance for flows adjacent to solid walls.

Chandrashekhar et al.[29]developed a physical and mathematical model and study the flow behaviour in continuous casting tundish .velocity vectors are plotted for different cases along with RTD curves with changing tracer density and investigated the effect on fluid flow and found that if tracer has a greater density than the liquid inside it then it alters the fluid flow because of buoyancy force that comes in effect to account density changes.

Jha et al.[30]investigated the flow analysis in six strand tundish to see the effects of changes in advanced pouring box height and position of outlets, ratio of dead volume is maximum only at particular positions of outlets so after getting optimized positions of outlets, effect of shroud immersion was studied for analyzing the ratio of mix to dead volume, mean residence time for outlet number 2 which shows if we use higher immersion depths mixing decreases significantly.

Chattopadhyay et al.[31]used 4 strand deltas shaped tundish for analysis on quality of steel of slight misalignment of shroud in two different planes on inclusions. For validation he uses full scale water model and model is validated with the help of flow pattern developed due to injection of ink. By making different combinations slag entrapment were obtained and results were compared for different cases of shroud inclination. After slag entrapment inclusion trajectories were plotted for different cases and concluded that small misalignment of shroud had adverse effects on steel quality and should be avoided.

Yang et al.[32]a mathematical model coupling fluid flow with heat transfer as well as solidification in continuous casting mold is presented. The model features the formations of meniscus and slag films, including the growth of slag rim. Furthermore, the model describes the evolution of heat flux and thicknesses of shell and slag films from cast-start to steady-state in combination with actual operating conditions.

2.1 Gaps and Opportunities

Most of the research in past was done on flow behaviour either in mold or tundish since the flow behaviour plays an important role in quality of product. Some analyzed RTD curves for optimization with help of different configuration but very few analyzed walls shear stress that also plays a significant role in tundish sequence life which can simultaneously affect the production rate due to stopping of process to relining and quality due to involvement of eroded worn material in molten metal. Thus, it gives an opportunity to analyze cases that were discussed in different literature for flow analysis which helps in predicting wall shear stress. Some of them analyzed flow by changing nozzle angle and depth in mold this gives an opportunity to change shroud depth in tundish and analyze wall shear stress.

2.2 Objective and Scope

On analyzing the relevant literature, the objective of the present work has been derived as –

"To explore the fluid flow analysis in tundish to analyze wall shear stresses and using that analyze the flow with changes in tundish in outlet positions with velocity, wall inclination, shroud depth and shroud inclination."

While considering the available resources the scopes of the present work are finalized as:

a) Wall shear stress analysis on boat shape tundish walls with different velocities and outlet positions.
b) Wall shear stress analysis on boat shape tundish walls with change in wall inclinations.
c) Wall shear stress analysis on boat shape tundish shapes and T shape with change in shroud immersion depth.
d) Wall shear stress analysis on boat shape tundish shapes and T shape with change in shroud immersion angle in xy plane.

CHAPTER 3

MATHEMATICAL MODEL

3.1 Need of Mathematical model

As we know that continuous casting process is a very sophisticated process in which it works on high temperature range due to that to do experimental work and analysis in refractory is very tedious with efforts and time, so to analysis this mathematical models are developed to understand the phenomenon that were involved in this process like flow analysis, heat transfer, transport phenomenon, solidification analysis. For particular phenomenon analysis we opted particular model for analysis with proper boundary conditions with proper assumptions of that particular model.

3.2 Governing Equations

Tundish becomes area of concern because during continuous casting lining of its material eroded due to various chemical attack, mechanical wear and softening of material due to high thermal shocks. Fluid flow in tundish regime are turbulent. Very few researchers[24], [25] analyzed the flow induced wall shear stresses on the tundish walls for this analysis we have to use different mathematical equations of flow.

For the flow analysis one of important equation is continuity equation that must be satisfied for the possibility of flow which was written below in equation form

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Where, ρ is the density of fluid through which flow is taking place and u_i is the flow velocity by that flow is taking place. This equation gives conservation of linear momentum under Navier Stokes equation. This equation is applicable under assumption of incompressible fluid in steady state.Momentum equation of Reynolds in detailed form can be written as below

$$\frac{D}{Dt}(\rho U_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_J}\left[\mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \overline{\rho u_i u_j}\right] \tag{2}$$

Where,

μ = effective kinematic viscosity of fluid, and

$$\overline{u_i u_j} = \frac{2}{3}k\delta_{ij} - v_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)$$

$$v_t = C_\mu f_\mu \frac{k^2}{\varepsilon} \quad , \quad \mu_{eff} = \rho v_t + \mu$$

Above momentum equation is also called as Reynolds equation.

For tracer dispersion analysis for plotting F and C curves for the validation of model dispersion equations are used that are written below

$$\frac{D(\partial k)}{Dt} = D_k + \rho P - \rho\varepsilon \tag{3}$$

$$D_\emptyset = \frac{\partial}{\partial x_J}\left[\left(\mu + \frac{\mu_t}{\partial x_i}\right)\frac{\partial \emptyset}{\partial x_j}\right], \qquad P = -\overline{u_i u_j}\frac{\partial U_j}{\partial x_i}$$

$$\frac{d(\rho\varepsilon)}{dt} = D_\varepsilon + C_1 G\frac{\varepsilon}{k} - C_2\frac{\rho\varepsilon^2}{k} \tag{4}$$

$$\mu_t = \rho c_\mu \frac{k^2}{\varepsilon} \qquad \text{(turbulent viscosity)}$$

Now for the calculation of wall shear stresses that is induced due to turbulent flow inside tundish an equation is given by launder and Spalding in their mathematical model that was used written below in equation form.[24], [25], [28], [33]

$$\frac{\rho u_p c_\mu^{1/4} k_p^{1/2}}{\tau_w} = \frac{1}{k} ln\left\{E\frac{\rho y_p c_\mu^{1/4} k_p^{1/2}}{\mu}\right\} \tag{5}$$

Where, ρ is density of fluid, τ_w is wall shear stress at particular wall and up is taken as mean velocity variable of the center of the mesh cell that is just adjacent to wall that is considered as frictionless and stationary whereas, y_p is taken as distance variable of a particular point p of cell that is adjacent to wall, turbulent kinetic energy variable of a particular point p is k_p, k is the Von Karman constant (0.4187), and E is the empirical constant (9.793)

Constants used in different models are as follow [10], [20], [23], [30], [34]

$\boldsymbol{k - \varepsilon}$ ***model***

$C^*_1 = C_2 = 1.44, \qquad C^*_2 = C_2 = 1.92, \sigma_c = 1.0$

$\sigma_k = 1.0, \sigma_\varepsilon = 1.3, \qquad f_1 = f_2 = f_\mu = 1, \; C_\mu = 0.0$

3.3 Problem Definition

A two different shape tundishes were used for the analysis of wall shear, one of them is simple boat shape and another one is T shape. After making the geometries basic variations are done in the geometries and then effect is analyzed on all cases. Boat shape and T shape six strand tundish is used for analysis of flow induced wall shear stress by changing velocity at inlet, positions of outlets, shroud angles and shroud submergence. Geometry of boat shape tundish and T shape tundish are shown below in Figure 4 and Figure 5 respectively. But for reducing numerical simulation time a symmetric half tundish about symmetric plane at inlet is used for analysis. Wall at bottom named as bottom wall while which is on near to outlets along $+z$ direction named as front wall and wall opposite to it named as back wall while wall opposite to symmetry wall is named as far wall. Boat shape tundishes that are used for simulations have three outlets namely near outlet, middle outlet, far outlet at a distance of 600mm, 1700mm, 2800mm respectively from inlet. Rectangle shaped inlet of area and square outlets holes of area are used because in circular holes mesh generated is unstructured due to this it creates problems in simulation process. Geometric dimension of tundish that were used for simulations are shown in Figure 4 below.

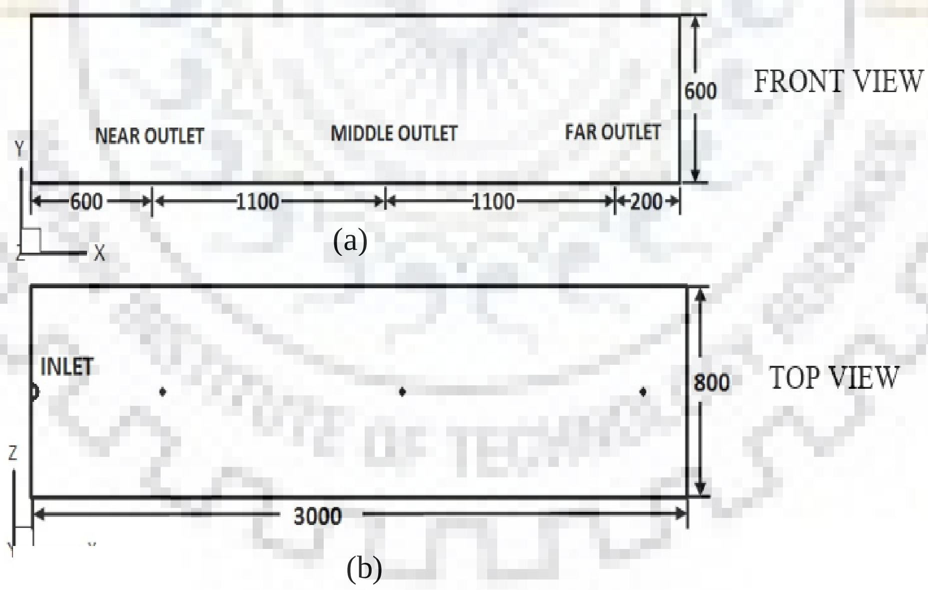


Figure 4 : Geometric dimensions of boat shape (a) front view (b) top view

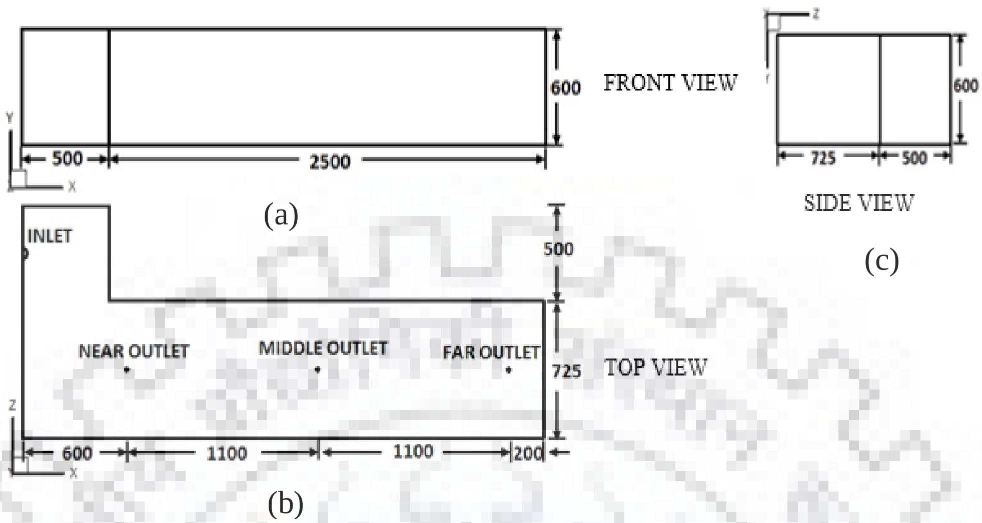


Figure 5 : Geometric dimensions of T shape (a) front view (b) top view (c) side view

From above Figure 5, we can see that a T shape tundish geometry was shown with their different views, which has three outlets namely near outlet, middle outlet and far outlet at 600 mm,1700 mm and 2800 mm respectively from inlet. Length of T shape tundish is 3000 mm with height same as of boat shape 600 mm. Inlet of rectangular shape of area 25.035×50.07 mm^2 was used while each outlet having square shape of 15.07×15.07 mm^2 area. Wall at bottom named as bottom wall while which is on near to outlets along $+z$ direction named as front wall and wall opposite to it named as back wall while wall opposite to symmetry wall is named as far wall. For reducing numerical simulation time, a symmetric half tundish about symmetric plane at inlet is used for analysis. The detailed dimension and values of geometry of actual and used for numerical simulation are shown in table 1 shown below. Which clearing showing that due to considering wall as symmetry along zy plane at inlet three outlets along x direction are used only for simulation and due to symmetry conditions, we can get similar results along second half of tundish. Thus, for simple boat shape and T shape the numerical calculation was done for only three outlet cases. Earlier geometries are used for analysis after the change in outlet position or wall inclinations or with change in shroud depth immersion and its misalignment in different plane. For shroud angle here we discuss only 5-degree rotation in xy plane in clockwise and anticlockwise direction.

Table 1 : Geometrical dimensions of tundish

Parameters	**Used for simulation**	**Actual geometry**
Volume	1.44 m^3	2.88 m^3
Length	3 m	6 m
Breadth	0.8 m for boat and 1.25 for T	0.8 m for boat and 1.25 for T
Height	0.6 m	0.6 m
Number of outlets	3	6
Inlet area	25.035×50.07 mm^2	50.07×50.07mm^2
Outlets area	15.07×15.07 mm^2	15.07×15.07 mm^2

3.3.1 Variation in Geometry Due to Positions of Outlets

Variation of outlets positions are done in boat shape tundish and after that effect of that change is analyzed by performing simulations with changes in velocities for particular cases and after that contours are plotted for wall shear stress on different walls. Four different geometries of dimensions as discussed in Table 1 are used for analysis having positions of outlets changes only along $+z$ direction while keeping other dimensions fixed. First case is of having all three outlets at $z = 0$mm and after that three cases of having their three outlets at $z = 100$ mm , $z = 200$ mm, z = 350 mm from symmetry line i.e. z = 0 mm along x axis on the bottom wall of tundish as discussed in case form in Table 2 below and top views of their geometries are shown in Figure 6 below.

Table 2 : Geometry cases due to outlet positions

Geometric configuration	**Name of the case**
All three outlets at z = 0 mm line	case A
All three outlets at z = 100 mm line	case B
All three outlets at z = 200 mm line	case C
All three outlets at z = 350 mm line	case D

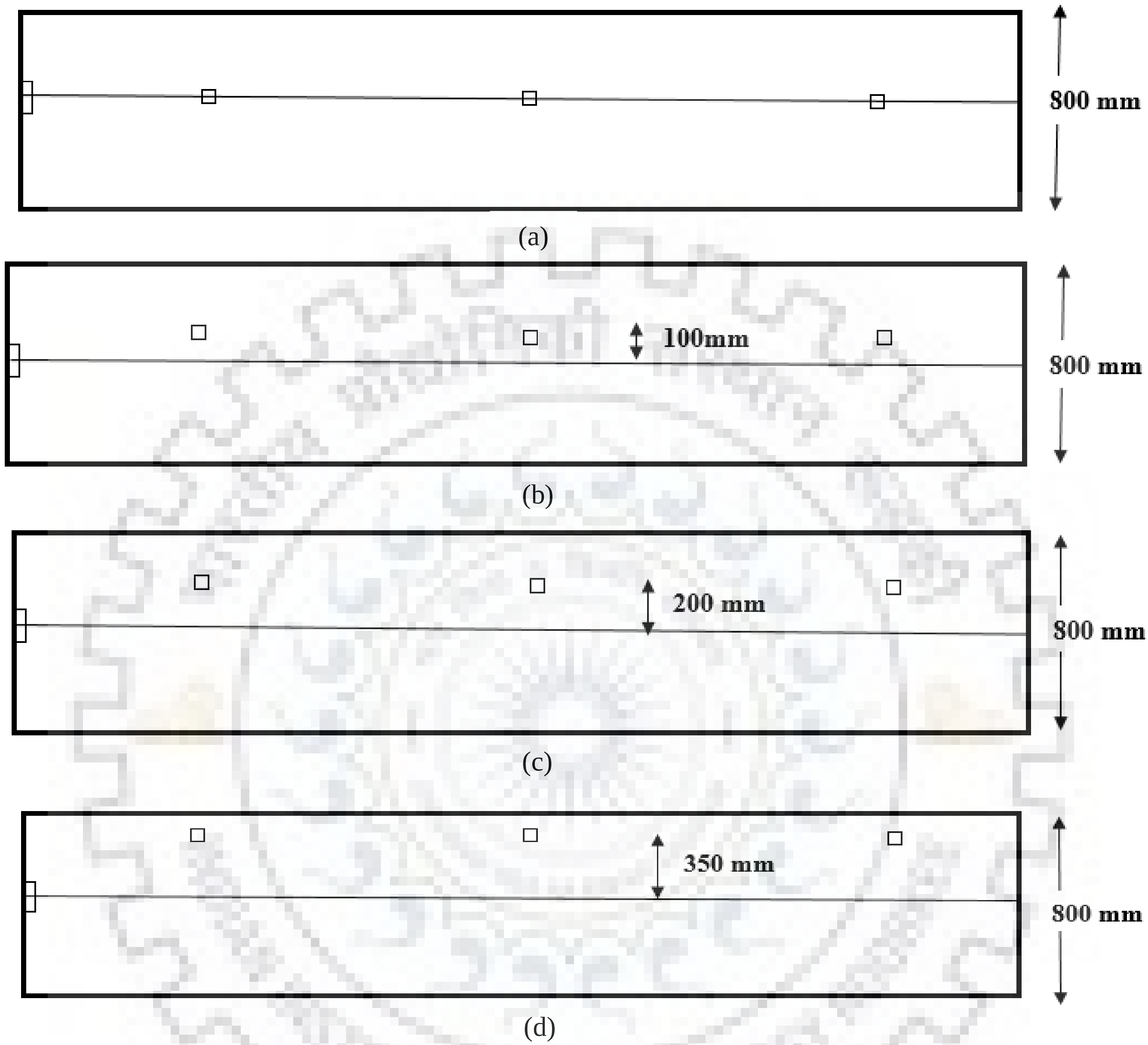


Figure 6 : Top view of boat shape tundish (a) case A(b) case B(c) case C(d) case D

3.3.2 Variation in Geometry Due to Wall Inclinations

In this, cases are made by changing inclination of walls of simple boat shape tundish discussed in problem definition of simple boat shape tundish with all three outlets at the symmetric line along xz plane with. z = 0 mm along x axis. Two variations are made with inclinations of large and small walls angle in which θ_s represents angle of small wall and θ_l represents angle of large walls of tundish. These combinations are discussed in Table 3 below and their front and right views of all three cases are shown in Figure 7 below.

Table 3 : Geometry cases due to wall inclinations

Geometric configuration	Name of the case
$\theta_s = 0°$ and $\theta_l = 0°$	case A
$\theta_s = 5.7°$ and $\theta_l = 11.3°$	case B
$\theta_s = 7.1°$ and $\theta_l = 14.0°$	case C

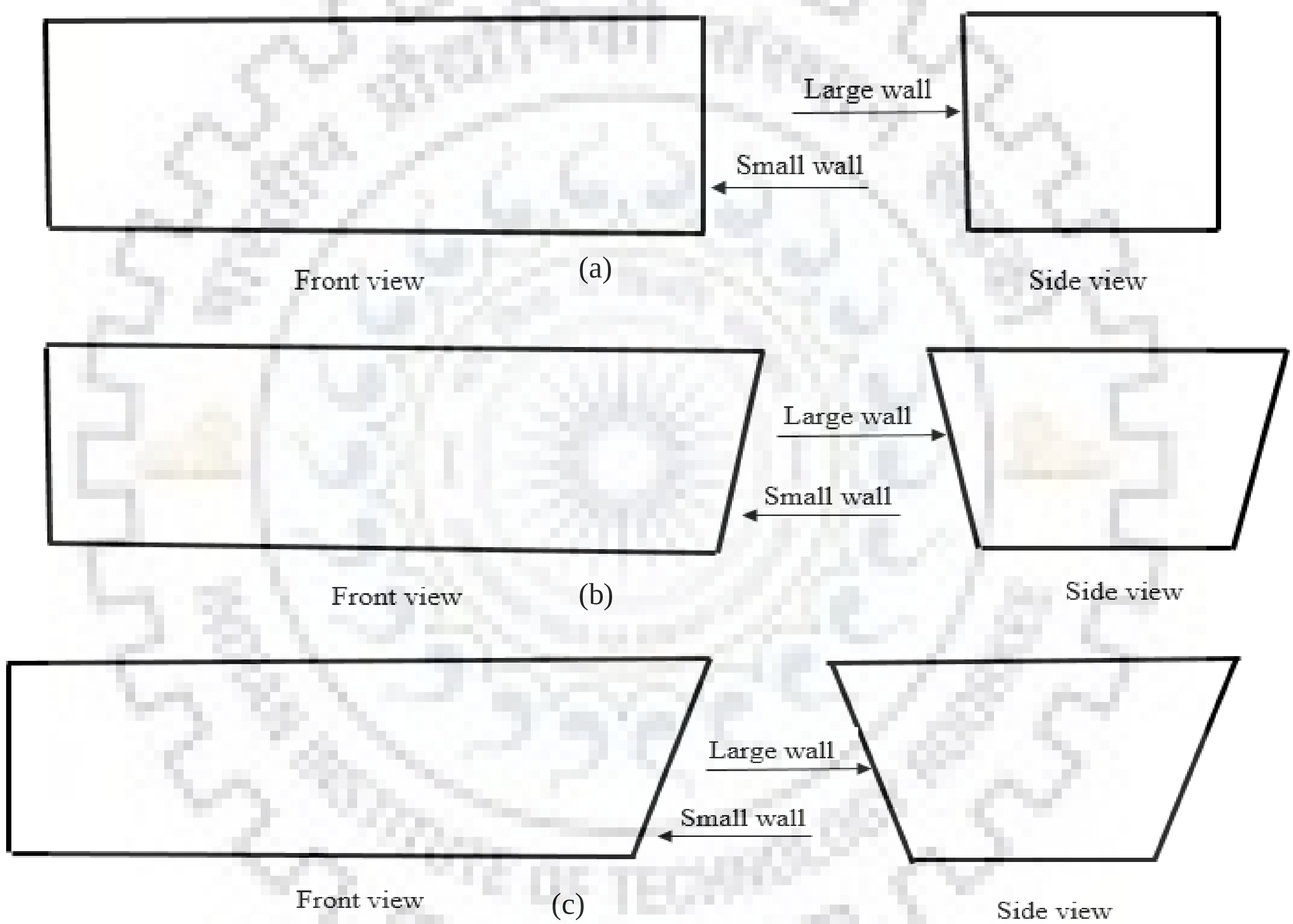


Figure 7 : Front and side view of wall inclination (a) case A (b) case B (c) case C

3.3.4 Variation in Geometry Due to Submergence Depth of Shroud

The shroud through which liquid steel is flows into inlet of tundish, its depth changes for the analysis of wall shear of walls in the four possible geometries with simple boat case, two boat shapes with wall inclinations discussed in previous section of 3.3.2 and T shape tundish. The simple boat shape tundish inlet taken as reference and depth is measured from that reference and movement along downward direction taken as positive. Possible cases were listed in the Table 4 below

Table 4 : Geometry cases due to shroud depth

Geometric configuration	Name of the case
Shroud depth 0 mm	case A
Shroud depth 100 mm	case B
Shroud depth 200 mm	case C
Shroud depth 300 mm	case D

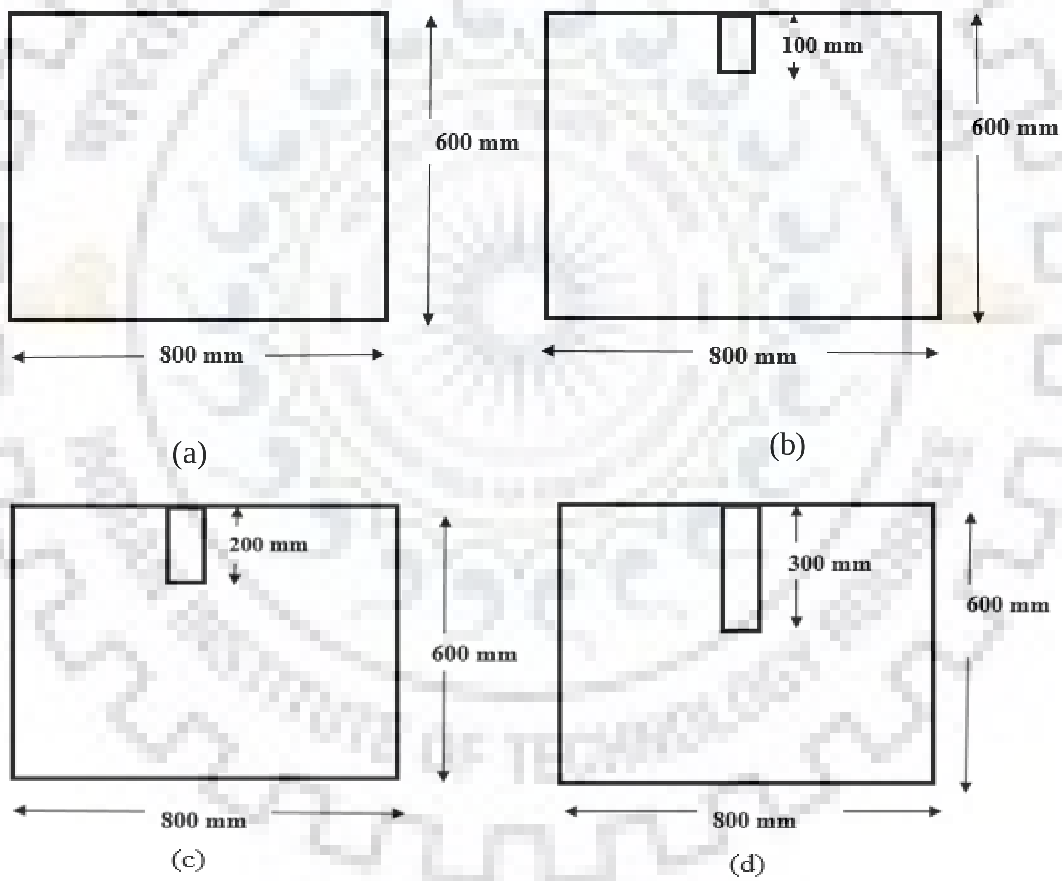


Figure 8 : Side view of boat shape for shroud depth (a) case A (b) case B (c) case C (d) case D

3.3.4 Variation in Geometry Due to Inclinations in Shroud

The shroud through which liquid steel is flows into inlet of tundish, variations in shroud angles were made and effect on wall shear has analyzed on different walls of tundish. In these variation shroud angles are changed in xy plane and its values are changed 5 degrees in clockwise and anticlockwise and we take clockwise direction rotation as positive and anticlockwise shroud rotation as negative, possible cases were listed in the Table 5 below.

Table 5 : Geometry cases due shroud inclination

Geometric configuration	**Name of the case**
Rotation = 0°	case A
Rotation in xy plane = 5	case B
Rotation in xy plane = -5	case C

3.4 Boundary Conditions

Our objective is to obtain wall shear stress variation and velocity vectors due to turbulent flow inside it, no slip conditions in walls follows log law function for calculation of shear stress. For that we have to apply certain boundary conditions in ANSYS software. At inlet position turbulent intensity of 2% with turbulent length scale of .07 times inlet diameter are set, walls are set with no slip condition, zero velocity and considered as frictionless. At symmetry wall along which the geometry is symmetric along length symmetry conditions is applied and at outlets outflow conditions are set at near, middle, far outlets to maintain mass flow rate and steady state. For tracer dispersion analysis with all above conditions it was also considered that walls are impervious to the tracer i.e. zero flux is considered at all boundary surfaces and all conditions with parameters are shown in Table 6 below.

For analysis of heat transfer in tundish different heat transfer flux are considered at different walls .Wall that is constructed in positive z direction in xz plane is named as front wall and the wall that is constructed in negative z direction in xz plane named as back wall while heat flux from both these walls is taken as 3200 Wm^{-2} with thickness of wall as 200 mm .Wall that is opposite to symmetric plane is named as far wall and heat flux from that wall is taken as 3600 Wm^{-2} with thickness of wall as 200 mm .Wall that is at bottom of tundish named as bottom wall and from that heat flux is taken as 1400 Wm^{-2} with thickness of wall as 200 mm. Top wall of tundish i.e. free surface is named as top wall and flux through that wall is taken as 10000 Wm^{-2} with thickness of wall 50 mm. Initially simple boat shape tundish with changes in outlets position was simulated for wall shear stresses with changes in velocity of value 1 ms^{-1}, 1.2 ms^{-1} and 1.5 ms^{-1} respectively of all four different cases of outlets positions in which temperature at inlet is taken as constant and have a value of 1853 K and effect of velocity change is analyzed on wall shear values with changes in outlet positions. After that all other discussed cases are computed with constant velocity of magnitude 1.4 ms^{-1}

Table 6 : Boundary conditions and operating parameters [24],[25],[7]

Parameter	Value
Inlet velocities	1m/s,1.2 m/s,1.4 m/s ,1.5 m/s
Inlet turbulent intensity	2%
Turbulent length scale	0.07 times of inlet diameter
Inlet temperature	1 853 K
Inlet condition	Velocity inlet
Outlet condition	Outflow
Heat flux at free wall of tundish	10 kWm^{-2}
Heat loss at bottom wall of tundish	1.4 kWm^{-2}
Heat loss at long wall of tundish	3.2kWm^{-2}
Heat loss at short wall of tundish	3.6 kWm^{-2}
Thickness of free wall	50 mm
Thickness of bottom wall	200 mm
Thickness of small wall	200 mm
Thickness of large wall	200 mm
Submergence depth	0 mm, 100 mm, 200 mm, 300 mm

3.5 Assumptions

a) Tundish is assumed to be operated at isothermal condition.[7]

b) Fluid flow of liquid steel is considered as incompressible.[24]

c) Density of liquid steel considered as invariant.

d) Specific heat considered as invariant.

e) Production and dissipation of turbulence kinetic energy are assumed to in equilibrium in wall adjacent to control volume.[17], [18], [25]

f) Entrapment of gas and air in tundish is neglected for analysis.

g) Mold oscillations, bending of strand, effect of segregation etc. have been ignored and perfect contact between shell and mold is considered as shrinkage due to solidification is ignored. [6], [7], [17]

3.6 Computational Procedure

After creating geometry of different cases that has been studied for wall shear stress analysis a fine mesh is generated in meshing tool after that multi-zone method is applied on whole body for creating fine meshes and overcome error in meshing due to discontinuities and at inlet again resizing is done by dividing it into further 50 divisions and at all three outlets are resized with dividing it into 25 divisions with high dense structures and after that inflation is applied at all boundaries using 5 layers and 1.2 growth rate. A fine grid mesh was generated near the walls since it incorporates boundary phenomenon. We cannot take very fine mesh due to the fact that numerical computation time increases significantly. Near discontinuities we have also to take care of that by again providing better fine mesh to consider the effect of boundary layer phenomenon. After that the geometry and meshing, we take pressure based, absolute velocity and steady state with consideration of gravity as general setting for analysis. For calculation we use standard 2 equation k- ε model and make sure to on the energy equations. In material we use steel as our fluid material and refractory of certain property as a solid material that has been used for walls and the properties related to fluid and solid materials are mentioned in Table7.

Table 7 : Material properties of liquid steel and refractory wall [7], [18], [19], [22], [24], [25], [31], [34]

Material properties	**Value**
Steel density	7020 kg m^{-3}
Viscosity of liquid steel	0.007 kg $m^{-1}\cdot s^{-1}$
Thermal conductivity of steel	41 W $m^{-1}K^{-1}$
Specific heat of steel	750 J kg^{-1} K^{-}
Density of refractory wall	2490 kg m^{-3}
Specific heat of wall	1260 J kg^{-1} K
Thermal conductivity of wall	1.5 W $m^{-1}K^{-1}$

Now in cell zone conditions we change material to steel from air. In solution method SIMPLE scheme is applied i.e. semi implicit method for pressure linked equations, green gauss cell method was used for faster convergence and good results. A second order upwind was set for variables like pressure, momentum, turbulent kinetic energy, and turbulent dissipation rate which ensures high accuracy results. In controls section under relaxation factors having constant value are inserted that are for pressure is 0.3, density is 1, body forces are 1, momentum is 0.7, turbulent kinetic energy is 0.7, turbulent dissipation rate is 0.8, energy 1, turbulent viscosity is 1. Converging conditions are set 10^{-4} for velocity in x direction, velocity in y direction, velocity in z direction, epsilon, and continuity and 10^{-6} for energy. For initialization of simulation we initialize it as standard initialization from inlet with relative to cell zones. After that contours and velocity vectors were plotted for different cases with the help of CFD post.

3.7 Model Validation

A simple T shape model is validated with the help of plotting F curve for far outlet with numerical procedure and compared with experimental results. F curve is a variation of concentration with time. Initially the F curve is plotted numerically by considering steady state and making species transport tracer concentration zero and flow is solved in computationally by considering the same boundary conditions that were discussed in section 3.4 of this chapter.After converging the solution same case and data is imported with making unsteady state and activating species transport model with steel tracer as a mixture with inlet diffusion. After that putting the same boundary conditions that were used for steady state change the tracer concentration at inlet and patch the steel zone with tracer after initialization and curve is plotted in monitor output. Schematic of T shape tundish that is used for experimental process is shown below in Figure 9.

Figure 9 : Schematic of T shape tundish used for validation

Experimental set up for this validation is shown below in Figure 10 in which one ladle has water and other ladle has tracer.

Figure 10 : Experimental set up of continuous casting process.

After experiment F curve is plotted for far outlet of T shape tundish and compared with F curve obtained through numerical procedure as shown below in Figure 11. On comparison the characteristic of F curve for T shape tundish at far outlet is almost similar for both the cases with some possible error due to solving model computationally with some assumptions and thus found model applied is validated.

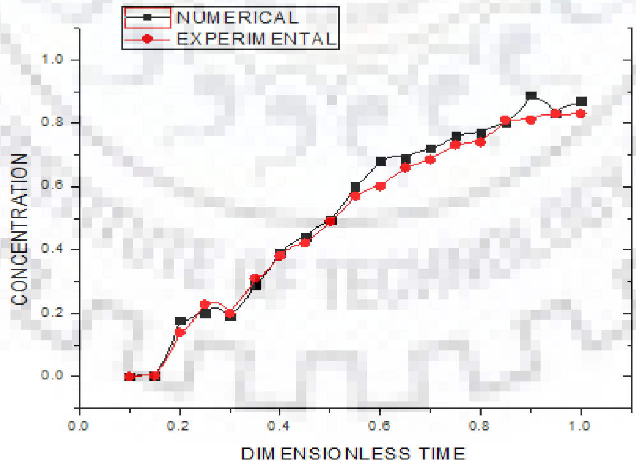


Figure 11 : Comparison of F curve for T shape at far outlet

CHAPTER 4

RESULTS AND DISCUSSIONS

The different geometries with different velocity by keeping other things constant were simulated with the help of ANSYS FLUENT 19 and contours developed are shown below for different cases. Flow-induced wall shear stress has been computed in the tundish mainly observing the maximum wall shear stress because it is that limits the life of the tundish First the effect of change of outlets positions with change in velocity were analyzed. After that wall shear was analyzed with change in wall angles of simple boat shape tundish after that effect of shroud depth with different immersion depth were analyzed for all possible geometries like simple boat shape, with changes in wall inclination and T shaped after that angle variations in shroud were analyzed and contours of wall shear stresses and velocities were plotted for different planes. Different cases that were analyzed are given in bullet forms below.

a) Effect of outlet positions with changes in velocity on wall shear stress.
b) Effect of wall angle inclinations on wall shear stress and comparison of results with T shape.
c) Effect of submergence depth of shroud in possible four different tundish geometries discussed on wall shear stress.
d) Effect of shroud angles in four different tundish geometries on wall shear stress.

4.1 Effect of Outlet Positions on Wall Shear Stress

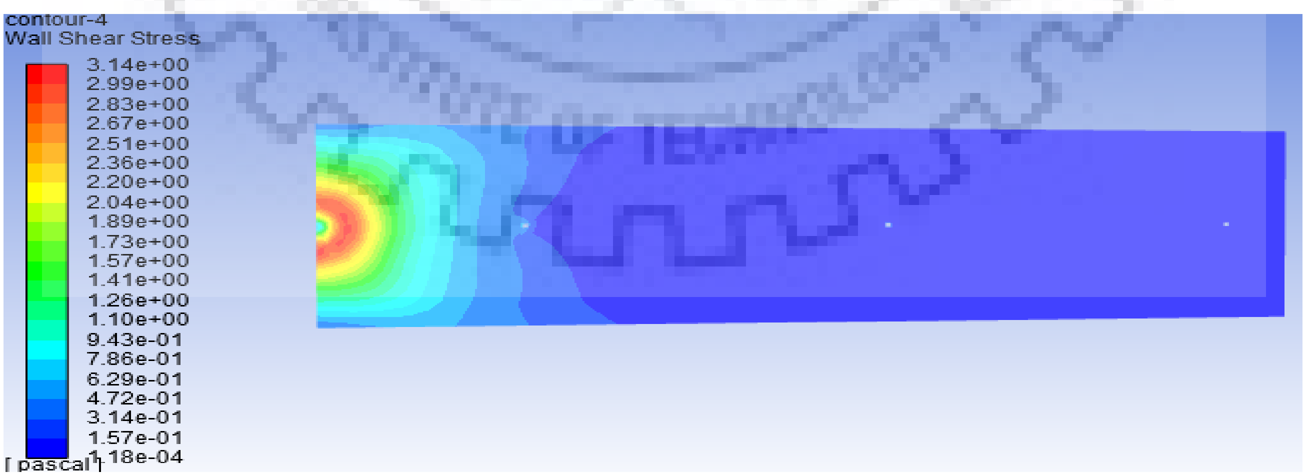
All four geometries that are discussed in problem definition section 3.3.1 in chapter 3 are solved for wall shear stresses with changing three different inlet velocities and keeping all other things constant. Results of contours and plots for wall shear stresses variations at different velocities and different walls are discussed below for different cases and their wall shear contours and velocity vectors for different walls and planes to discuss the effect.

4.1.1 Outlets at z = 0 mm Line

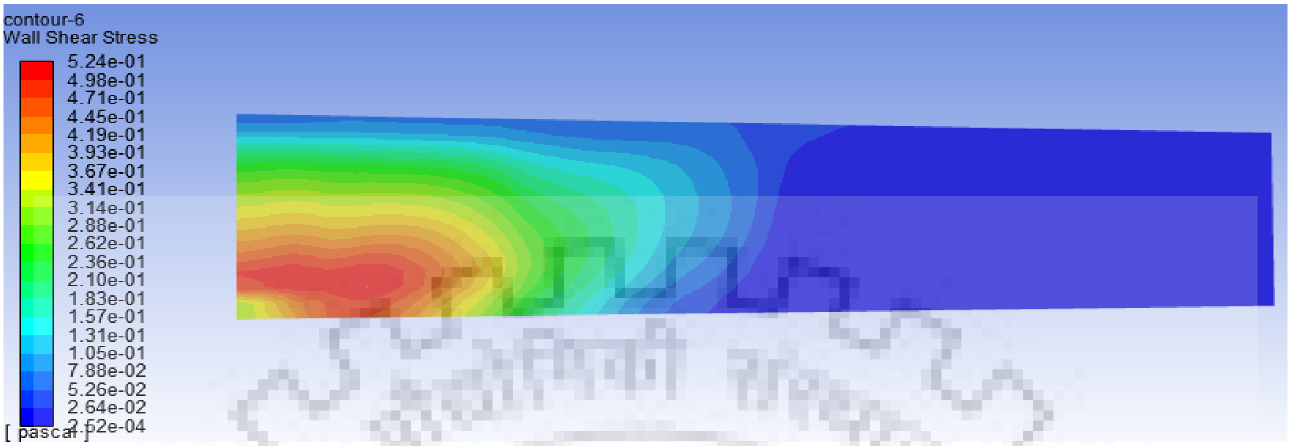
In this case the positions of three outlets are at $z = 0$ mm as depicted in section 3.3.1 in chapter 3 and in figure 6(a), and keeping all other parameters constant and effect of inlet velocity is observed on wall shear stresses on different walls by using its value of velocities of 1m/s, 1.2 m/s, 1.5 m/s. Outlet plane is defined as a plane parallel to XY plane and passes through all three outlets and wall shear and velocities are plotted for different velocities.

(a) V = 1.2 m/s

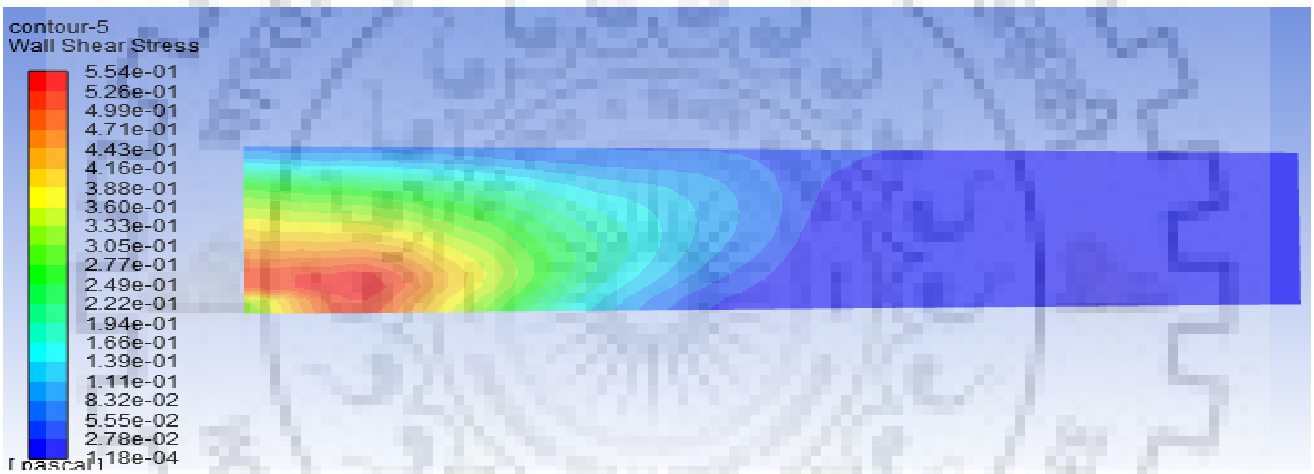
For symmetric case that having all three outlets at center line i.e. $z = 0$ is simulated with for the calculation of wall shear stresses, contours of wall shear stresses for different walls are shown below in Figure 12, from where we can see that maximum shear stress is generated on bottom wall due to high flow and magnitude of velocities on the bottom wall. Therefore, erosion takes place due to high shear stress on the bottom wall. Once the fluid stream crosses the near outlet and reaches in between near and middle outlet, the velocity seems to be less in x-direction and slowly some part of fluid stream seems to move toward the top free surface and also the extent of wall shear along length is mostly near to inlet where more turbulence and the density of velocity vectors are maximum near to near outlet up to middle outlet there is sudden increase of wall shear stress on the positions of three outlets at bottom wall due to sudden turbulence at outlets leads to more erosion and sudden small peaks were observed. After that wall shear contours were shown in which wall the shear stress generated is maximum near to inlet along length for both the wall .Velocity vectors are shown in Figure13, at bottom plane and outlet plane to provide evidence that wall shear stress generated along Front wall is less than back wall due to reason that after inlet number of particles moved towards back wall is more so the flow induced stress generated is more on back wall than on front wall. The extent of turbulence along length on front and back wall is more in comparison of bottom wall but along height the front wall has more effect of turbulence than back wall. Contours of wall shear and velocity are plotted below for different walls for this particular geometry case.



(a)

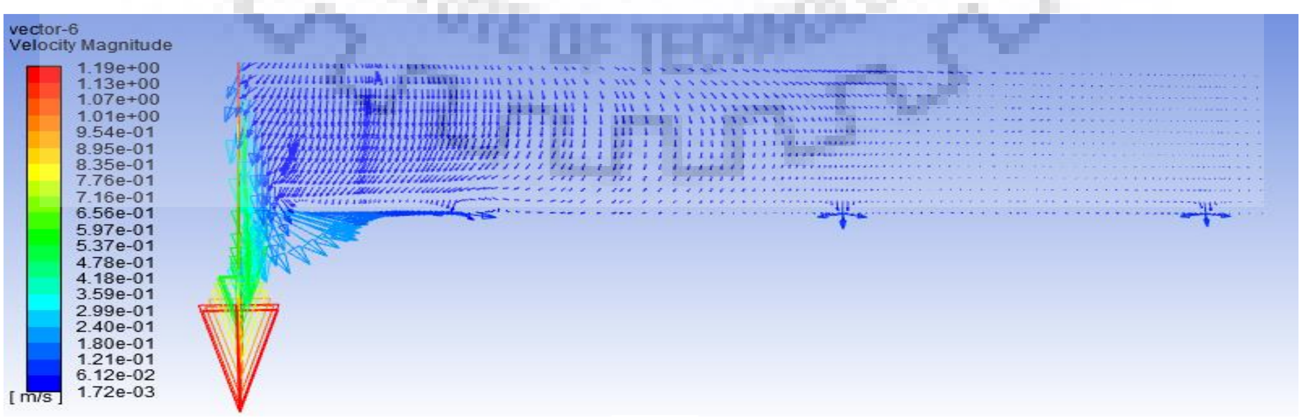


(b)

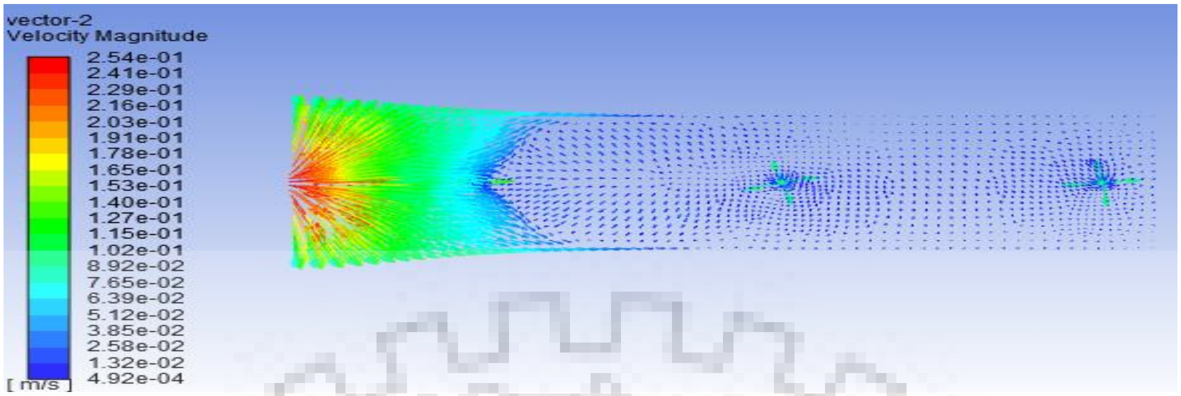


(c)

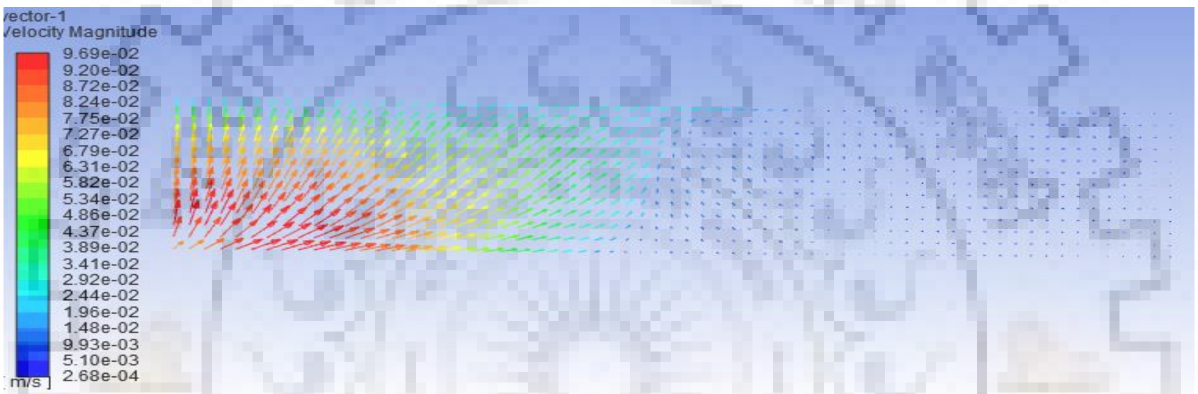
Figure 12 : Wall shear contours for case A i.e. outlets at (z=0) (a) bottom (b) front (c) back



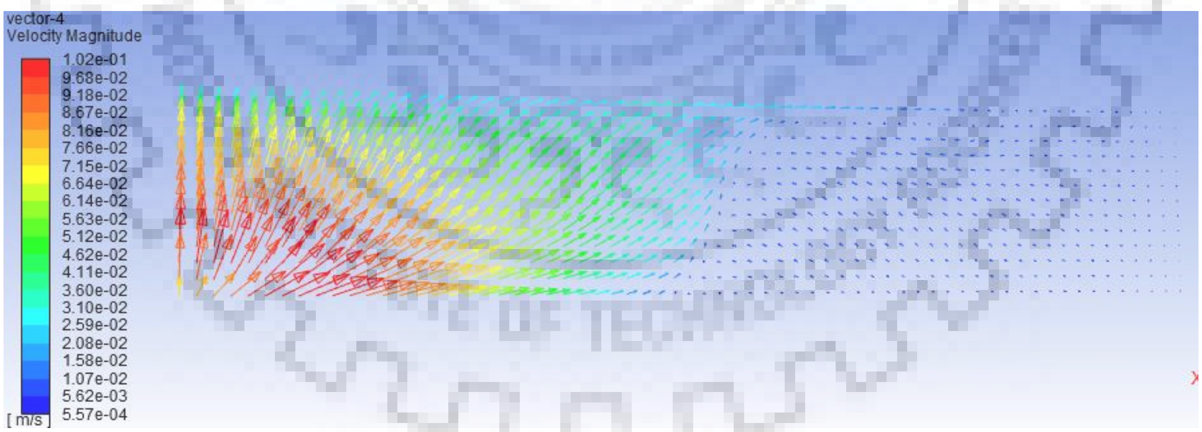
(a)



(b)



(c)



(d)

Figure 13: Velocity vectors for case A i.e. outlets at (z=0) (a) outlet plane (b) bottom (c) front (d) back

(b) V = 1 m/s

For symmetric case that having all three outlets at center line i.e. $z = 0$ is simulated with for the calculation of wall shear stresses Contours of wall shear stresses for different walls and velocity vectors .we got the pattern of contours and velocity vectors similar to the case of velocity 1.2 m/s but with decreased value than 1.2 m/s case and we have value of wall shear stresses are 2.22, 0.369, 0.393 in Pa for bottom, front and back wall respectively and value pattern are also same like bottom wall has more shear than other two walls and back wall has more value of shear than front that can be easily evident with the value and pattern of velocity vectors.

(c) V = 1.5 m/s

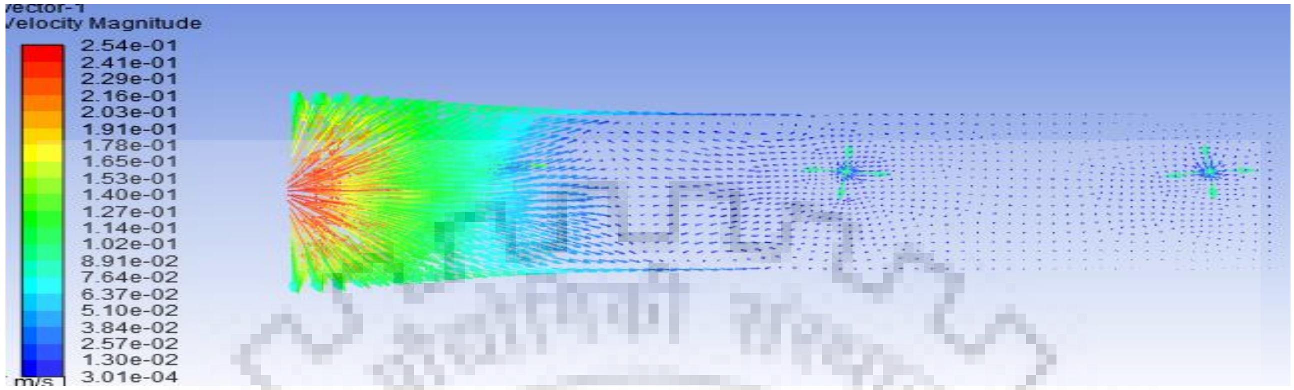
For symmetric case that having all three outlets at center line i.e. $z = 0$ is simulated for the calculation of wall shear stresses Contours of wall shear stresses for different walls and velocity vectors .we got the pattern of contours and velocity vectors similar to the case of velocity 1.2 m/s but with increased value than 1.2 m/s case and we have value of wall shear stresses are 4.68, 0.708, 0.853 in Pa for bottom ,front and back wall respectively and value pattern are also same like bottom wall has more shear than other two walls and back wall has more value of shear than front that can be easily evident with the value and pattern of velocity vectors.

4.1.2 Outlets at z = 100 mm Line

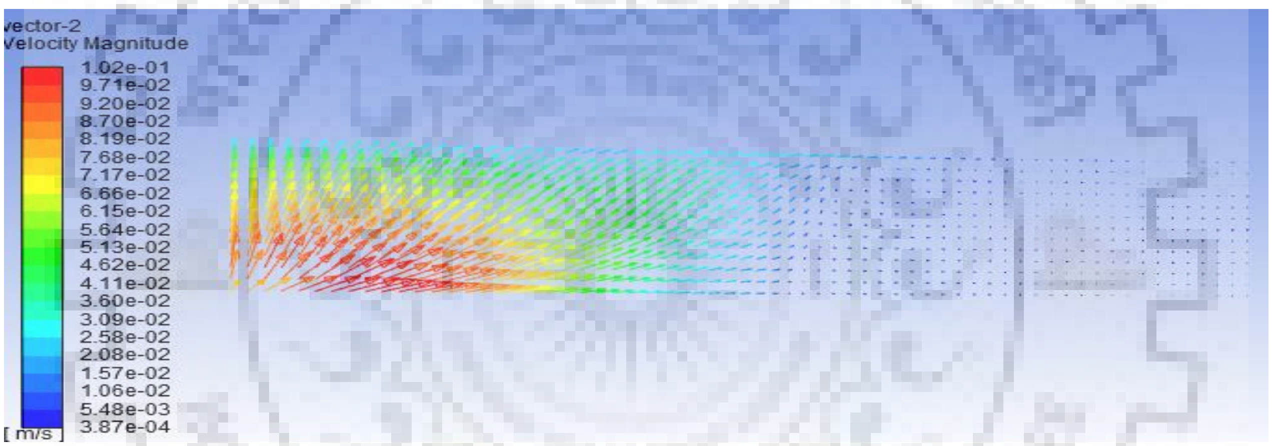
In this case the positions of three outlets are at $z = 100$mm as depicted in section 3.3.1 in chapter 3 and in figure6 (b), and keeping all other parameters constant and effect of inlet velocity is observed on wall shear stresses on different walls by using its value of velocities of 1m/s, 1.2 m/s, 1.5 m/s .

(a) V = 1.2 m/s

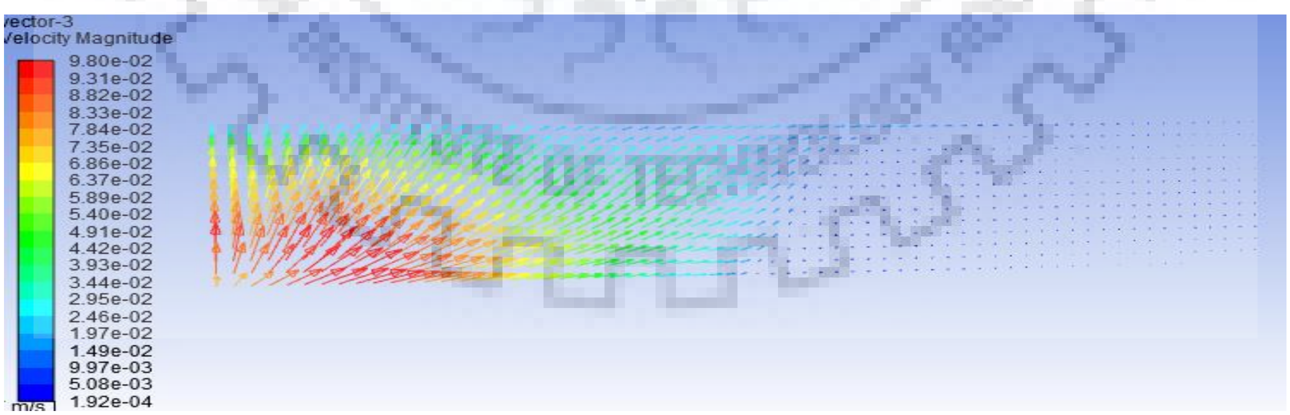
The variation and pattern of wall shear contours are almost similar like for bottom wall, back wall and front wall the shear stress generated is maximum near to inlet and pattern of contours on the bottom wall, front wall, back wall as plotted in case when outlets are at symmetry line and are of velocity v = 1.2 m/s only variation is their magnitude and in this geometry the value of front wall shear is more than back wall Velocity vectors are shown in Figure 14 at bottom plane to provide evidence that wall shear stress generated along front wall is less than back wall due to reason that after inlet number of particles moves along front wall created turbulence near the outlets because in this case flow is not symmetric on both sides and turbulence is more along the front wall side due to having outlets on their side. The magnitude of wall shear values is 3.02, 0.544, and 0.524 in Pa for bottom, front and back wall respectively.



(a)



(b)



(c)

Figure 14 : Velocity vectors for case B i.e. outlets at (z=100) (a) bottom (b) front (c) back

(b) V = 1 m/s

The variation and pattern of wall shear contours are almost similar like for bottom wall, back wall and front wall only change in magnitude of values and they are less than that of 1.2 m/s velocity case and their value are 2.14, 0.382, 0.371 in Pa for bottom, front and back wall respectively.

(c) V = 1.5 m/s

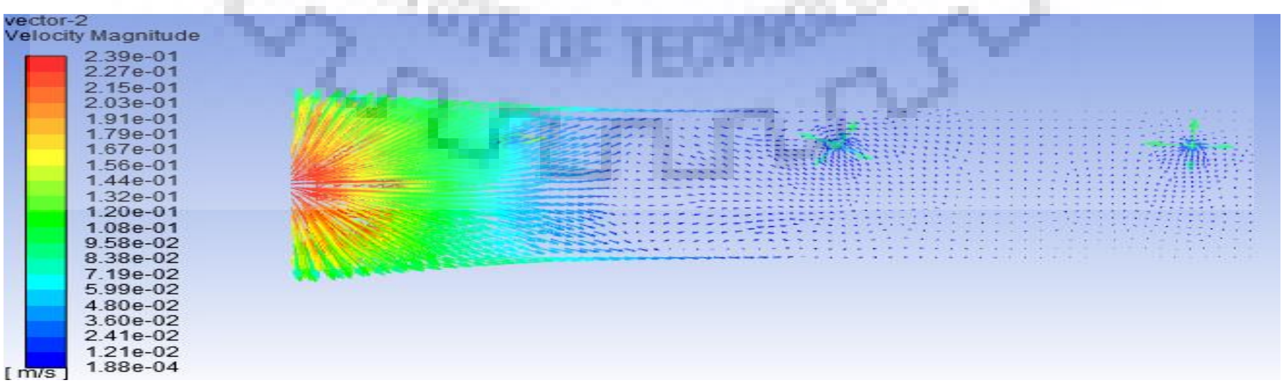
The variation and pattern of wall shear contours are almost similar like for bottom wall, back wall and front wall only change in magnitude of values and they are more than that of 1.2 m/s velocity case and their value are 4.61, 0.848, 0.810 in Pa for bottom, front and back wall respectively.

4.1.3 Outlets at z = 200 mm Line

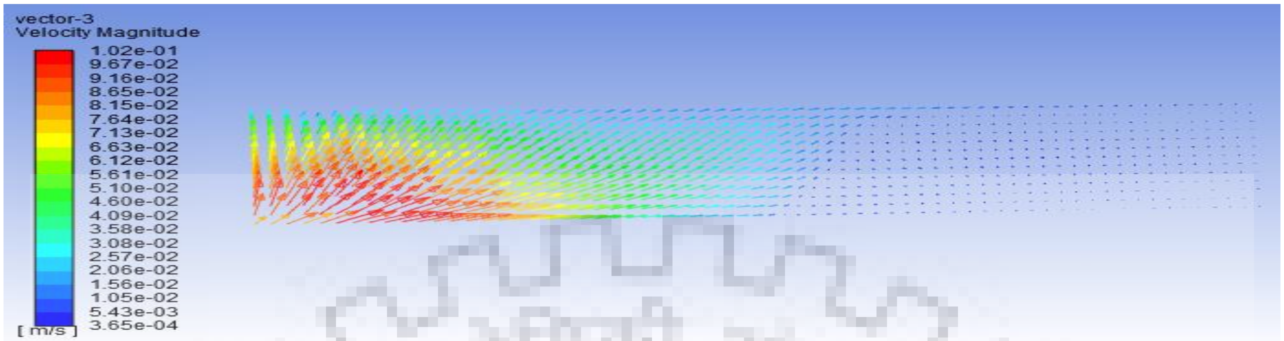
In this case the positions of three outlets are at $z = 200$mm as depicted in section 3.3.1 in chapter 3 and in figure 6 (c), and keeping all other parameters constant and effect of inlet velocity is observed on wall shear stresses on different walls by using its value of velocities of 1m/s, 1.2 m/s, 1.5 m/s .

(a) V = 1.2 m/s

The variation and pattern of wall shear contours are almost similar like for 4.1.2 case and values for different walls are of similar pattern like bottom has maximum wall shear after that front wall and then back wall because Velocity vectors are shown in Figure15. at bottom plane to provide evidence that wall shear stress generated along front wall is less than back wall due to reason that after inlet number of particles moves along back wall created turbulence near the outlets because in this case flow is not symmetric on both sides and turbulence is more along the front wall side due to having outlets on their side and only difference is the magnitude of wall shear values and they are 3.95,0.573,0.540 in Pa for bottom, front and back wall respectively.



(a)



(b)

Figure 15 : Velocity vectors for case C i.e. outlets at (z=200) (a) bottom (b) front

(b) V = 1 m/s

The variation and pattern of wall shear contours are almost similar like for bottom wall, back wall and front wall only change in magnitude of values and they are less than that of 1.2 m/s velocity case and their value are 2.17, 0.398, and 0.395 in Pa for bottom, front and back wall respectively.

(c) V = 1.5 m/s

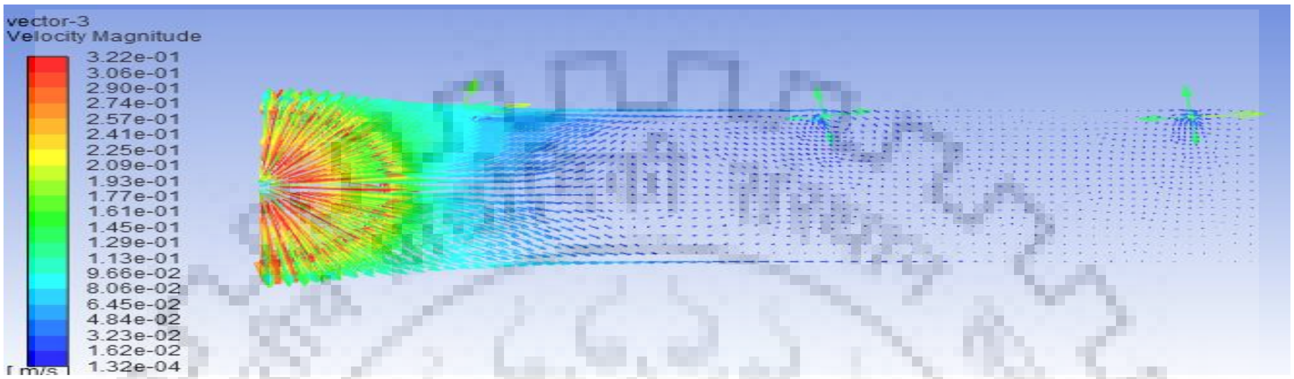
The variation and pattern of wall shear contours are almost similar like for bottom wall, back wall and front wall only change in magnitude of values and they are more than that of 1.2 m/s velocity case and their value are 4.520, 0.855, and 0.847 in Pa for bottom, front and back wall respectively.

4.1.4 Outlets at z = 350 mm Line

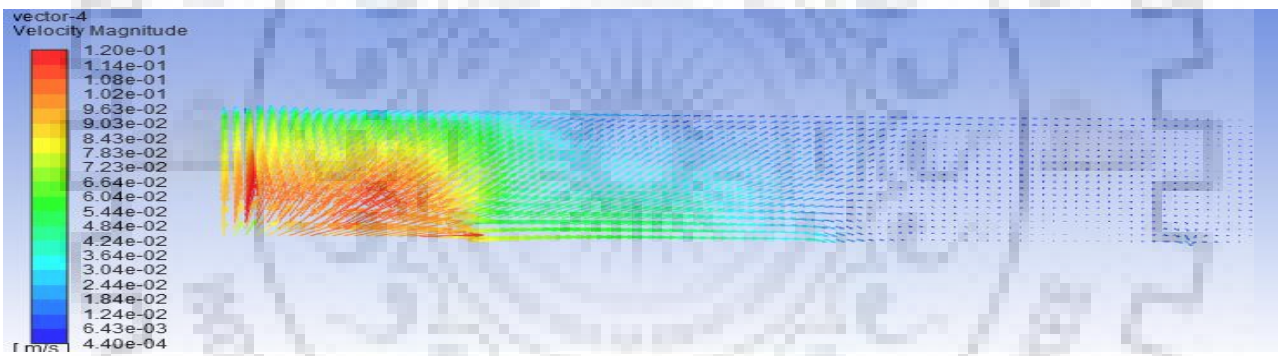
In this case the positions of three outlets are at $z = 200$mm as depicted in section 3.3.1 in chapter 3 and in figure 6 (d), and keeping all other parameters constant and effect of inlet velocity is observed on wall shear stresses on different walls by using its value of velocities of 1m/s, 1.2 m/s, 1.5 m/s .

(a) V = 1.2 m/s

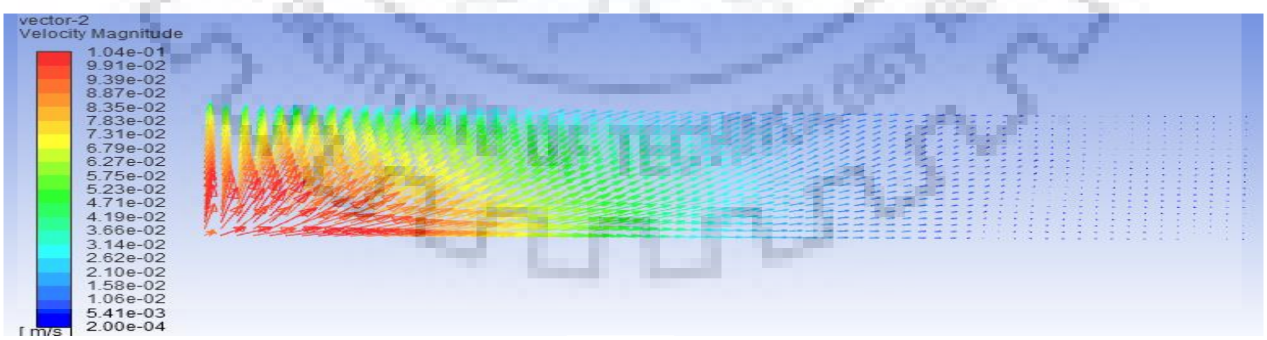
The variation and pattern of wall shear contours are almost similar like for 4.1.2 case and values for different walls are of similar pattern like bottom has maximum wall shear after that front wall and then back wall because Velocity vectors are shown in Figure 16(a) at bottom plane to provide evidence that wall shear stress generated along front wall is less than back wall due to reason that after inlet number of particles moves along back wall created turbulence near the outlets because in this case flow is not symmetric on both sides and turbulence is more along the front wall side due to having outlets on their side and only difference is the magnitude of wall shear values and they are 7.40,0.685,0.669 in Pa for bottom, front and back wall respectively.



(a)



(b)



(c)

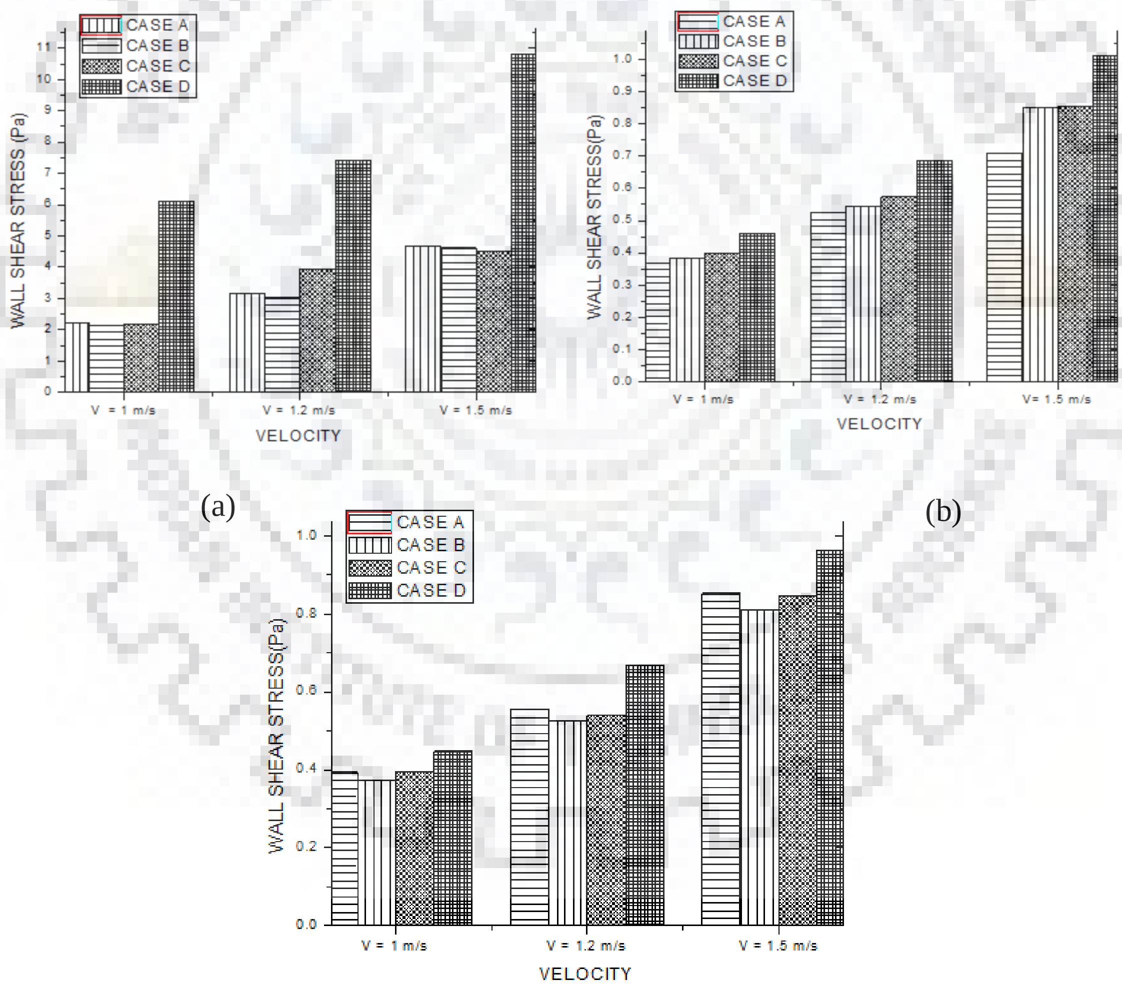
Figure 16 : Velocity vectors for case D i.e. outlets at (z=350) (a) bottom (b) front (c) back

(b) V = 1 m/s

The variation and pattern of wall shear contours are almost similar like for bottom wall, back wall and front wall only change in magnitude of values and they are less than that of 1.2 m/s velocity case and their value are 6.11, 0.461, and 0.448 in Pa for bottom, front and back wall respectively.

(c) V = 1.5 m/s

The variation and pattern of wall shear contours are almost similar like for bottom wall, back wall and front wall only change in magnitude of values and they are more than that of 1.2 m/s velocity case and their value are 10.80, 1.01, and 0.963 in Pa for bottom, front and back wall respectively. Comparison of all the cases together of wall shear stress done with the help of histogram shown below in Figure 17



(c)

Figure 17 : Comparison of wall shear for outlet positions with velocity (a) bottom (b) front (c) back

4.2 Effect of Wall Inclination Angles on Wall Shear Stress

In simple boat shape wall angles were changes to made two different geometries that were discussed in chapter 3 and section 3.3.2 in that discussion we named simple boat shape as case A i.e.($\theta_s = 0°$& $\theta_l = 0°$) and after that increase angle of walls as case B i.e.($\theta_s = 5.7°$& $\theta_l = 11.3°$) and another case of wall angles more than previous case as case C i.e.($\theta_s = 7.1°$& $\theta_l = 14.0°$). Taking all other parameters are same as previous section for thus analysis we take inlet velocity as 1.4 m/s after studying the effect of velocity now we consider it as same for all upcoming cases. Comparison of wall shear on different walls with changes in angles are shown in Figure 18 below after that in Figure 19 and 20 contours are shown to conclude the values of wall shear and its pattern that were discussed in Figure 18.

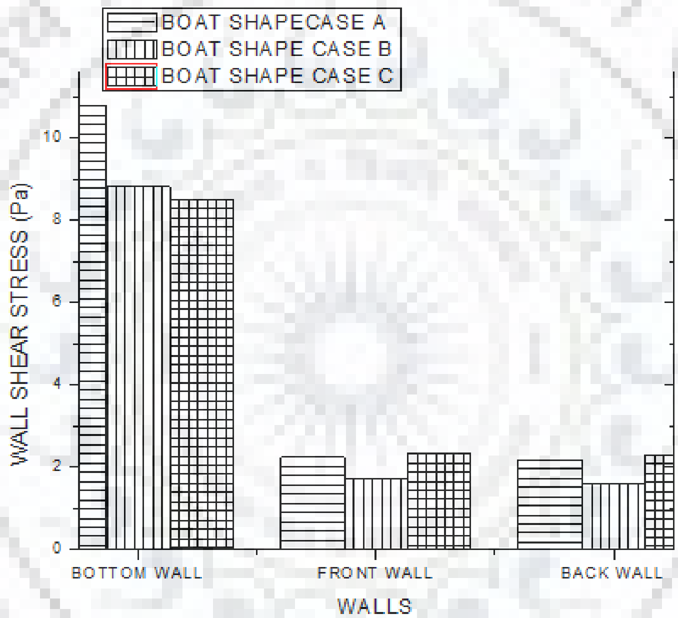
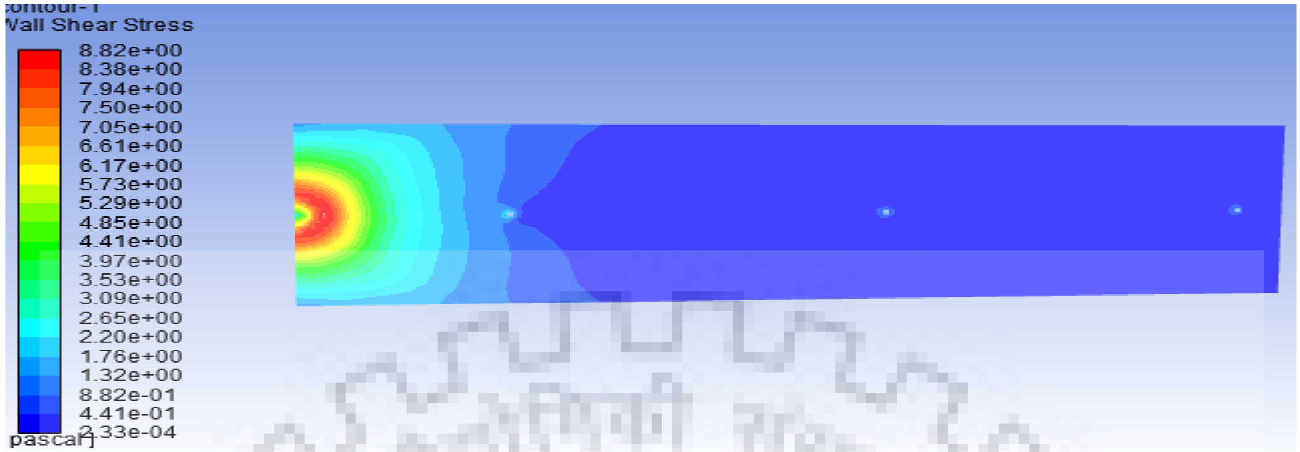
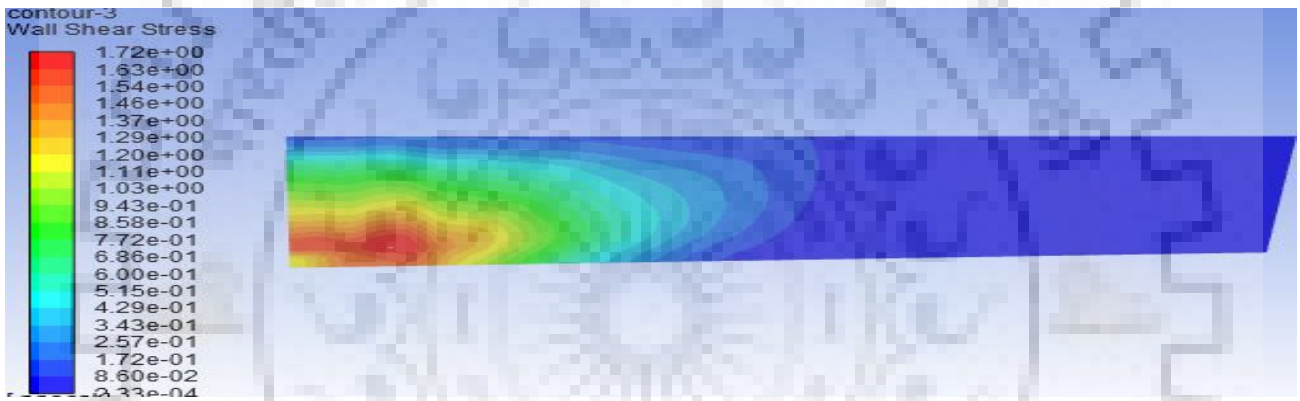


Figure 18 : Comparison of wall shear stress on different walls of Boat shape cases of wall inclinations

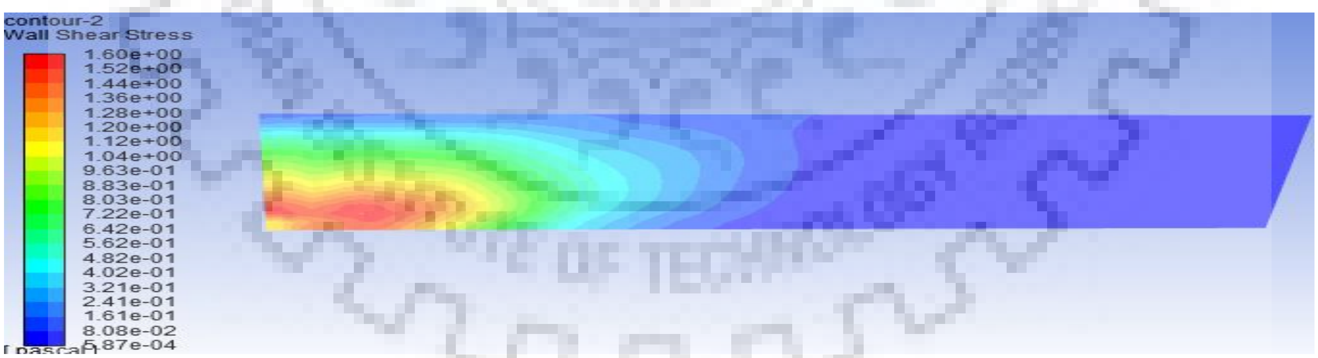
Contours of wall shear sress at bottom, front and back wall is plotted for cases of boat shape tundish with making changes in wall inclination angles.The variation of shear stress on bottom wall has similar pattern like of simple boat shape case only magnitude value changes .From the above figure we can say from results that simple boat shape has maximum wall shear on bottom wall while with increase in wall angle its value decrease for bottom wallwhile for front and back wall it decrease then increase with increase in angle of walls inclinations.



(a)

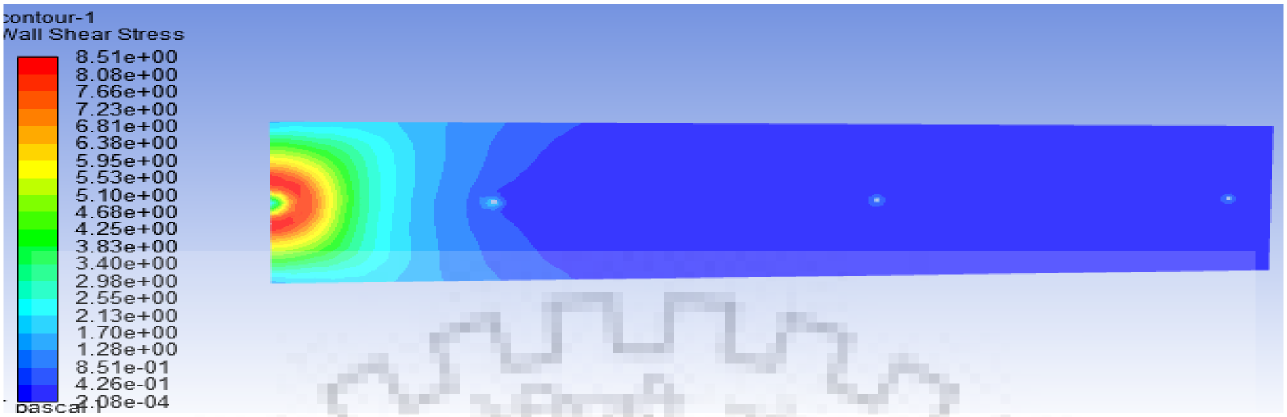


(b)

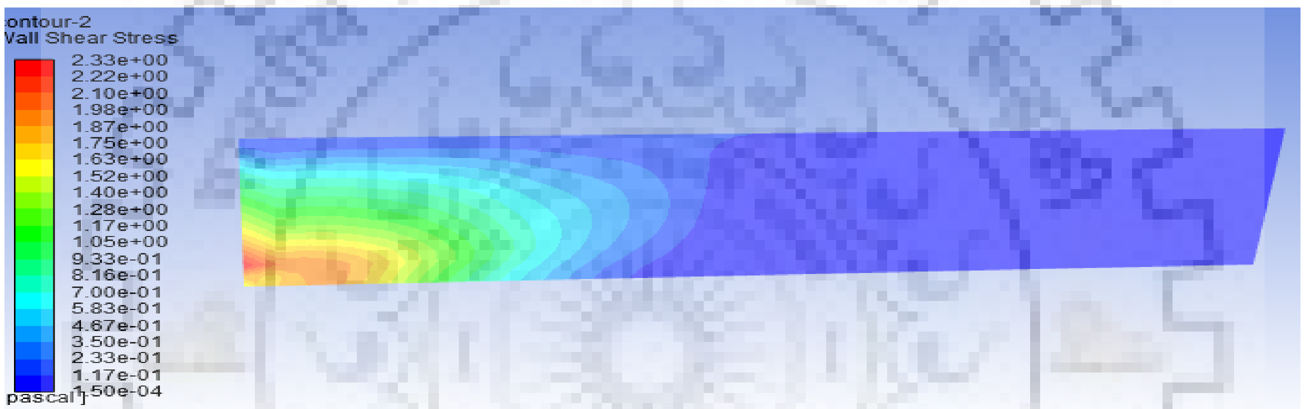


(c)

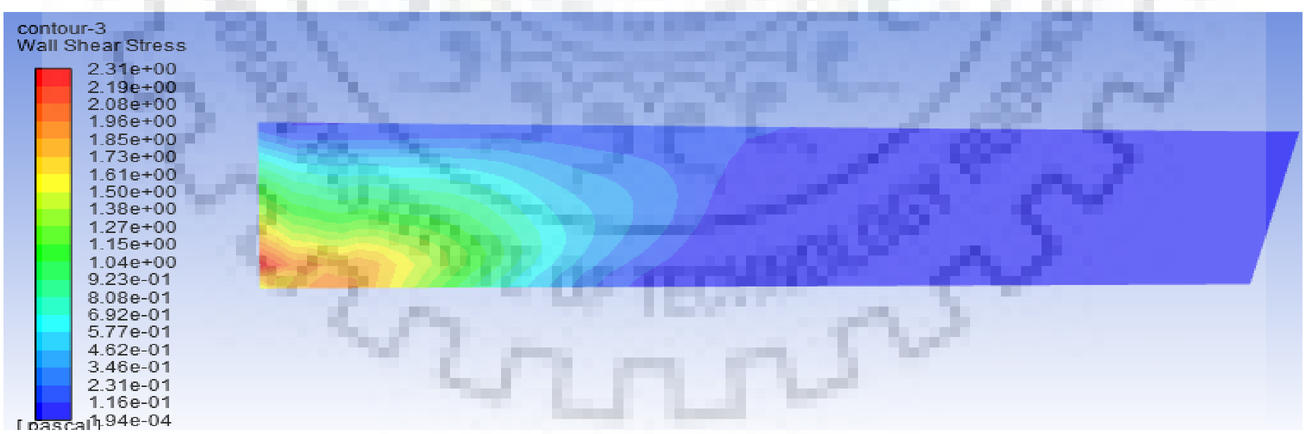
Figure 19 : Wall shear contours for case B i.e.(θ_s = 5.7°& θ_l = 11.3°) (a) bottom (b) front (c) back



(a)

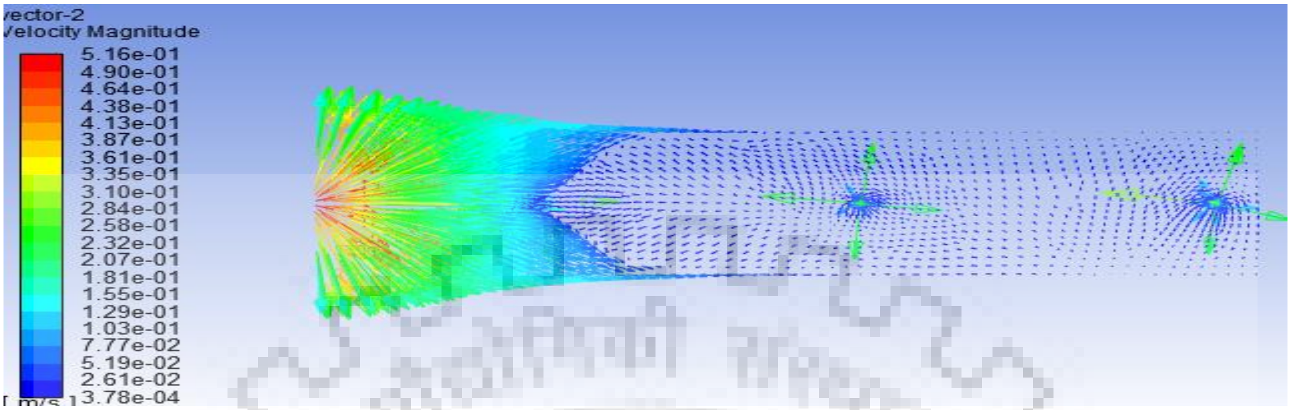


(b)

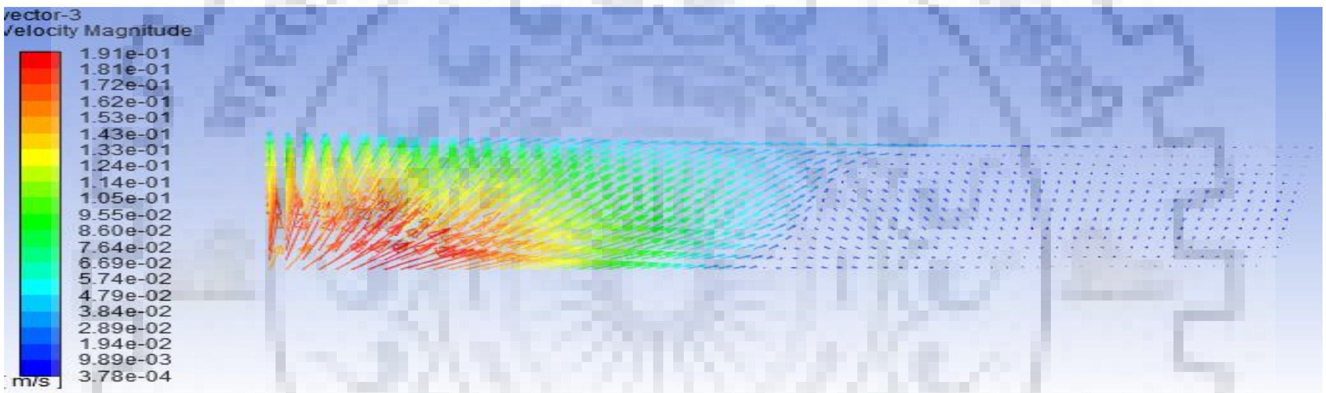


(c)

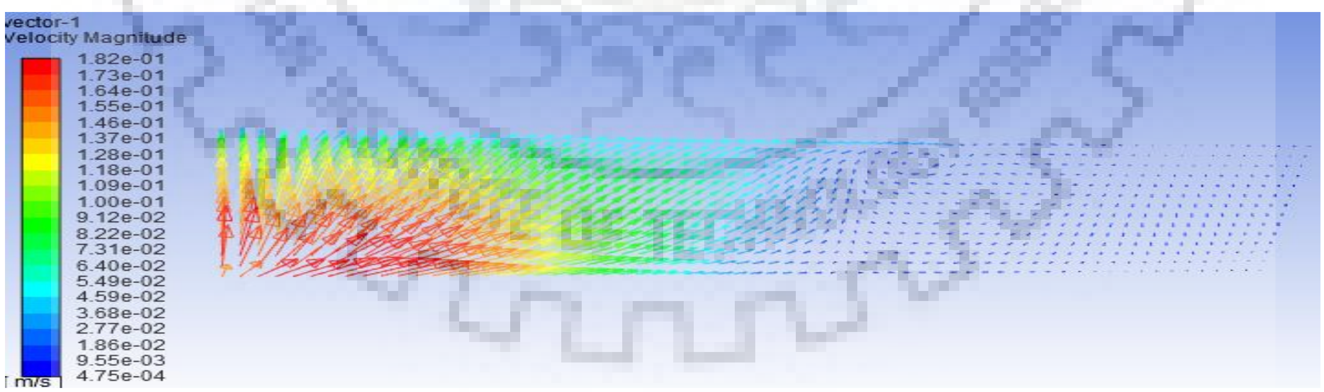
Figure 20 : Wall shear contours for wall case C i.e.($\theta_s = 7.1°$ & $\theta_l = 14.0°$) (a) bottom (b) front (c) back



(a)

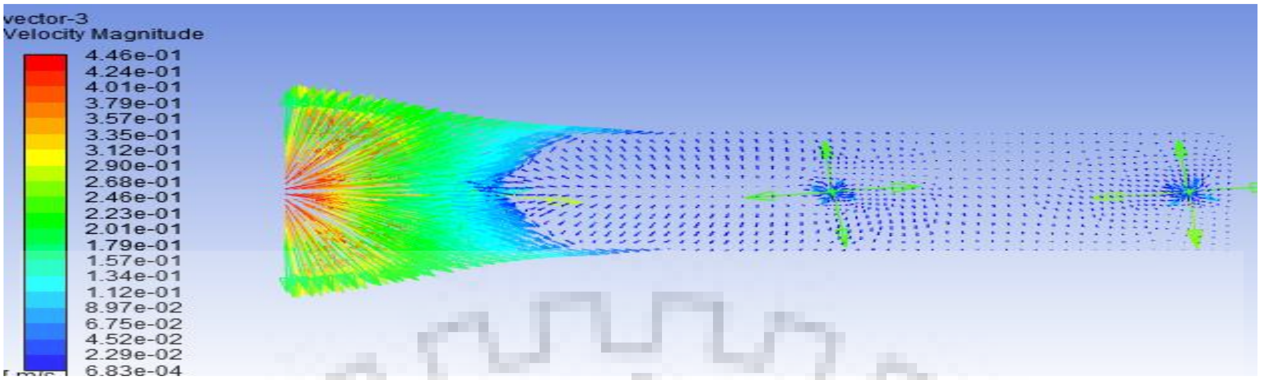


(b)

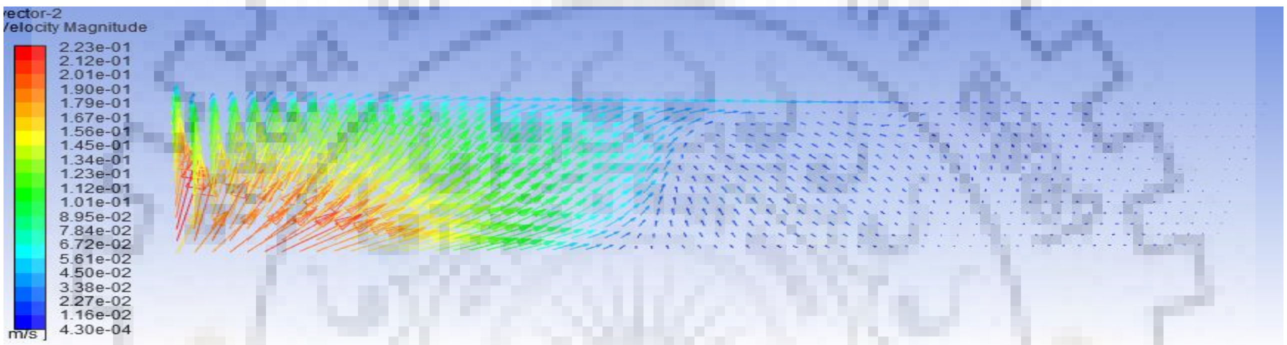


(c)

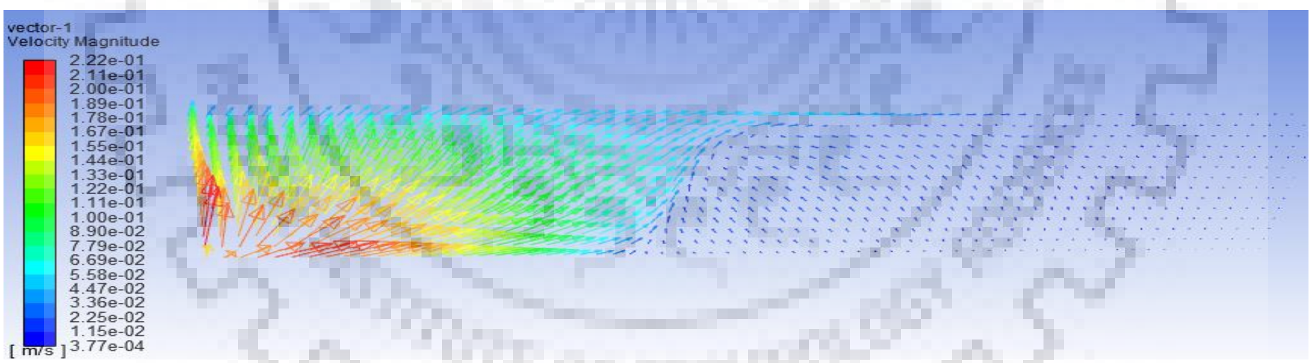
Figure 21 : Velocity vectors for wall case B i.e.(θ_s = 5.7°& θ_l = 11.3°) (a) bottom (b) front (c) back



(a)



(b)

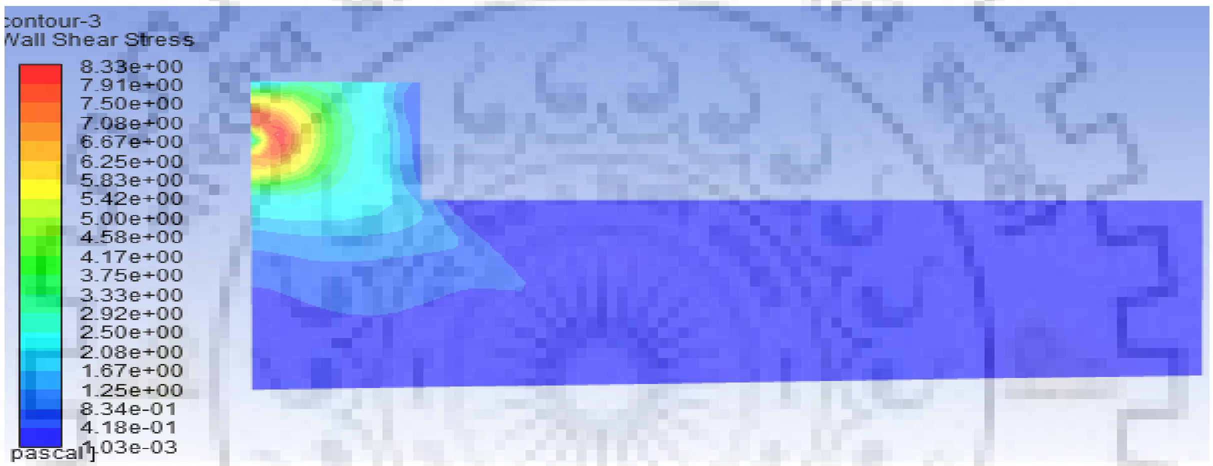


(c)

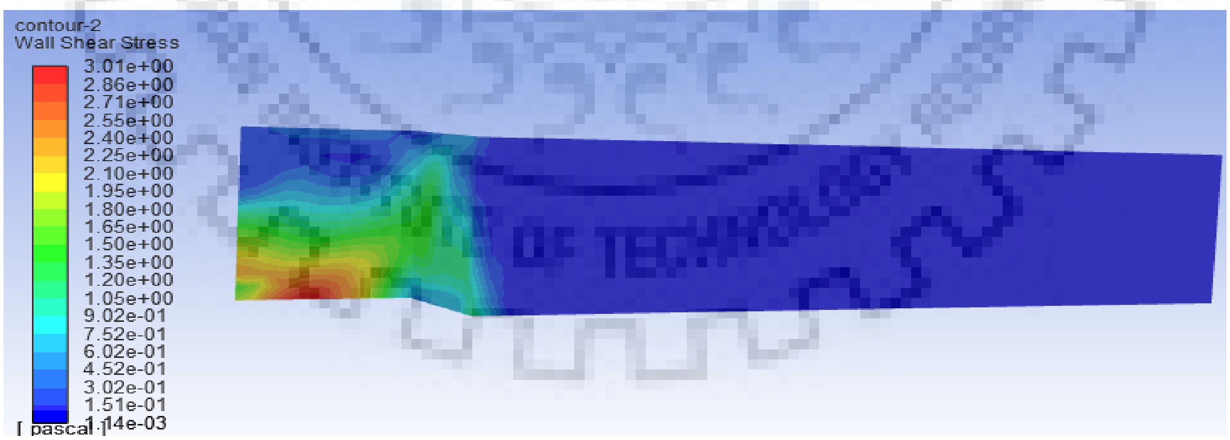
Figure 22 : Velocity vectors for wall case C i.e.($\theta_s = 7.1°$ & $\theta_l = 14.0°$) (a) bottom (b) front (c) back

4.2.1 Comparison of Boat Shape Cases with T Shape

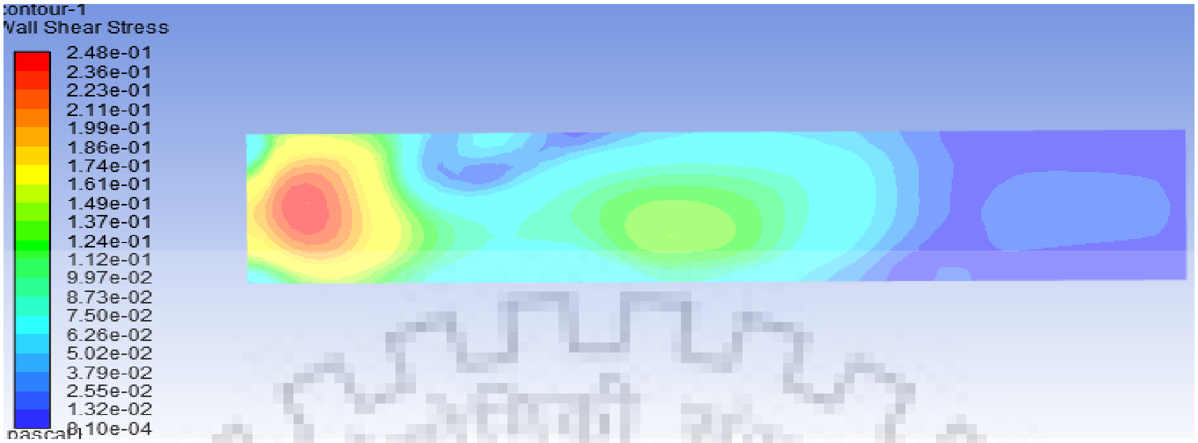
A T shape tundish geometry as discussed in chapter 3, figure. 5 is simulated for calculation of wall shear with velocity 1.4 m/s and their wall shear contours for different walls and velocity vectors are plotted shown below in Figure 23 and 24 respectively. The pattern of bottom wall shear is looks like simple boat shape case while front wall has different pattern and maximum stress has compared to other boat shape cases and has maximum shear at near to inlet and along length and height because a large fraction of fluid jet coming from inlet are redirected and T shape has tundish has maximum wall shear stress on front wall than other cases due to having circuital flow that creating more turbulence on the walls toward the front wall. Back wall shear in T shape is minimum from all boats shape due to magnitude of very less magnitude and due to geometry, the back wall distance increases and erosion and the magnitude of velocity is also less in magnitude for back wall in comparison of other boat shape cases.



(a)

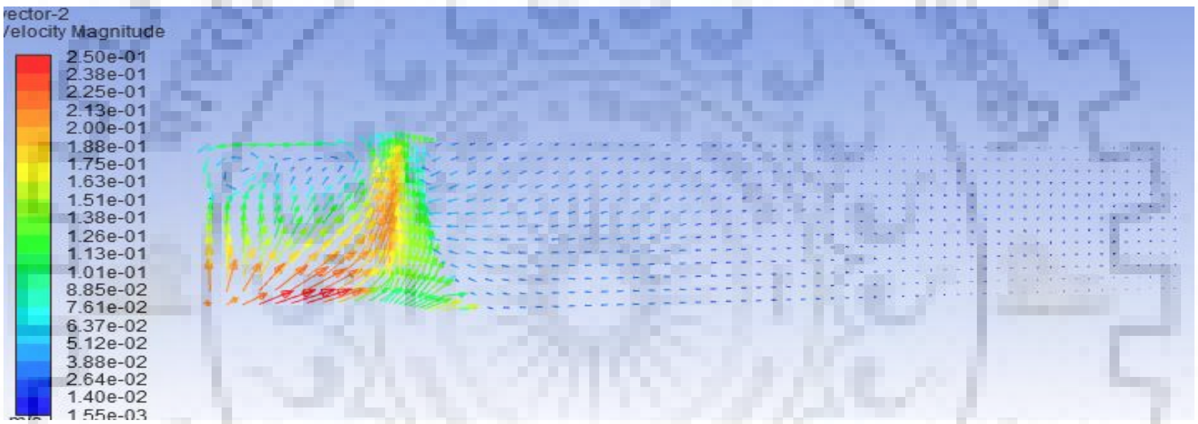


(b)

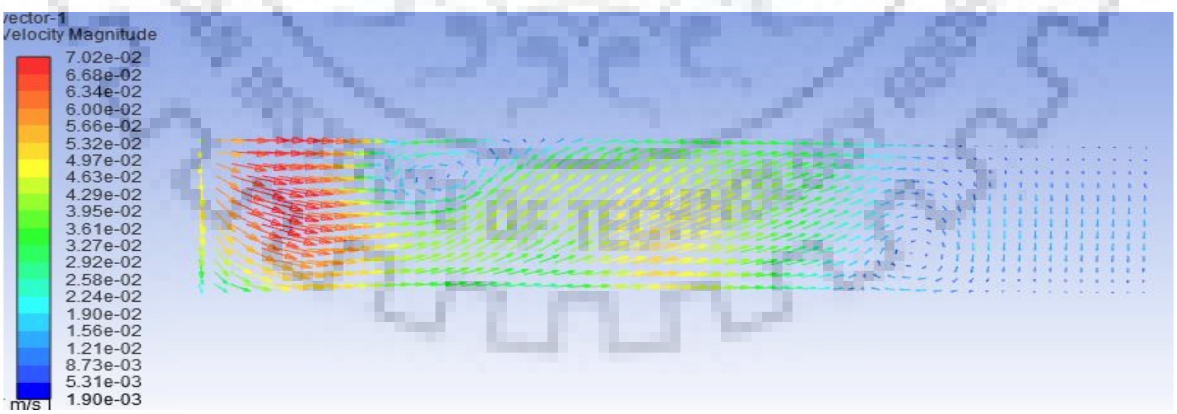


(c)

Figure 23 : Wall shear contours for T shape wall (a) bottom (b) front(c) back



(a)



(b)

Figure 24 : Velocity vectors for T shape wall (a) front (b) back

A comparison between walls shear on different walls with T shape with boat shape cases of wall inclination like case A i.e.($\theta_s = 0^\circ$& $\theta_l = 0^\circ$),case B i.e.($\theta_s = 5.7^\circ$& $\theta_l = 11.3^\circ$) and case C i.e.($\theta_s = 7.1^\circ$& $\theta_l = 14.1^\circ$) shown below in Figure 25.

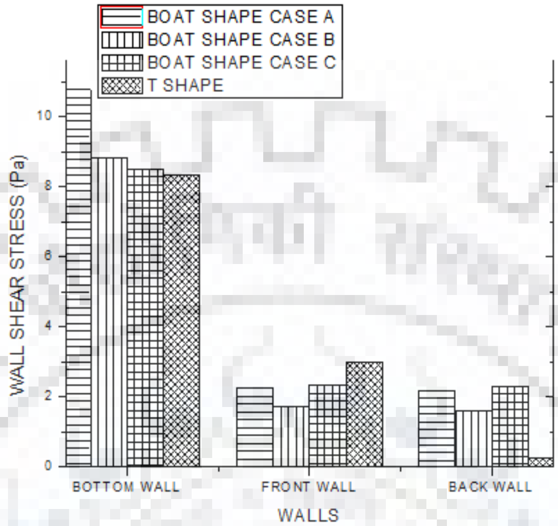
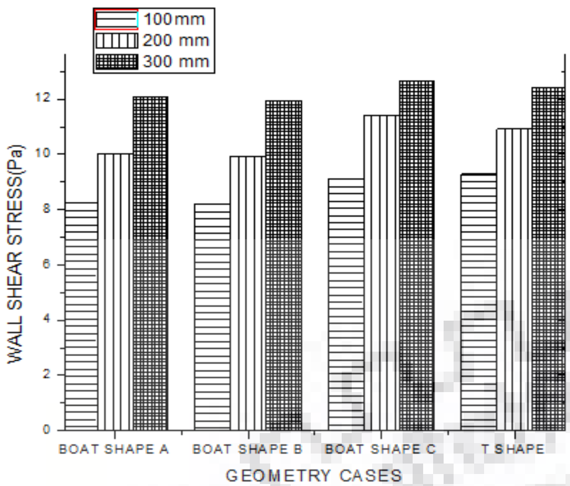


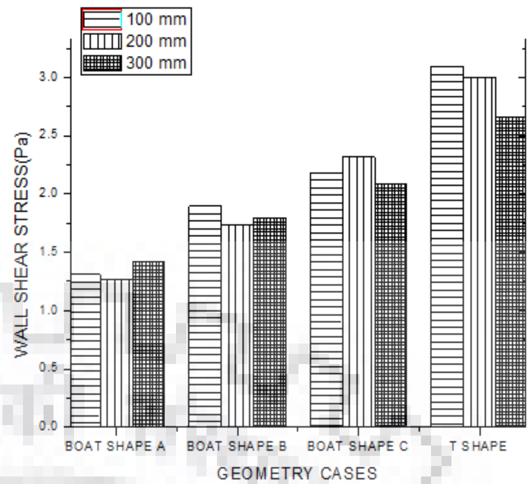
Figure 25 : Comparison of wall shear stress on different walls of boat shape cases and T shape

4.3 Effect of Shroud Depth on Wall Shear Stress

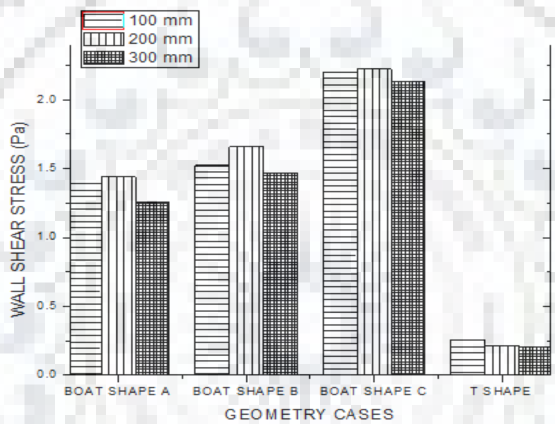
Different shapes of tundish like simple boat shape A, simple boat shape Simple boat shape C, and T shape were simulated with using velocity 1.4 m/s for shroud depth 100, 200, 300 mm and the pattern of contours and velocity are of same nature that were plotted for previous section of boat shape tundish for different walls and values of wall shear stress for these cases are compared with the help of Figure 26, Which shows that bottom wall shear for each geometry increased with shroud depth while front wall stress decreased then increased for boat shape cases but increased from 200 to 300 mm for T shape while back wall stress increases then decreases up to less than its initial value for boat shape cases but continue to decrease with depth for T shape. This is because of different flow pattern for T shape than others for back and front walls. From the figure it can be easily seen that value of maximum velocity keeps on decreasing with submergence depth for T shape on front wall. Velocity vectors for back and front walls for T shaped are plotted in Figure 27 and 28 to show the magnitude behind maximum value of shear for front and minimum value of shear for back walls.



(a)

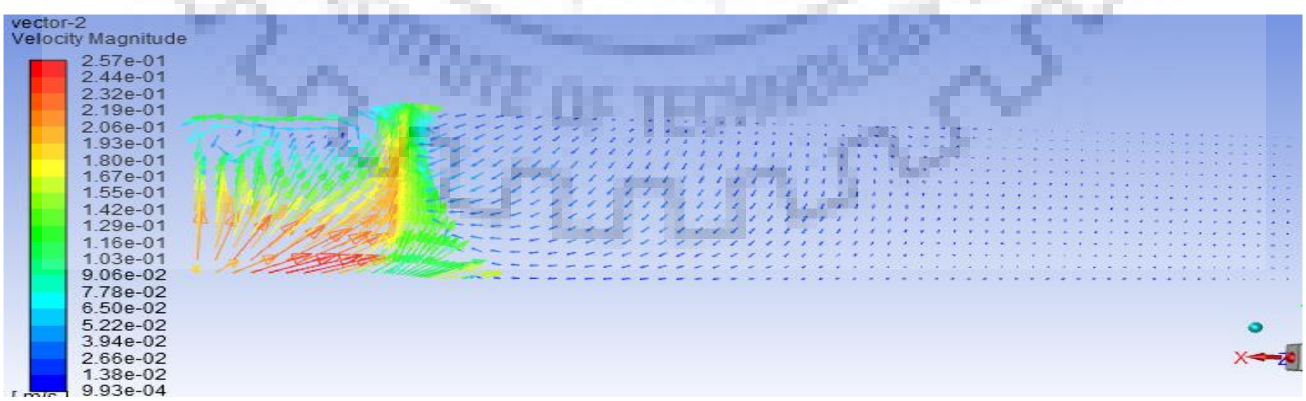


(b)

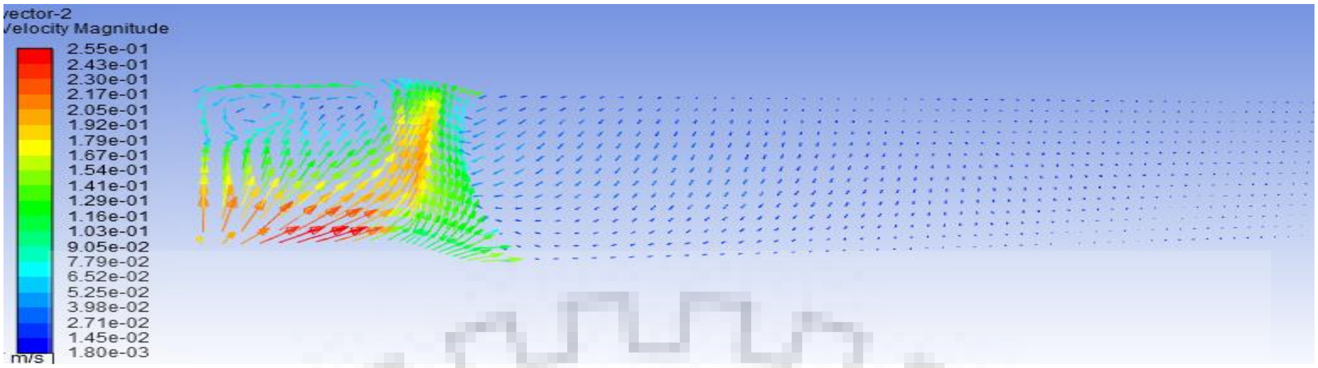


(c)

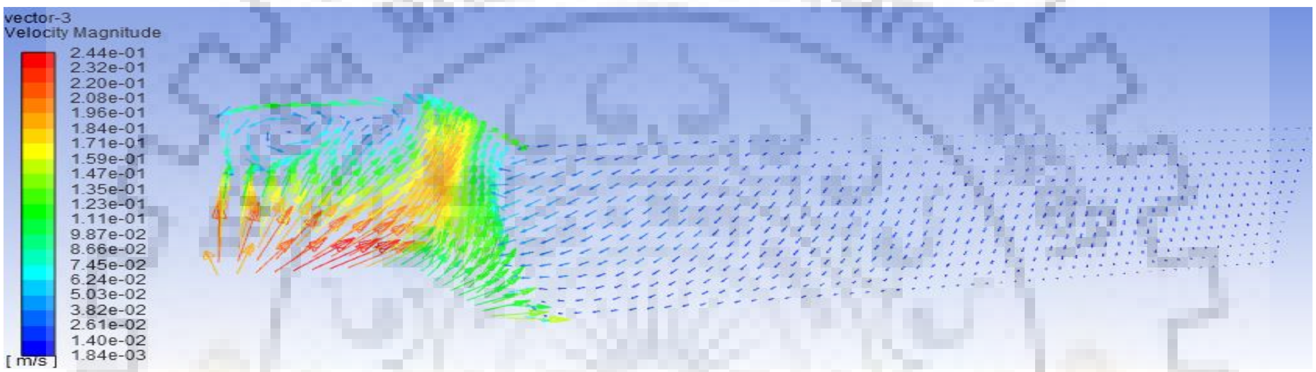
Figure 26 : Comparison of wall shear in shapes with shroud depth (a) bottom (b) front (c) back



(a)



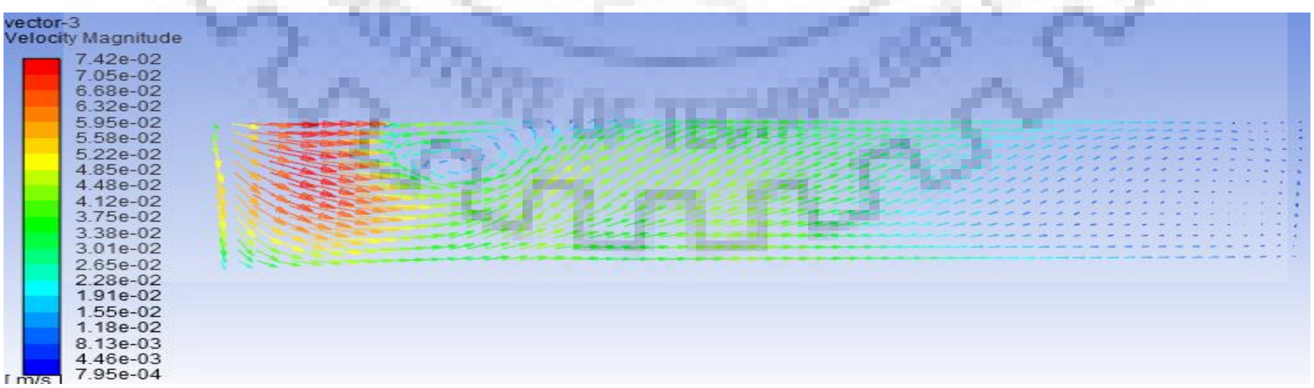
(b)



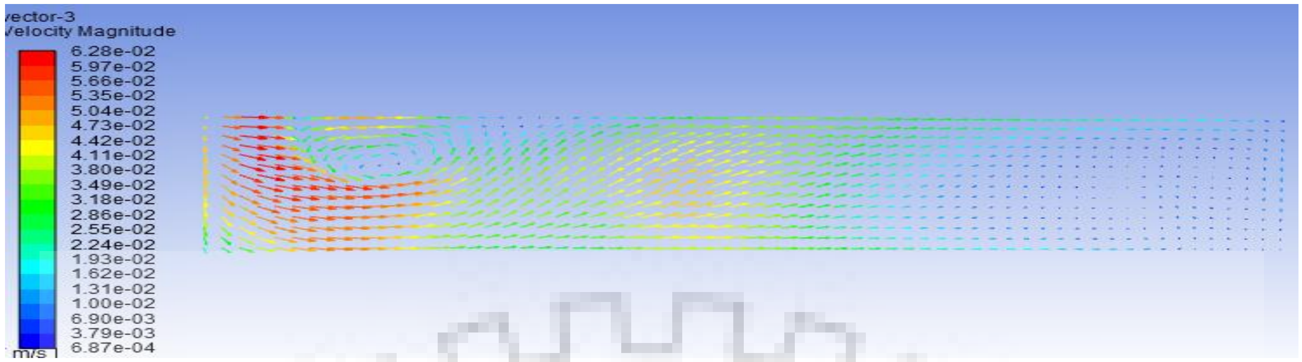
(c)

Figure 27 : Velocity vectors for T shape front wall for shroud depth (a) 100mm (b) 200mm (c) 300mm

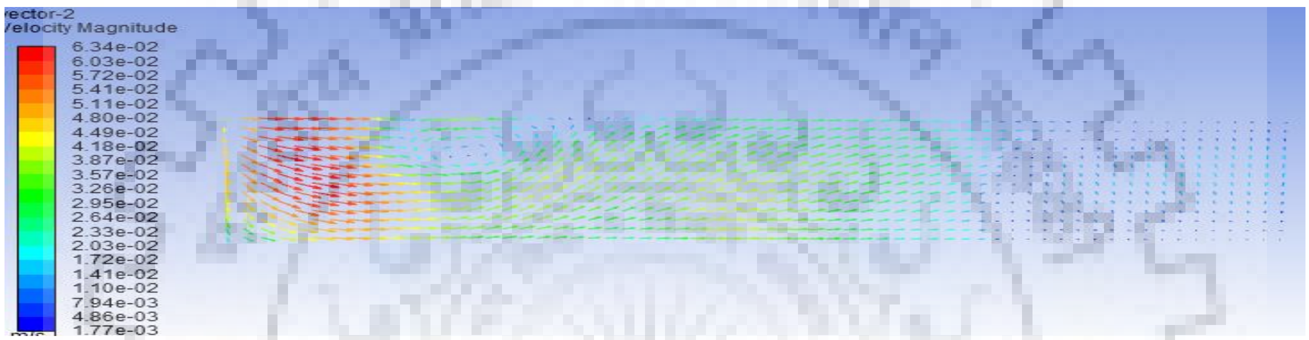
Velocity vectors for back wall for different shroud depth are plotted for T shape as shown in Figure 28 below.



(a)



(b)



(c)

Figure 28 : Velocity vectors for T shape back wall for shroud depth (a) 100mm (b) 200mm(c) 300mm

4.4 Effect of Shroud Angle on Wall Shear Stress

Different shapes of tundish like simple boat shape A, simple boat shape B, Simple boat shape C, and T shape were simulated with using velocity 1.4 m/s for shroud angle of 5 degrees in both direction and the pattern of contours and velocity are of same nature that were plotted for previous section of boat shape tundish for different walls and values of wall shear stress for these cases are compared with the help of Figure 29, Which shows that Bottom wall shear continue to decrease with change in angle case for boat shape case A and B while decrease then increase for boat shape case C and T shape .Front wall shear for boat shape case A and T continue to decrease in angle case while decrease and increase for boat shape case B and C. Back wall shear for boat shape case A continue to decrease with angle while decrease and increase for boat shape case B and C.

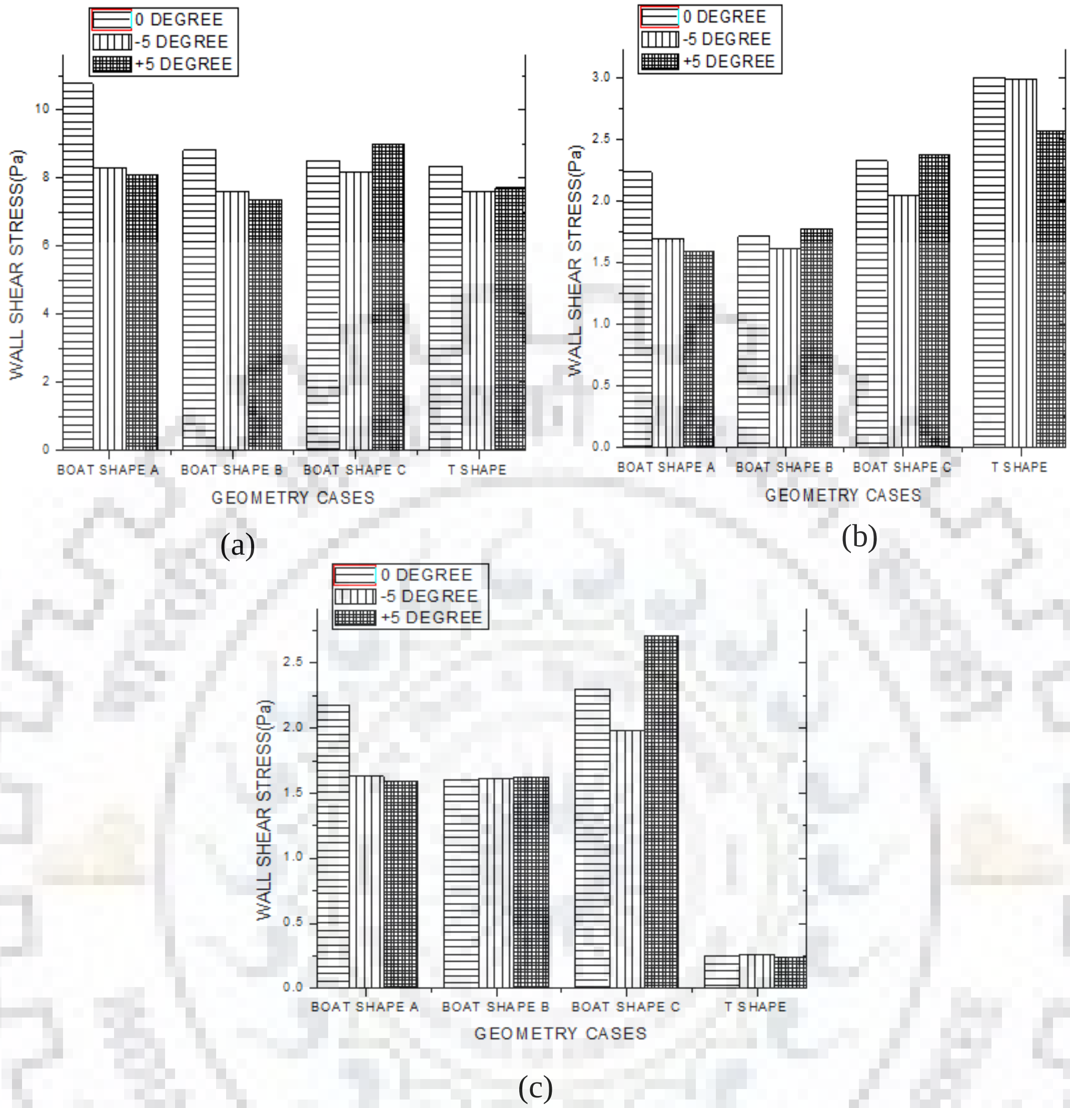
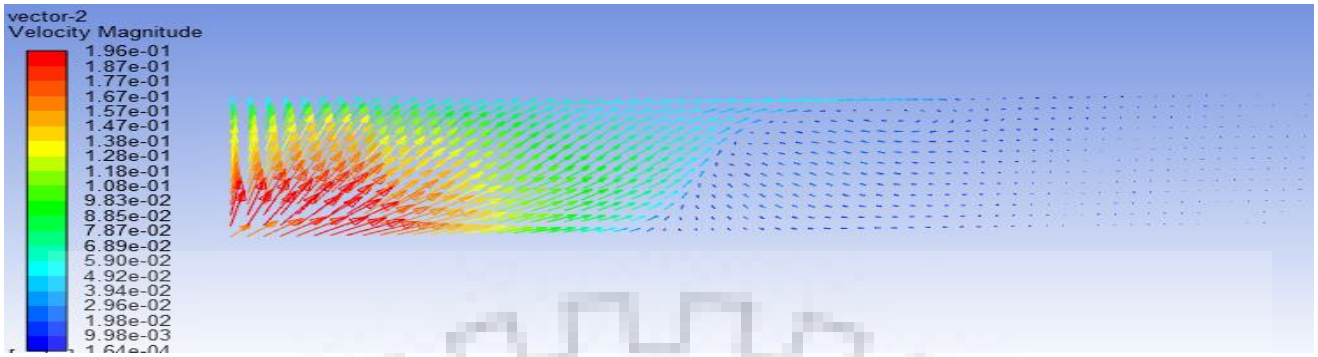
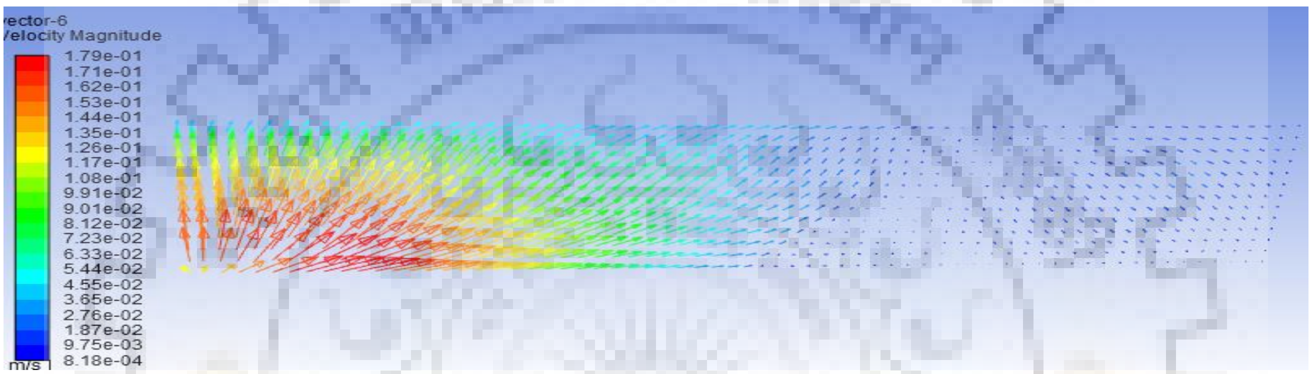


Figure 29 : Comparison of wall shear in cases with shroud angle (a) bottom (b) front (c) back

Variation in the values of wall shear stress are due to having different magnitude of velocities and velocity vectors are plotted for boat shape case B i.e.(θ_s =5.7°& θ_l = 11.3°) and boat shape case C .e.(θ_s =7.1°& θ_l = 14.1°) for shroud angle +5 degree and -5 degree for front and back wall in Figure 30,31,32 ,33.Velocity vectors clearly shows the correlation of wall shear stress magnitude for different cases with their magnitude values.

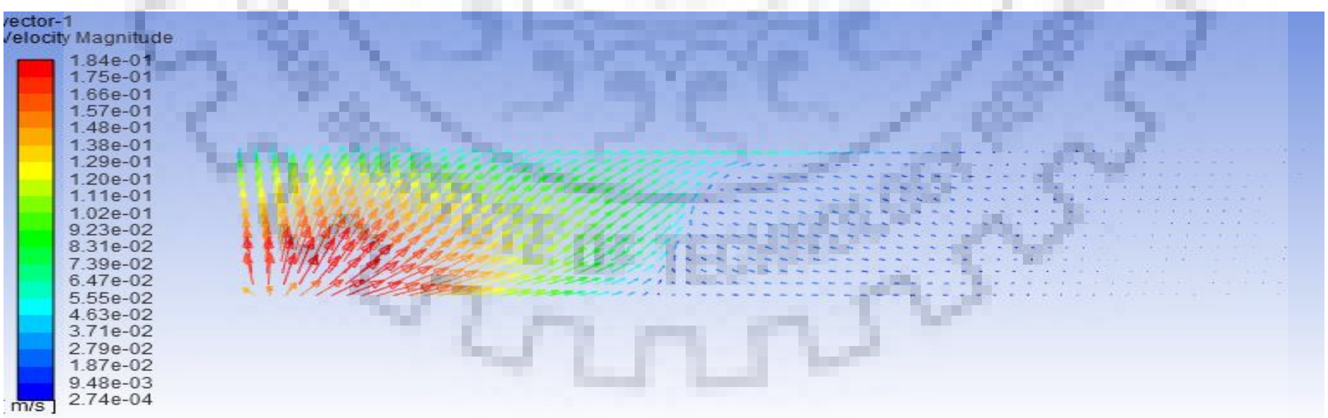


(a)

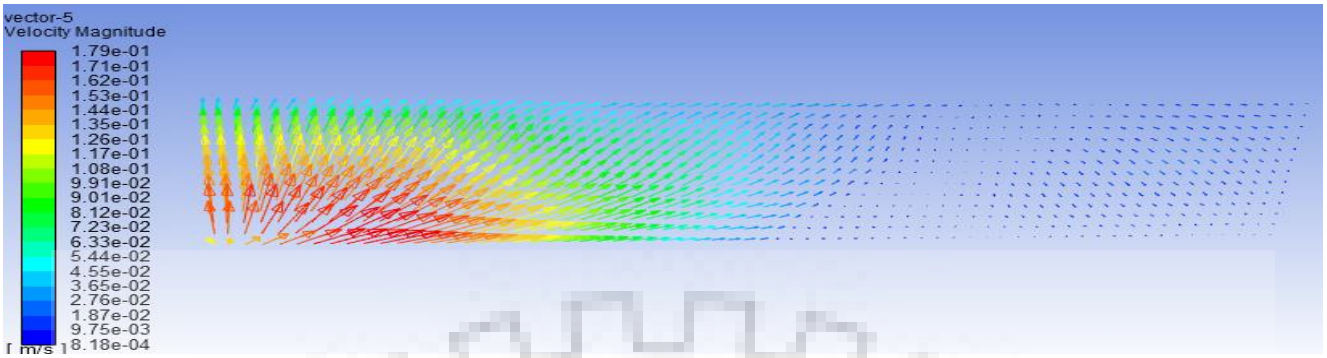


(b)

Figure 30 : Velocity vectors for case B i.e. (θ_s =5.7°& θ_l = 11.3°) on front wall (a) +5° (b) -5°

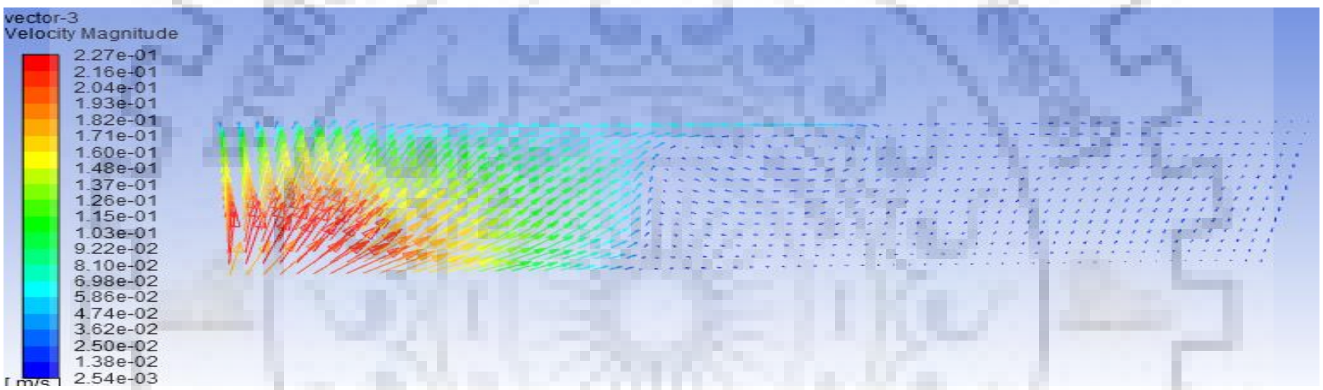


(a)

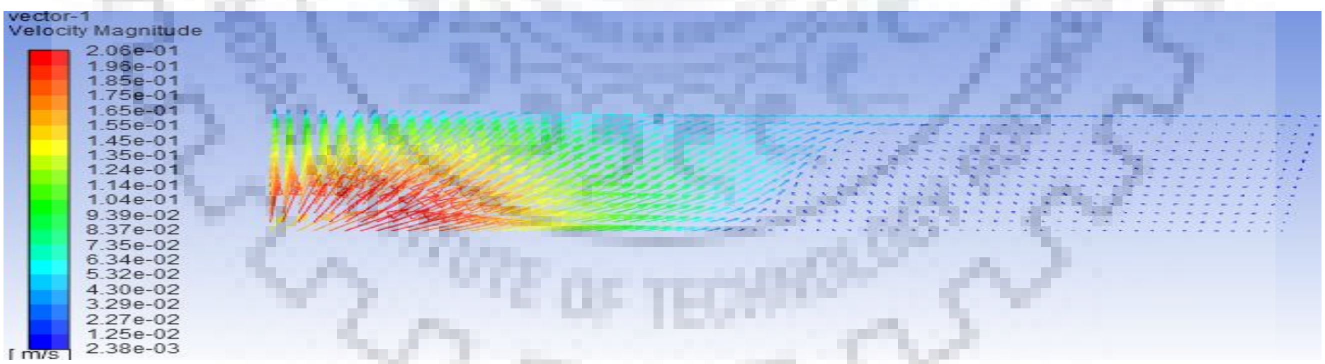


(b)

Figure 31 : Velocity vectors for case B i.e. (θ_{s} =5.7°& θ_{l} = 11.3°) on back wall (a) +5° (b) -5°

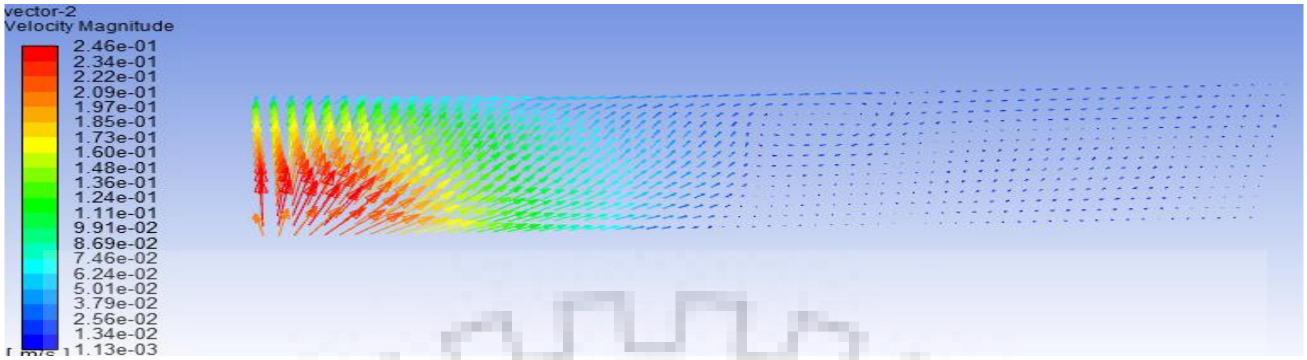


(a)

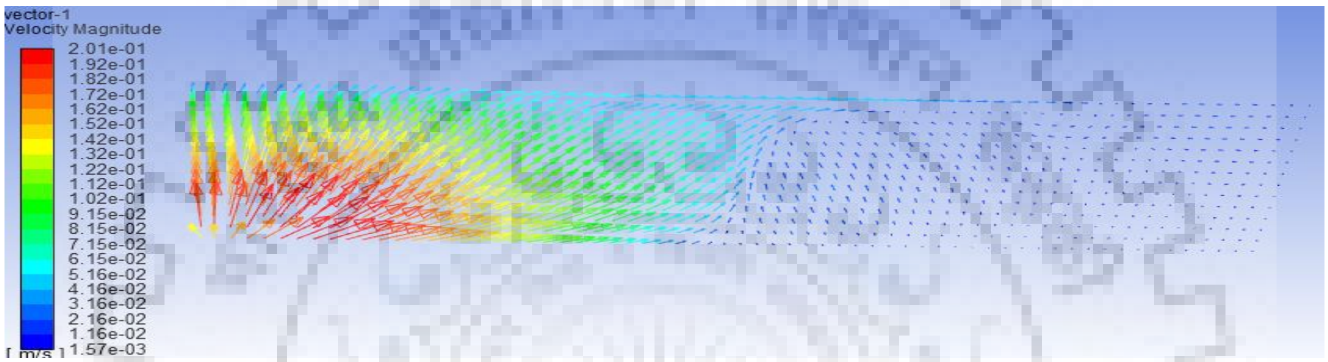


(b)

Figure 32 : Velocity vectors for case C i.e. (θ_{s} =7.1°& θ_{l} = 14.0°) on front wall (a) +5° (b) -5°



(a)



(b)

Figure 33 : Velocity vectors for case C i.e. ($\theta_s = 7.1°$& $\theta_l = 14.0°$) on back wall (a) +5° (b) -5°

From above velocity vectors results shows that for case B front and back wall of -5 degree angle inclination have same magnitude of velocity as shown in Figure 30 (b) and Figure 31 (b), due to this these both have also the same magnitude of wall shear as shown in Figure 29 (b) and Figure 29 (c).Other comparisons also justified with the help of these vectors that are done in Figure 29.

CHAPTER 5

CONCLUSIONS AND FUTURE SCOPE

5.1 Conclusions

Wall shear stress in boat shape tundish was analyzed with change in outlet positions with velocities, wall inclinations with constant velocity, shroud depth in different shapes with constant velocity and shroud inclination in different geometries with constant velocity. After analyzing results following conclusions can be drawn from present work.

- With increase in velocity for a particular geometry while keeping other parameters constant, Wall shear stress on individual wall increases. Bottom wall of each geometry leads to maximum wall shear in all cases of outlet positions that are simulated.
- Front wall which is closer to outlets has more wall shear stress than back wall at a given velocity because of turbulent flow near outlets and thus front wall has more wall shear stress. But in case of symmetry the back wall has more wall shear stress due to flow towards back wall.
- Simple boat shape has more wall shear stress on bottom and front wall than other two boat shape cases B and C obtained with wall inclinations but T shape has maximum wall shear stress on front wall among geometry shape cases A, B and C.T shape has also minimum wall shear stress on back wall among geometry shape cases A, B and C due to having different flow pattern and magnitude of velocity. Boat shape case B has minimum front wall shear stress than other geometries.
- For all the cases bottom wall shear stress decreases with increase in shroud depth. For back wall with increase in shroud depth, wall shear stress value first increases then decreases for boat shape cases, but continue to decrease for T shape tundish because of decrease in magnitude of velocity on the back wall. Front wall shear stress for boat shape tundish A and B decreases and then increases, while for boat shape tundish C increases and then decreases. For T shape its value continue to decrease with shroud depth.
- For boat shape case A tundish wall shear stress on bottom, front, back wall continues to decrease with shroud angle and for boat shape case C tundish decrease and then increase for all three walls with shroud angle. For boat shape case B tundish wall shear stress on bottom continue to decrease and for front and back wall it decreases and then increases with angle cases. For T shape, bottom wall decreases and then increases, front wall continues to decreases and for back wall increases

and then decreases.

5.2 Future Scope

The present work can be extended further for better understanding of wall shear stress in different cases are as follows

- Flow modifiers like dams, weirs, baffles can be used in geometries to see the effect on wall shear stress in different cases.
- Dam height and its position inside tundish can be altered to see the effect on wall shear stress.
- Use of different turbulent model can be studied to see the effect on wall shear stress.
- T shape and V shape tundish with change in outlet positions can be studied to see the effect on wall shear stress.
- Shroud angle and immersion depth can also be studied in V shape tundish to see the effect on wall shear stress.

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