Effect of Surface Roughness on Boundary Layer Thickness

Saurabh Powar, Neha Chitrakar, Lalit Chacharkar, Prakhar Adarsh, Shankar Karhale, Rohan Patil, and Pramod Kothmire

Abstract Surface roughness effects over a rough flat plate are compared for different surface roughness conditions using CFD techniques. Velocity readings were taken at equal intervals over the flat plate with a free stream velocity of 11.11 m/s. Velocity profiles are plotted at different sections along the boundary layer thickness. The growth of the boundary layer for different conditions gives us a brief idea of flow over the plate surface. Results such as eddy viscosity, turbulent kinetic energy, velocity variations and wall shear variations are presented.

Keywords Flat plate · Boundary layer · Surface roughness · Wall shear · Near wall effects

1 Introduction

During the manufacturing process of fluid devices, the surfaces produced do not have ideal surface roughness due to some manufacturing defects or burr formation. The fluid interacting surfaces which are being used for different applications are analyzed for an ideal surface roughness condition. Hence, the boundary layer thickness obtained is for the ideal condition. For real conditions, surface roughness may vary which impacts on changing the boundary layer thickness, wall shear and transition from laminar to turbulent boundary layer. The current study focuses on varying the surface roughness for different conditions and obtaining results based on that. The geometry used here is of a flat plate with different values of surface roughness.

The model used in this study is the *k*-omega SST model which captures surface effects. Also, PISO Scheme is taken into use for solving governing equations. For surface roughness, roughness height and roughness constant are provided which determine irregularity of the surface. Inlet velocity is given to be 11.11 m/s over a flat plate. Four different manufacturing processes of plate are used namely as casting,

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forging, shaping and planning having different values of surface roughness and the corresponding results are compared.

During literature review, the major gap identified was that the account of the surface roughness by different manufacturing processes was not taken into consideration. Due to this, the experimental results were not validating with the practical results. So, here four differently manufactured plates having different surface roughness values and compared their boundary layer thickness results. The CFD techniques are used in order to see how the surface roughness increases the overall wall shear and boundary layer thickness. Furthermore, understanding and predicting the effects of drag would help in the development and performance of some other applications whose parameters are changed and affected by surface roughness.

2 Literature Review and Objective

In some papers, experiments were conducted in slow-moving wind tunnel testing with velocity ranges of 10–25 m/s [1]. The wind tunnel is made up of a testing section in the center where its velocity in the air flow is nearly uniform [1]. Wu [2018] studied separating the turbulent boundary layer with LES (large eddies simulation) on a flat plate, which solves filtered equations of conservation of mass and momentum [3]. Usta [2013] used Reynolds Averaged Navier Stokes (RANS) solver for modeling incompressible, viscous, unsteady and turbulent layers. The governing equations were solved by using a realizable k-epsilon turbulence model [4]. Song [2020] used the roughness function in the wall function of CFD boundary conditions to represent surface roughness. The flow was modeled using the Unsteady Reynolds Averaged Navier Stokes (URANS) method, with second order upwind thermal scheme and first order sequential discretization for momentum equations. The SIMPLE algorithm served as the foundation for the overall solution procedure [5]. Akbar Javadi [2020] conducted research on the DH turbine using NACA 0015 aerofoil. The CFD model was used to simulate the turbine in 6 different average roughness heights. The turbulence model was the k-(SST) model [6]. Mohamed M. El-Mayit conducted theoretical and experimental studies on the boundary layer properties across a flat plate. Smooth surface boundary layers were discovered to have denser boundary layers than rough surface boundary layers [7]. Walid varied the magnitude and position of the roughness on the airfoil's aerodynamic properties in order to study the impact of surface roughness. It was discovered that the airfoil model with the roughness at the trailing edge exhibits the least amount of drag and the maximum lift [8]. Vivek Gupta investigated the effects of boundary layer inclination in a low-speed wind tunnel under various roughness conditions [1]. By Schultz, measurements of turbulence for boundary layers on a rough wall are shown and compared to those for a smooth wall. Using velocity-defect scaling, he found out that the mean velocity profiles for the smooth and rough walls reveal remarkable similarities in the outer layer [9]. Mohammadreza's research concludes that the structure of turbulent flow is still not completely understood. This is primarily due to a lack of research studies on the structural system of turbulent flow, as well as the wide range of roughness that influences flow dynamics in roughness sublayers [10]. The effects of surface roughness on a separating turbulent boundary layer were investigated by Wen Wu. The separated shear layer has increased turbulent kinetic energy in the case of the rough-wall (TKE) [3]. Ibrahim studied the effect of surface roughness on turbulent flow. For various roughness values, CFD analysis is performed to determine how heat transmission and fluid properties change as roughness increases [11]. Mohammad found out that surface roughness has a significant impact on the resistance properties of flat plates [4]. Mohammad's experimental and simulation-based analysis of a Darrieus hydro turbine shows that surface roughness degrades turbine performance and increases turbulence and reduces the active dynamic energy required to rotate it [6]. Joná discovered that the transitional zone gets shorter as the roughness number increases. He investigated the transition of flat plate boundary layers on surfaces near the acceptable roughness limit [12]. By comparing measurements taken over two rough walls to measurements taken from a boundary layer on a smooth wall, the effects of surface roughness on a turbulent boundary layer are examined by Krogstadt. The turbulent energy generation and the turbulent diffusion between the two rough surfaces were found to be considerably different [2]. R. A. Antonia investigated the impact of the surface roughness on the boundary layer and discovered that rough surfaces exhibit different turbulent transport features [2]. The impact of surface roughness on the vane endwall of an axial turbine's heat transmission was studied numerically by Lutum [5].

3 Methodology

In this study, CFD simulations were performed in order to simulate flow on a rough flat plate. To represent surface roughness in CFD simulations, roughness special wall functions were applied in boundary conditions. The objective of study was to see transition of flow from laminar to turbulent flow on the flat plate with variations of roughness affecting the transition region. Initial flow velocity and plate length was selected accordingly to render flow from laminar to turbulent region, with the flow velocity of 11.11 m/s and plate length of 2.2 m. Theoretical Reynolds number up to length 0.8 m had a value of 4×10^5 which is in the laminar region and from beyond that point the turbulent region would start.

3.1 Software

ANSYS Fluent 19.2 is a general-purpose computational fluid dynamics (CFD) software that can be used to simulate fluid flow, heat and mass transfer, chemical reactions, as well as other phenomena. Fluent has a modern, user-friendly interface which

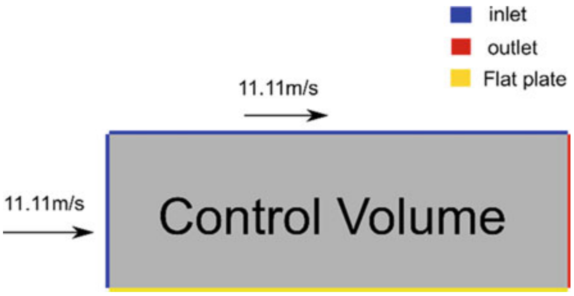


Fig. 1 Schematics of flat plate

simplifies the CFD process from pre-processing to post-processing inside a single window workflow.

3.2 *Geometry*

The geometry used for this study is a rectangular surface geometry with dimensions of 2200 mm length and 80 mm height for 2D flow simulation in which the lower edge is considered as a rough flat plate (Fig. 1).

3.3 *Meshing*

Mesh size	Edges	3 mm
	Surface	0.8 mm
Mesh element	Quadrilateral	
No. of nodes	86,990	
No. of elements	41,903	

The fine mesh was performed near the plate boundary to properly capture the boundary layer development and its transition from laminar to turbulent.

Meshing was done in ANSYS software with size of face mesh 3 mm and at boundary, mesh size is 0.8 mm as shown in Fig. 2.

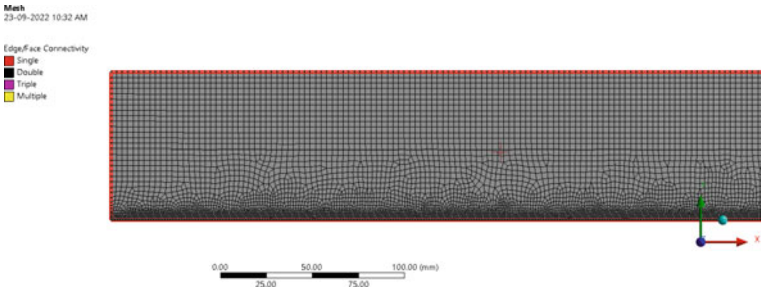


Fig. 2 Meshing of flat plate

Table 1 Surface roughness associated with machining processes

Machining	Roughness (Ra) (µm)
Casting	500
Forging	105
Shaping and planning	25
Surface grinding	6

3.4 Boundary Conditions

The 2D flow simulations were performed with control volume being cut plane in direction of flow.

In boundary conditions, the inlet velocity of 11.11 m/s was given with flat plate treated as wall and roughness was provided with roughness height and roughness constant, latter giving how the roughness is distributed over flat plate.

From the literature review, the surface roughness values for various machining operations were found and are listed in Table 1.

3.5 Governing Equations

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = \rho P - \beta^* \rho \omega k + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma_k \frac{\rho k}{\omega}\right)\frac{\partial k}{\partial x_j}\right], \text{ With } P = \tau_i \frac{\partial(\rho\omega)}{\partial t}$$

$$\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \frac{\alpha\omega}{k}\rho P - \beta^* \rho \omega^2 + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma_\omega \frac{\rho k}{\omega}\right)\frac{\partial \omega}{\partial x_j}\right] + \frac{\rho\sigma_d}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}$$

The k-omega SST model was selected to simulate the flow; the k-omega model is used to capture flow properties near the boundary. It used k-omega near the boundary and k-epsilon in the free stream. Shear stress transport model is used to model turbulence effects and hence it was included.

To solve the governing equations, the PISO scheme was used, with a second order scheme for gradient, a second order upwind scheme for momentum equations, and a first order upwind scheme for turbulent kinetic energy.

4 Results and Discussion

After simulating flow over flat plate for 4 different surface roughness, comparison was done based on the boundary layer thickness and wall shear for each case.

Initially, the flow is laminar ($Re = 5 \times 10^5$ for flat plate) till $x = 0.55$ (for Ra = 6 µm), then after that at $x > 0.55$, the flow becomes turbulent ($Re > 5 \times 10^5$). This pattern was the same for all 4 cases that were studied. The eddy viscosity contour is a proportionality factor that describes the turbulent energy transfer caused by moving eddies. It is seen that after some distance, the eddy viscosity starts increasing indicating the starting of the transition region and then the turbulent region starts.

For every case, the transition region was started around 0.25 m, with only in Ra 500 µm case, the transition was delayed by 10–15 mm (Fig. 3).

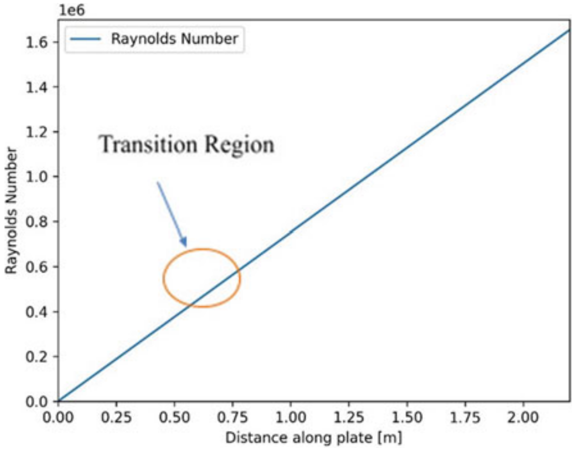
In contour for Turbulence kinetic energy, there is color distribution showing the mean kinetic energy per unit mass, associated with the respective eddy in a turbulent flow. It measures the intensity of turbulence in a flow. As shown in fig at $x = 2.2$ m, there is change in turbulence kinetic energy. As shown in Fig. 4c, the velocity contour has changed in velocity at the end of plate.

Figure 4a–c show the contours for Turbulent kinetic energy, Eddy Viscosity Contour, velocity at the inlet wind velocity of 11.11 m/s on a flat plate for surface roughness value of 6 Ra µm.

4.1 Velocity Profile Graphs

In the velocity graph for the Ra 6 µm case, velocity distribution profile along boundary layer at various locations of plate is observed. This distribution indicates how the boundary layer has developed over the length of the plate. From the velocity

Fig. 3 Reynolds number at various locations along plate



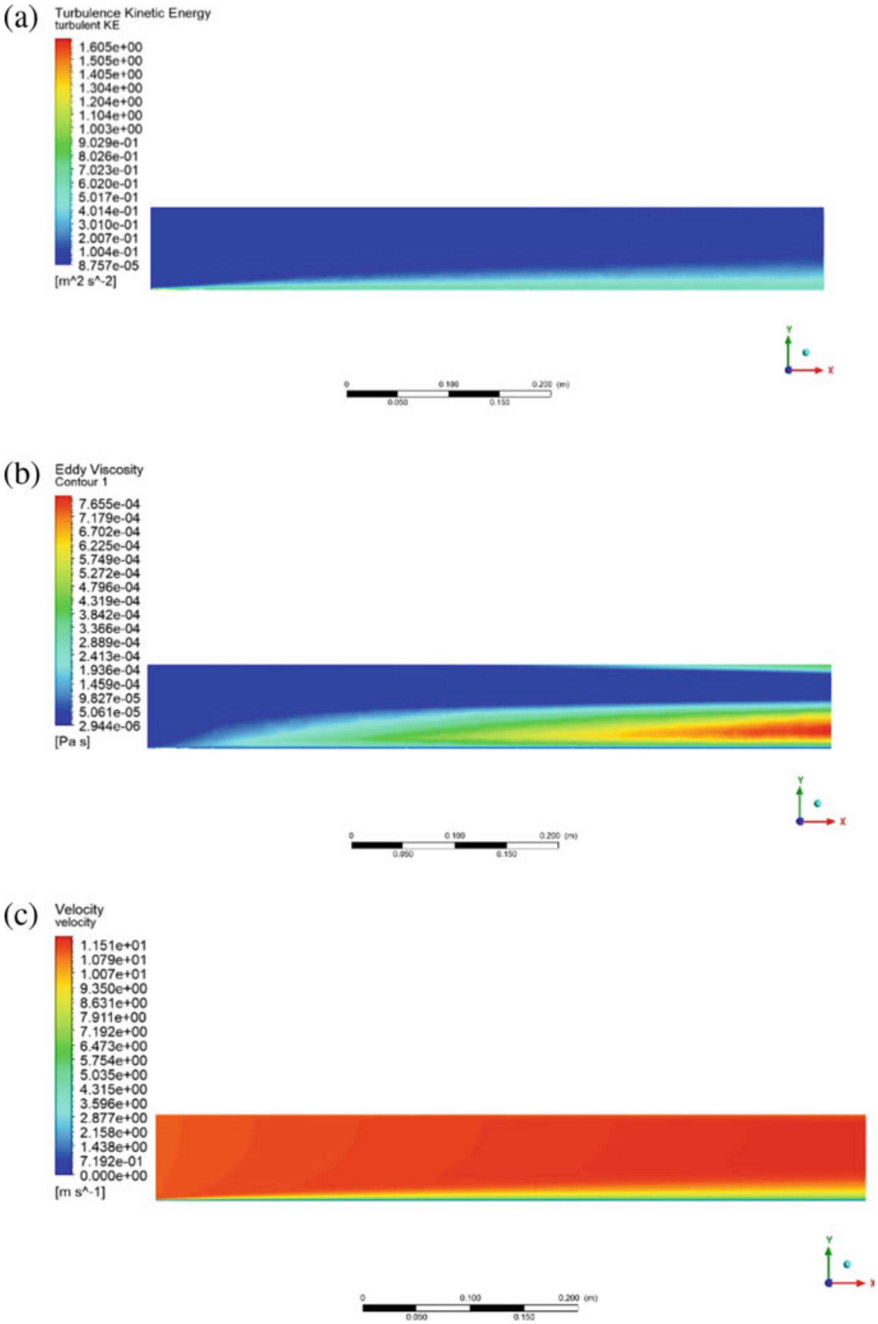


Fig. 4 **a** Turbulent kinetic energy contour. **b** Eddy viscosity contour. **c** Velocity contour

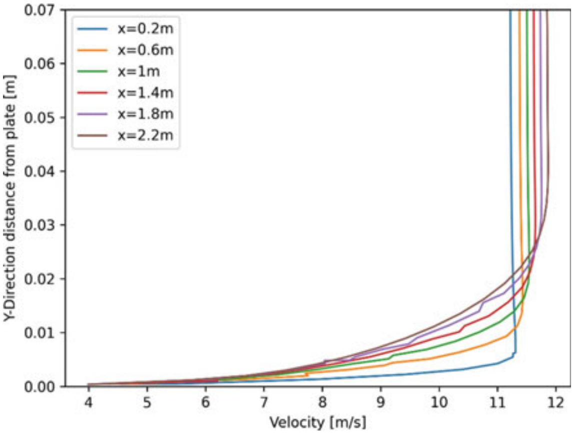


Fig. 5 Velocity profile in Ra 6 µm plate at various locations

profile graph, as the boundary layer converts to turbulent region, the $U_{99\%}$ increases with turbulence (Fig. 5).

4.2 Boundary Layer Thickness

In Fig. 6, the boundary layer thickness variation as the roughness of plate is changed, with BL thickness increasing with surface roughness.

For the Ra 6 µm and Ra 25 µm, the BL thickness is closely matched with little variations, but for the Ra 105 µm and Ra 500 µm case, it can be seen that there is a variation in BL thickness.

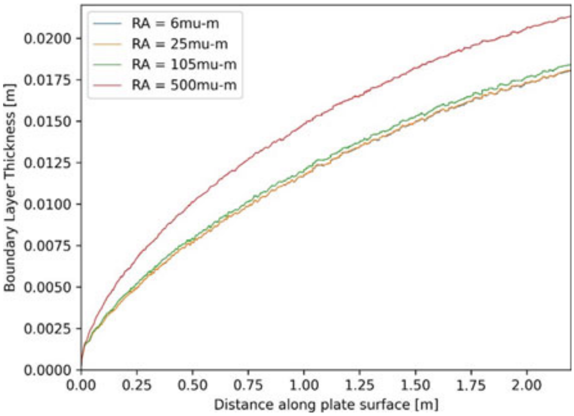


Fig. 6 Boundary Layer thickness along plate for different plate roughness

Table 2 Wall shear with roughness of each plate

Surface roughness (Ra) (µm)	Unit wall shear (N/mm^2)
6	0.281691
25	0.282081
105	0.290569
500	0.406072

4.3 Wall Shear

From Table 2, we can see trends similar to BL thickness, for the Ra 6 µm and Ra 25 µm case, the wall shear has changed negligibly but the variation starts to occur with Ra 105 µm and Ra 500 µm case.

5 Conclusions

In this analysis, a 2-D rectangular flat plate is considered & variations of four different surface roughness values were done by which different results like the roughness increases and the disturbance in the boundary layer increases. It was observed that for surface roughness to have significant impact on BL thickness and wall shear minimum deviation should be around 100 µm.

For transition from laminar to turbulent region, there was no significant impact due to surface roughness change, with only difference of Ra 500 µm causing to delay transition by 10–15 mm.

Nomenclature

Ra	Roughness Average [µm]
Re	Reynolds number
BL	Boundary Layer

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