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EXPERIMENTAL STUDY ON THE TECHNIQUES OF DETERMINING THE SKIN FRICTION IN ADVERSE PRESSURE GRADIENT BY USING THE BOUNDARY LAYER VELOCITY PROFILE

Necmi Anıl KIRIKKANAT*
Turkish Aerospace, Istanbul Technical University
Istanbul, Turkey

Duygu ERDEM†
Istanbul Technical University
Istanbul, Turkey

ABSTRACT

Three different graphical methods for estimating skin friction in the wall-bounded turbulent shear flow are investigated in terms of achieving the value of skin friction and application range. While Clauser Chart Method is suitable in zero pressure gradient, the method does not show the same effectiveness in the adverse pressure gradient due to adverse pressure gradient which disrupts the non-dimensional velocity profile. Available experimental data in adverse pressure gradient is taken from the literature and MATLAB code was written for Clauser Chart, Modified Clauser Chart, and Corrected Clauser Chart calculations. After the calculations were validated with the literature data, an experimental setup was established in ITU Trisonic Laboratory. In the experiment, wall shear stress and velocity measurements were made in the boundary layer for 10 m/s, 15 m/s, and 20 m/s free-stream velocities. Clauser Chart, Modified Clauser Chart, and Corrected Clauser Chart methods were applied to velocity data in the boundary layer. The wall shear stress results obtained from the chart methods and the wall shear stress data obtained directly from the surface were compared.

INTRODUCTION

Skin friction is an important phenomenon to evaluate resistance against the flow on the skin of the moving body through the viscous fluid. Basically, the drag of the moving body can be separated into two parts, one of them is viscous drag which occurs due to shear stress near to the body. It is important to measure the local skin friction to increase the performance of the moving body. The stability of the boundary layer has a significant role in the performance of the aircraft, missiles and etc. Especially, the circumstances like positive pressure gradients which affect the stability of the boundary layer cause a disruption in the universal velocity profile inside of the boundary layer. Generally, there are two different approaches for examining skin friction in a fully turbulent flow in an adverse pressure gradient. Mainly, the first approach is direct or indirect measurements by using floating elements, flush-mounted probes, or optical methods applied on the wall. The other approach is based on measurements inside the boundary layer. Graphical methods which examine boundary

*Thermal Analysis and Fluid Dynamics Engineer, Email: kirikkanat@itu.edu.tr
†Assistant Prof., Email: erdem@itu.edu.tr

layer velocity profile and manometric methods such as Preston and Stanton tube can be classified among the methods that use this approach. Furthermore, there are different graphical methods that focus on viscous sublayer, inner or outer regions of the turbulent boundary layer. In this study, inner layer methods that deal with the logarithmic region are used to determine wall shear. The main advantage of using a velocity profile is no need for an extra fluid element sensor or floating element sensor which can disturb the flow. Also, the direct measurement of velocity inside of the boundary layer is much simpler and applicable in experimental studies. Although graphical methods such as Clauser Chart Method(CCM) are considered to be reliable in the zero-pressure gradient, there is a limit in application in adverse pressure gradient turbulent flow. New methods like Modified Clauser Chart(MCCM) and Corrected Clauser Chart(CCCM) encourage hope to evaluate local skin frictions in adverse pressure gradients. The purpose of this study is to investigate these new methods experimentally.

GRAPHICAL METHODS

A universal velocity profile for boundary layer profile was always desired for researchers in the fluid mechanic's field. Once this universal velocity profile can be determined, this graph can be a reference to determine features of the boundary layer. Prandtl tried to derive an equation in pipe flow from conducted experiments [Tani I., 1977]. Finally, he derived a one-seventh power-law profile for pipe flows. Although this approach is good enough to explain pipe flow, there was not a commonly derived relation for a flat plate. Von Karman indicated the necessity of a non-dimensional parameter to be able to reach a non-universal velocity profile and introduced the frictional velocity (u_τ) concept. Von Karman expressed the logarithmic change of local velocities with the distance from the wall which is called law of the wall [Tani I., 1977]. Later, Prandtl introduced the mixing layer theory in order to simplify non-linear viscous terms in the Reynolds Averaged Navier Stokes equation. This mixing length theory was improved by Von Karman and the law of the wall is derived from the mixing length once again [Kundu P., Kohen I.M., Dowling D.R. , 2016].

$$\frac{u}{u_\tau} = \frac{1}{K} \ln\left(\frac{y u_\tau}{v}\right) + C \tag{1}$$

With the help of the law of the wall, the universal velocity profile in the turbulent boundary layer can be presented as in Figure 1. On a logarithmic scale, there is a linear relation can be realized.

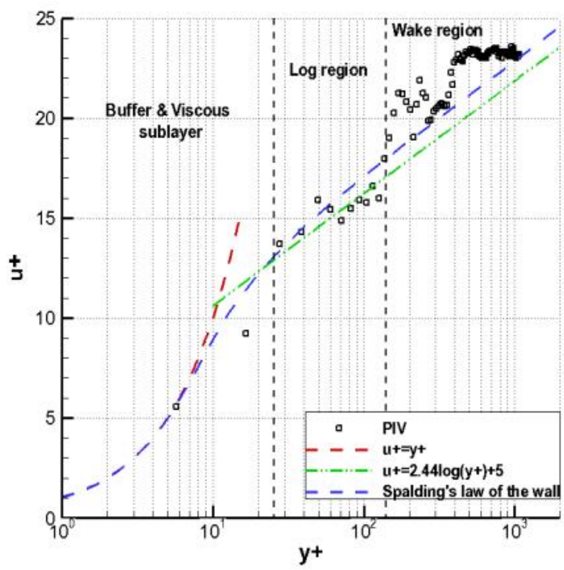

Figure 1: Universal log law [Hyuk L. et al., 2017]

Clauser Chart Method

Since the relationship between velocity and C_f is well known in the universal log-law region, this relationship can also be used as a prediction. If the velocity profile in the logarithmic region in the boundary layer can be determined properly, the same velocity profile can be found by trying appropriate C_f values. Since the dimensionless velocity, u^+ in the universal log-law region contains the u_τ parameter dependent on C_f that we actually want to find, some arrangements have to be made in the original velocity profile equation in the logarithmic region. Using the $u_\tau/U_e = \sqrt{C_f/2}$ relation the resulting equation is obtained as follows.

$$\frac{u(y)}{U_e} = \left(\frac{1}{K}\sqrt{\frac{C_f}{2}}\right)\ln\left(\frac{yU_e}{v}\right) + \frac{1}{K}\sqrt{\frac{C_f}{2}}\ln\left(\sqrt{\frac{C_f}{2}}\right) + C\sqrt{\frac{C_f}{2}} \tag{2}$$

Using the newly obtained equation, suitable C_f values are tried for a point whose velocity profile is known. An example of these trials is shown in Figure 2.

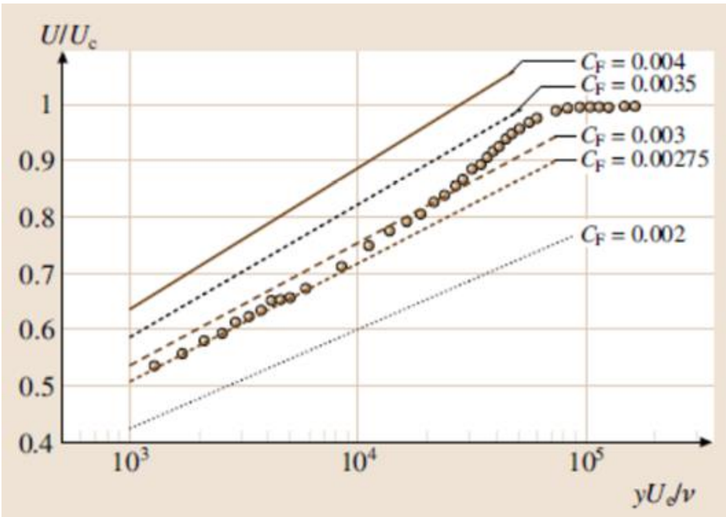

Figure 2: Skin friction determination by Clauser Chart [Klewicki J. et al., 2007]

The limitation of this approach is that the boundary layer should be in equilibrium. Large scale structure-activity triggered the small-scale structures which produce wall shear near the wall. To be able to define this equilibrium, he introduces the non-dimensional Clauser-Rota parameter, β;

$$\beta = \frac{\delta^*}{\tau_w}\frac{dp}{dx} \tag{3}$$

If the Cluaser-Rota parameter is equal alongside the streamwise direction, this method can be valid for calculating wall shear stress. On the other hand, the pressure gradient is disrupting the velocity profile with the change of the Clauser-Rota parameter [Clauser, F.H., 1954]. In the graphical aspect, log-law region disappearance is the main problem. There are new approaches to eliminate the pressure gradient effect.

Modified Clauser Chart Method

Dixit and Ramesh offer a new method that the constants in the law of the wall can be determined by the function of pressure gradient parameter [Dixit S.A., O. N. Ramesh , 2009]. The new pressure gradient term depends on the relationship between experimental data results and sensitivity of the constants in the law of the wall. The pressure gradient parameter is;

$$\Delta_p = \frac{v}{\rho u_\tau^2}\frac{dp}{dx} = \frac{-K}{(C_f/2)^{3/2}} \tag{4}$$

While the pressure gradient parameter is calculated from the skin friction, skin friction has to be calculated from the pressure gradient parameter based on the law of the wall. Therefore, two hold iteration is needed for the application of the Modified Clauser Chart.

$$u^+ = \frac{1}{K}(\Delta_p)\ln(y^+) + C(\Delta_P) \tag{5}$$

$$\frac{1}{K} = 2.452 + 19.534\Delta_p + 113.08\Delta_p^2 \tag{6}$$

$$C = 5.3048 - 185.82\Delta_p + 1033.2\Delta_p^2 + 25172\Delta_p^3 \tag{7}$$

It is important to note that the coefficient in the constants function is coming from the experimental database. This database can be seen in Table 1.

Data Set Code	c_f	Δ_p	$1/K$	C
DR1	0.00401	-0.0086	2.349	6.96
DR2	0.00403	-0.0104	2.282	7.666
DR3	0.00416	-0.0129	2.201	8.289
DR4	0.0043	-0.0175	2.087	9.31
DR5	0.00433	-0.0288	1.999	10.603
JMP3	0.00437	-0.0053	2.379	5.403
HN2	0.00375	-0.0026	2.369	5.395
ZPG	-	0	2.439	5.2
SL5	0.00487	0.0182	2.845	2.896
SL6	0.00456	0.0377	3.349	1.003

Table 1: Database which used in Modified Clauser Chart [Dixit S.A., O. N. Ramesh , 2009]

Corrected Clauser Chart Method

Corrected Clauser Chart Method: Dróżdż and Elsner indicated that the range of logarithmic region is well-known in zero pressure gradient according to recent experimental data and it can be used for the turbulent boundary layer profile with adverse pressure gradient (Skin Friction Estimation in Strong Decelerating Flow, 2018). The weakest part of the Clauser Chart Method is determining the boundary of the log-law region in the non-dimensional graph when the adverse pressure gradient has occurred. Corrected Clauser Chart method offers an assumption that large-scale structure is placed geometric center of the boundary layer both in adverse and zero pressure gradient. With the help of this assumption lower boundary of the logarithmic region is determined by y^+=150 value in adverse pressure gradient. On the other hand, upper boundary is considered by 0.15δ^+. While the constants are defined as K=0.379 and K=3.56 according to Dróżdż, later experimental studies show that K=0.38 and C=4.1 is suitable [Niegodajew P., Dróżdż A., Elsner W., 2019]. Fluid history along the streamwise direction is needed for calculation because the zero-pressure gradient boundary layer profile is part of this application.

METHODS

MATLAB Code is created for all three different approach. Experimental data taken from Dróżdż's study is used for validation of MATLAB code [Dróżdż A., Elsner W. and Sikorski D., 2018]. For this purpose, wall shear stresses were calculated with the help of the Dróżdż's boundary layer data and compared with his findings. The results of MATLAB Code compared with Dróżdż's data can be found in Table 2 and 3. It has been observed that the calculated shear stresses are in good agreement with those of Dróżdż's results.

U=10 m/s							
X	**Beta**	**[Dróżdż Results] Twall(CCM) (K=0.38 C=4.1)**	**MATLAB Result Twall (CCM) (K=0.38 C=4.1)**	**[Dróżdż Results] Twall (CCCM)**	**MATLAB Result Twall (CCCM)**	**MATLAB Result Twall (MCCM)**	**OFI Measured Data**
700	11.53	0.063	0.063777466	0.071	0.07128	0.061693	0.072
800	17.18	0.037	0.037187108	0.051	0.0512	0.036012	-
900	26.26	0.021	0.021452163	0.029	0.0290	0.020724	0.047
1000	43.44	0.011	0.011372282	0.019	0.0192	0.011027	0.032
1100	93.96	0.008	0.009378138	0.013	0.0132	0.009054	0.011

Table 2: MATLAB code result for Dróżdż's data at 10 m/s

U=20 m/s							
X	**Beta**	**[Dróżdż Results] Twall(CCM) (K=0.38 C=4.1)**	**MATLAB Result Twall (CCM) (K=0.38 C=4.1)**	**[Dróżdż Results] Twall (CCCM)**	**MATLAB Result Twall (CCCM)**	**MATLAB Result Twall (MCCM)**	**OFI Measured Data**
700	12.37	0.231	0.235881	0.262	0.266209	0.230826	0.267
800	16.65	0.156	0.152396	0.192	0.194383	0.149286	0.202
900	27.62	0.069	0.082835	0.111	0.118336	0.081356	-
1000	42.54	0.039	0.039294	0.066	0.075781	0.037890	0.1
1100	83.68	0.025	0.025178	0.041	0.042406	0.023853	0.035

Table 3: MATLAB code result for Dróżdż's data at 20 m/s

According to Table2 and Table3, when the Clauser-Rota parameter (β) is increased, divergence from the real value (oil-film interferometry results) is increased. On the other hand, it is clear that Modified Clauser Chart Method underestimates skin friction. This situation can be related to the non-dimensional pressure gradient parameter which heavily relies on experimental data in the Dixit's study [Klewicki J. et al., 2007]. These data are mostly coming from the favorable pressure gradient and this affects the result. The application range of the Clauser Chart Method is increased by Corrected Clauser Chart Method.

With the help of these findings, an experimental setup is designed in ITU Trisonic Research Laboratory. Characteristics of graphical methods in moderate adverse pressure gradients is investigated with this experiment. It is seen that the Clauser Chart and Corrected Clauser Chart results from Dróżdż's article show a great agreement with the MATLAB code results developed for this study. Thus, it was concluded that the MATLAB code created is suitable for use for the experimental setup created in the ITU Trisonic Research Laboratory.

EXPERIMENTAL SETUP

While designing the experimental setup, two different objectives were considered. The first is the formation of moderate adverse pressure on the backward-facing ramp. The second objective is to prevent flow separation. Before the experimental setup was designed, a backward-facing ramp setup from 3 degrees to 10 degrees was pre-calculated with computational fluid dynamics and it was seen that both targets were provided with a 10-degree ramp angle in the experimental setup.

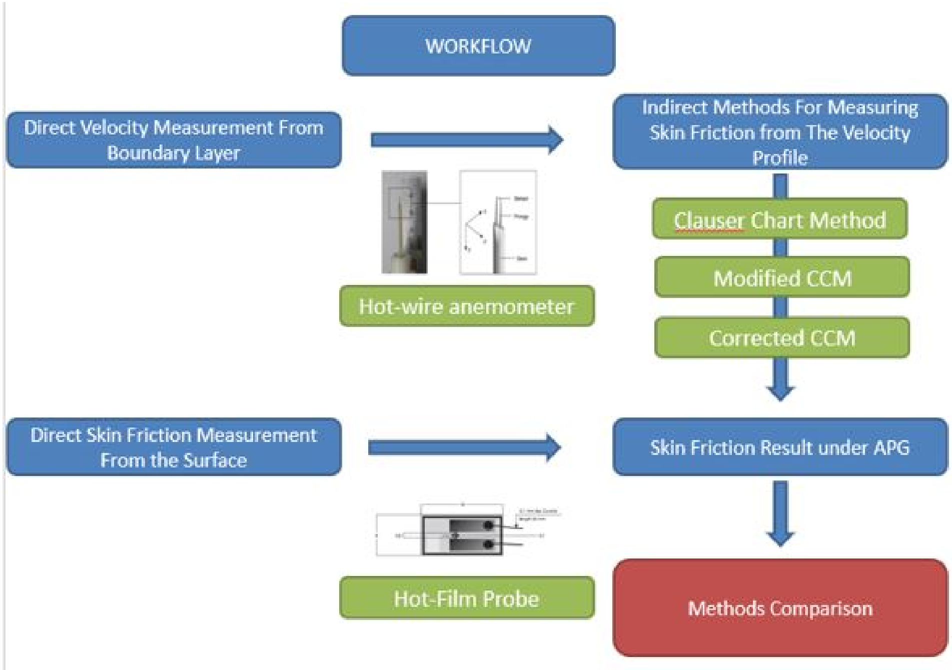

Figure 3: Experimental Flow Chart

Experiments are conducted in 80 cm x 80 cm open test section, Eiffel type subsonic wind tunnel in the Trisonic Laboratory of Istanbul Technical University at 10 m/s, 15 m/s and 20 m/s free-stream velocities. A backward facing acrylic ramp was manufactured for the experimental setup. In order to create an adverse pressure gradient in the assembly, there is a ramp with an angle of 10 degrees after the straight part of the model. ESP miniature 32 channel electronic pressure scanner was used to measure the pressure distribution. DANTEC Dynamic 55R47 glue-on probe was used to measure the wall shear stress distribution. Velocity distribution in the boundary layer is measured by using DANTEC 90C10 constant-temperature anemometer with boundary layer probes. The experimental setup is shown in Figure 4.

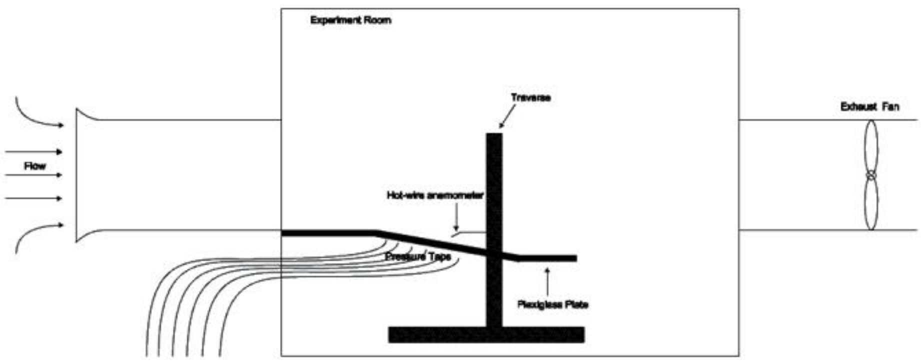

Figure 4: Experimental Flow Chart

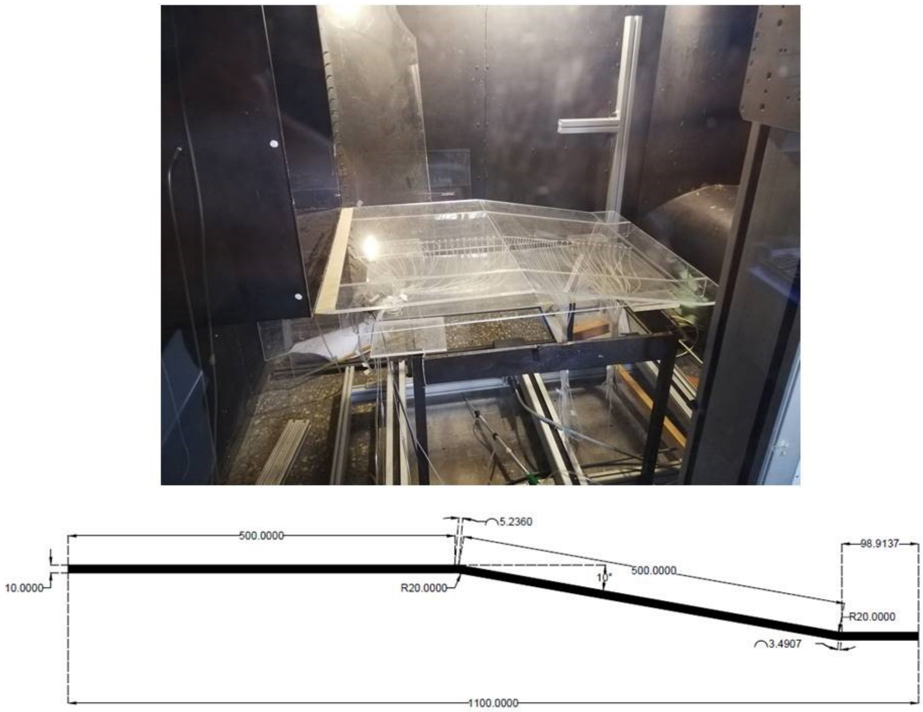

Figure 5: Acrylic Ramp Model

EXPERIMENTAL RESULTS

Firstly, the pressure distribution is measured and the pressure gradient at each measurement point is found. As can be seen from the pressure distribution (Figure 6), the pressure change is very small where the plate is flat for all three velocity values. Although the β value is not 0, this region is taken as the zero pressure gradient region since it is very close to 0.

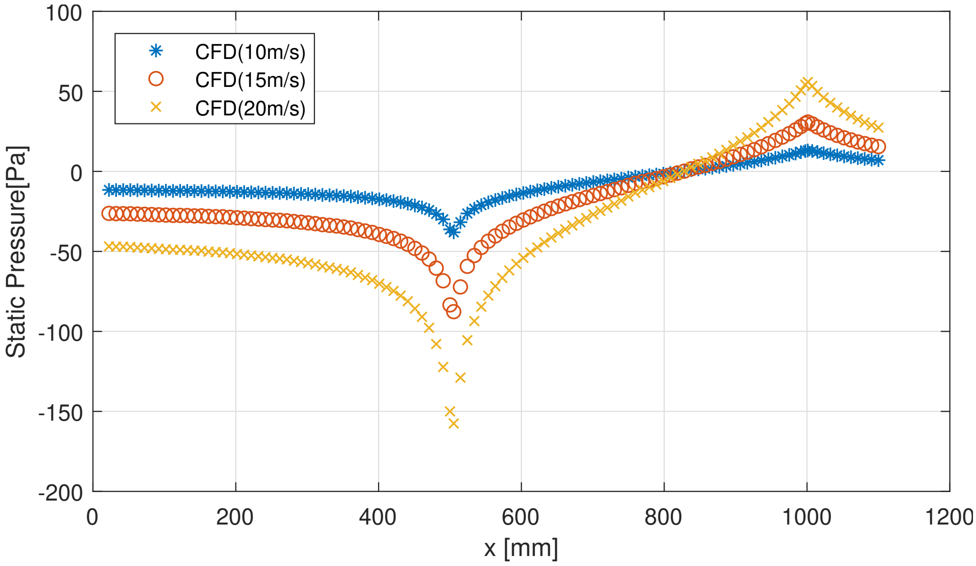

Figure 6: Pressure Distribution

In order to examine chart methods appropriately, velocity measurement in the boundary layer and wall shear stress measurement must be taken from the points where both zero pressure gradient and adverse pressure gradient occur. Station 10 and 16 points located on the flat part of the model, where the Clauser-Rota parameter is close to 0, were selected for the zero pressure gradient. In addition, stations 50 and 55, located on the inclined part of the plate, where the Clauser-Rota parameter is positive, were selected for the adverse pressure gradient.

Station No.	x[mm]	β ***(Clauser-Rota Parameter)***		
		10 m/s	**15 m/s**	**20 m/s**
Station10	200	-0.122156561	-0.038009047	-0.010861333
Station16	320	-0.265154514	-0.198350982	-0.177940179
Station40	662.779	-0.083724358	0.474094676	0.68407103
Station50	820.348	1.281752656	1.284948818	1.186344685
Station55	918.829	7.502380378	5.348605729	4.202793361

Table 4: Clauser-Rota Parameter (β) Distribution

Then, velocity measurement was made within the boundary layer for each selected measurement point (stations 10,16,40,50 and 55) and each free stream velocity.

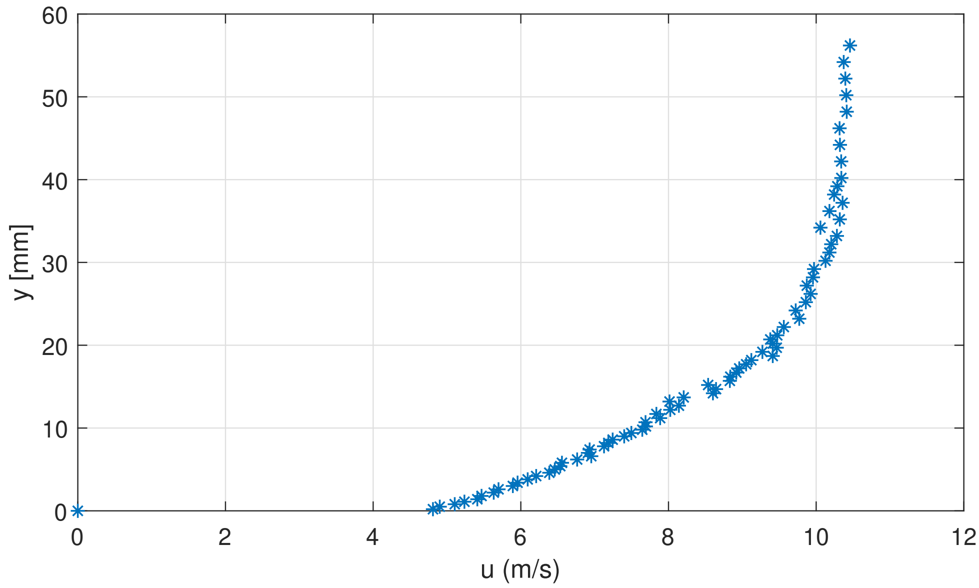

Figure 7: Boundary Layer Velocity Profile (Station 50 – U_{∞}=10 m/s)

The measured velocity data were transferred to the $u(y)/U_e - y \times U_e/v$ graphs on a logarithmic scale and visual inspection was performed to find the boundaries of the logarithmic region. After determining the logarithmic region, a linear line was drawn with the least square method from within the determined limits. This line is taken as a reference. Clauser Chart Method was applied and the closest Clauser Chart Method line to the reference line was found and wall shear stress, τ_w was calculated.

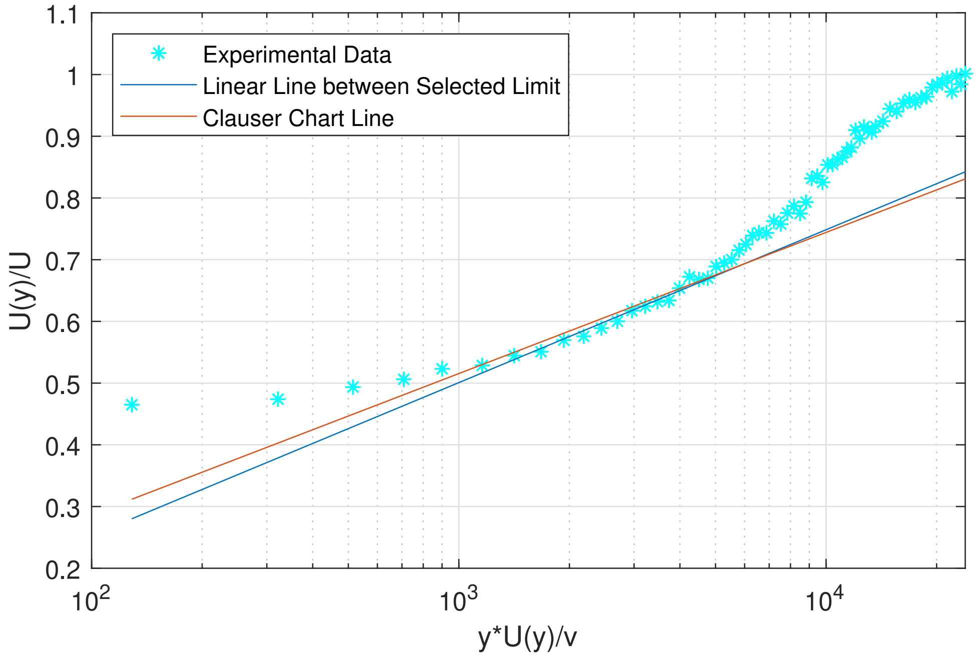

Figure 8: Clauser Chart Method (Station 50 – U_∞=10 m/s)

Just like in the Clauser Chart Method, the boundaries of the logarithmic region are determined in the Modified Clauser Chart method and the Modified Chart Method is applied within these limits. The selected logarithmic region boundaries are the same boundaries used in the Clauser Chart Method.

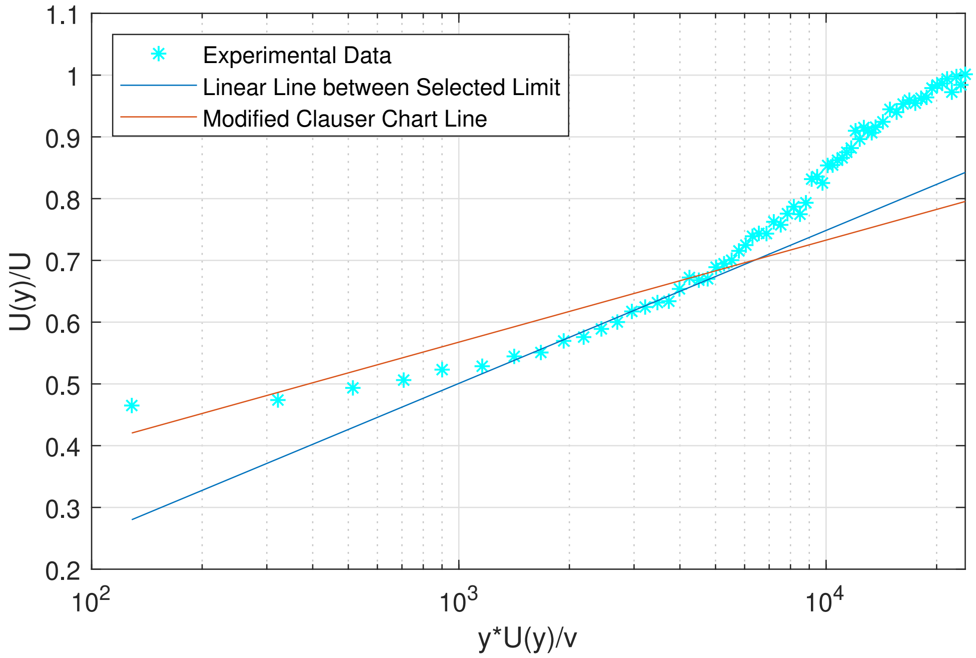

Figure 9: Modified Clauser Chart Method (Station 50 – U_∞=10 m/s)

Then, for the application of the Corrected Clauser Chart Method, the Clauser Chart Method was made using the velocity profiles at the zero-pressure gradient measurement point (station10) and the logarithmic region was determined. Then, with the help of zero pressure gradient results, Corrected Clauser Chart method was applied for velocity profiles at station 40, station 50 and station 55.

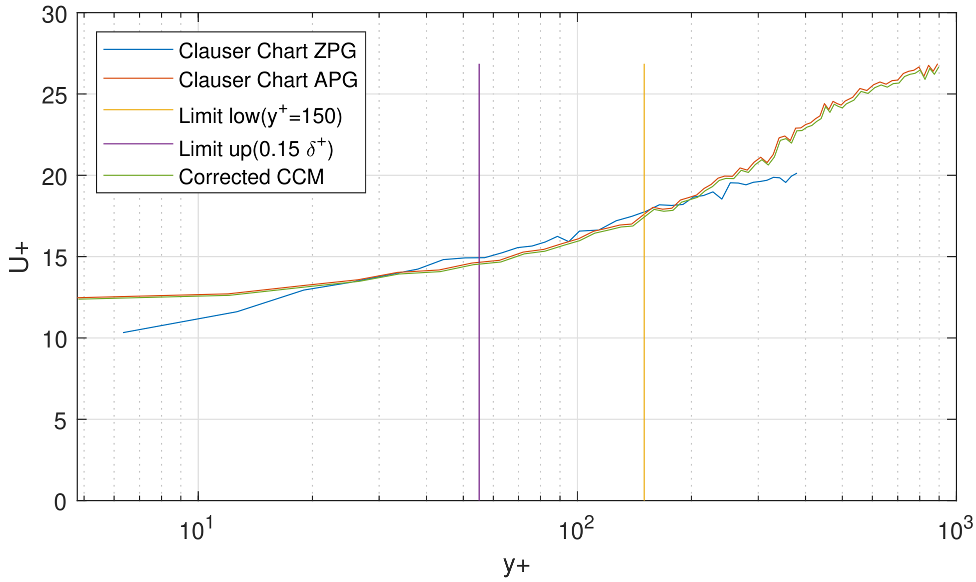

Figure 10: Corrected Clauser Chart Method (Station 50 – U_∞=10 m/s)

Wall shear stress, τ_w results were as in Figures 11, 12 and 13 when applied in all three methods for all measurement points.

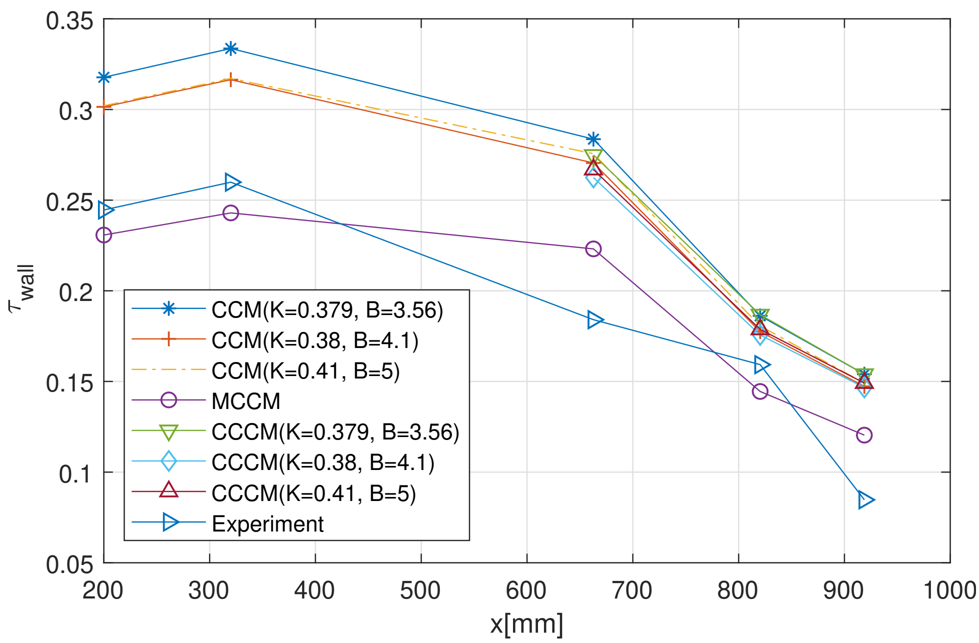

Figure 11: Comparison of Chart Methods Results in Stations (U_∞=10 m/s)

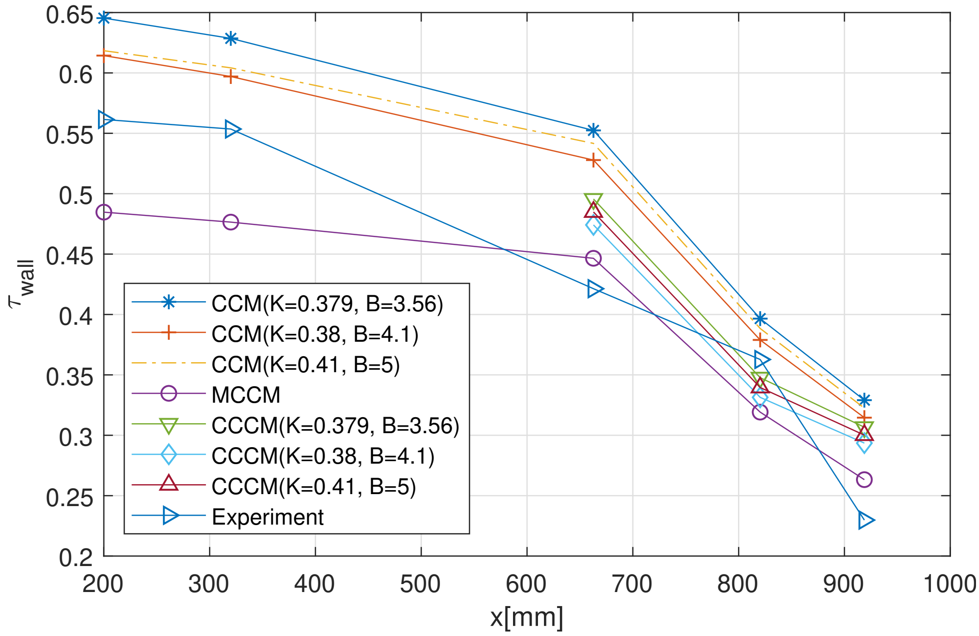

Figure 12: Comparison of Chart Methods Results in Stations (U_∞=15 m/s)

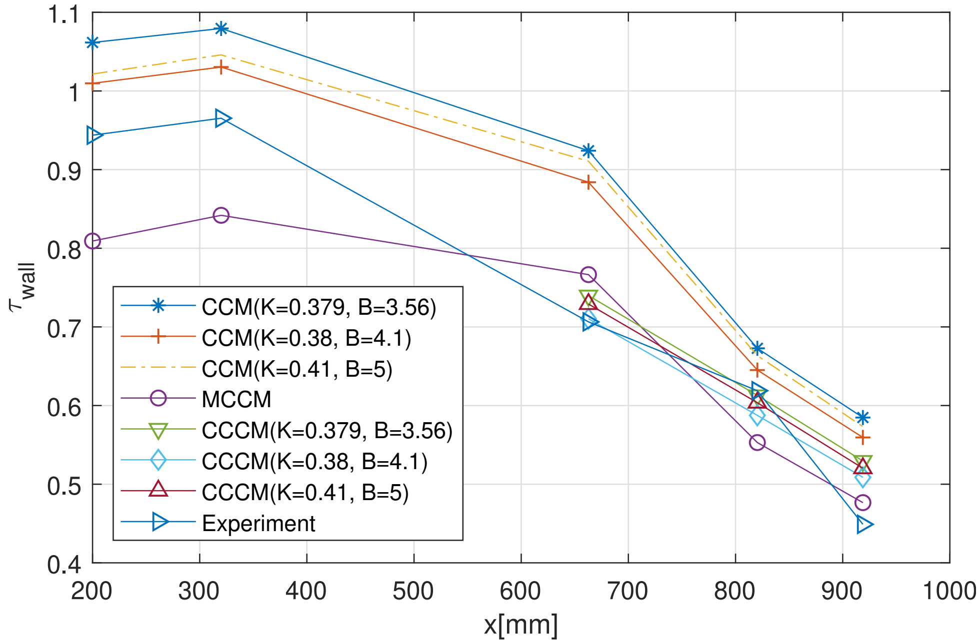

Figure 13: Comparison of Chart Methods Results in Stations (U_∞=20 m/s)

CONCLUSIONS

In this study, Cluaser Chart Method, Corrected Clauser Chart Method and Modified Clauser Chart Methods were examined. At the beginning of the study, MATLAB code was developed by using the experimental data of Arthur Dróżdż. The methods examined with this developed code were matched to the experimental data and it was seen that the results were consistent with the results in Dróżdż 's article [Dróżdż A., Elsner W. and Sikorski D., 2018]. Then, an experimental setup was realized in the Eiffel wind tunnel inside the ITU Trisonic Laboratory to check the applicability of these methods. Within the scope of the experiment, pressure, velocity and wall shear stress measurements were made both in the region with zero pressure gradient and in the region with adverse pressure gradient. With the velocity data taken from the boundary layer, the code previously validated with the data of Dróżdż was run and Clauser Chart, Modified Clauser Chart and Corrected Clauser Chart Methods were applied.

According to the results of the experiment, it was seen that the Modified Clauser Chart method approached the real τ_w data with less error rate. In the zero pressure gradient region (station 10, 16), Clauser Chart Method and Corrected Clauser Chart generally approached the real τ_w data with less error rate. At the same time, it was observed that Clauser Chart and Corrected Clauser Chart data overestimated when predicting the τ_w. While the Modified Clauser Chart underestimates the τ_w in the zero pressure gradient region, it made τ_w prediction with a smaller error rate in the adverse pressure gradient region (station 40, station 50, station 55). As a result, it was observed that the error rates increased when going from the zero pressure gradient region to the adverse pressure gradient region for all three methods. It has been observed that better results are obtained in Clauser Chart and Corrected Clauser Chart Methods when K=0.38 and C=4.1 are used for the coefficients used in the logarithmic region.

ACKNOWLEDGEMENT

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