T3 – Boundary Layers

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Summary:

This experiment seeks to measure velocity profiles in laminar and turbulent boundary layers on a flat plate. Additionally, it aims to establish a correlation between fluid momentum loss in the boundary layers and resulting skin friction drag. Furthermore, the investigation delves into the factors contributing to the higher drag on a bluff body compared to skin friction drag.

Experimental Setup and Procedure:

The details of the experiment setup and procedure can be found on the T3-Boundary Layers Lab Handout.

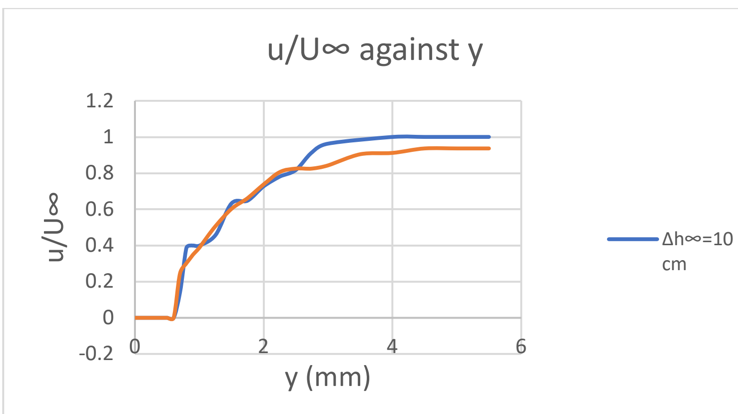
Readings and Results:

Laminar (where Δh∞ = 100)		
Position (mm)	Δh (mm)	(Δh/Δh∞)1/2
0	0	0
0.1	0	0
0.2	0	0
0.3	0	0
0.4	0	0
0.5	0	0
0.6	0	0
0.7	2	0.141421356
0.8	15	0.387298335
0.9	16	0.4
1	16	0.4
1.25	21	0.458257569
1.5	40	0.632455532
1.75	42	0.64807407
2	53	0.728010989
2.25	61	0.781024968
2.5	67	0.818535277
2.75	84	0.916515139
3	93	0.964365076
4	100	1
4.5	100	1
5	100	1
5.5	100	1

Fig1: Results for laminar boundary layer measurements at manometer reading of 10cm.

Laminar (where Δh∞ = 66)		
Position (mm)	Δh (mm)	(Δh/Δh∞)1/2
0	0	0
0.1	0	0
0.2	0	0
0.3	0	0
0.4	0	0
0.5	0	0
0.6	0	0
0.7	4	0.246182982
0.8	6	0.301511345
0.9	8	0.348155312
1	10	0.389249472
1.25	17	0.507519219
1.5	24	0.603022689
1.75	29	0.662867965
2	36	0.738548946
2.25	43	0.807164885
2.5	45	0.825722824
2.75	45	0.825722824
3	47	0.843872746
3.5	54	0.904534034
4	55	0.912870929
4.5	58	0.937436867
5	58	0.937436867
5.5	58	0.937436867

Fig 2: Results for laminar boundary layer measurements at manometer reading of 6.6cm.



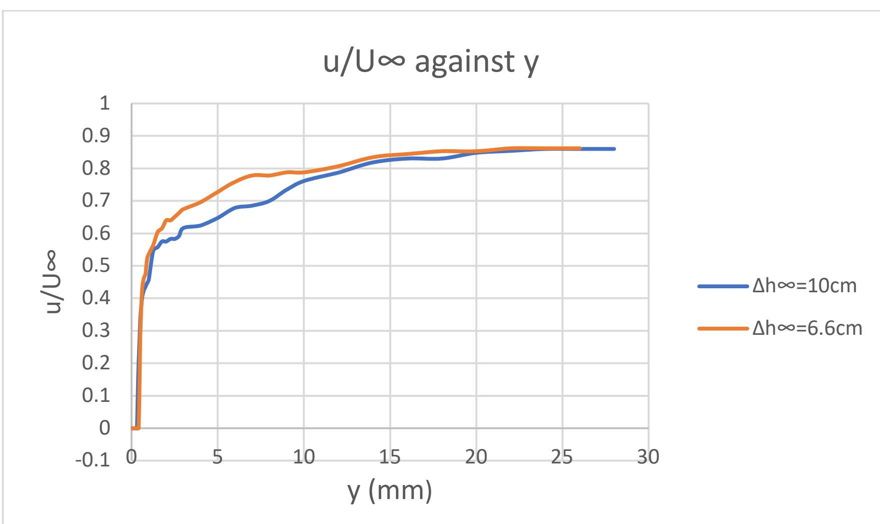
Graph 1: Graph u/U∞ against y at a manometer reading of 10cm and 6.6cm for the laminar boundary layer.

Turbulent (where Δh∞ = 100)		
Position (mm)	Δh (mm)	(Δh/Δh∞)1/2
0	0	0
0.1	0	0
0.2	0	0
0.3	0	0
0.4	4	0.2
0.5	11	0.331662479
0.6	16	0.4
0.7	18	0.424264069
0.8	19	0.435889894
0.9	20	0.447213595
1	21	0.458257569
1.25	30	0.547722558
1.5	31	0.556776436
1.75	33	0.574456265
2	33	0.574456265
2.25	34	0.583095189
2.5	34	0.583095189
2.75	35	0.591607978
3	38	0.6164414
4	39	0.6244998
5	42	0.64807407
6	46	0.678232998
7	47	0.68556546
8	49	0.7
9	54	0.734846923
10	58	0.761577311
12	62	0.787400787
14	67	0.818535277
16	69	0.830662386
18	69	0.830662386
20	72	0.848528137
22	73	0.854400375
24	74	0.860232527
26	74	0.860232527
28	74	0.860232527

Fig 3: Results for turbulent boundary layer measurements at manometer reading of 10cm.

Turbulent (where Δh∞ = 66)		
Position (mm)	Δh (mm)	(Δh/Δh∞)1/2
0	0	0
0.1	0	0
0.2	0	0
0.3	0	0
0.4	0	0
0.5	5	0.275240941
0.6	12	0.426401433
0.7	14	0.460566186
0.8	15	0.476731295
0.9	18	0.522232968
1	19	0.53654337
1.25	21	0.564076075
1.5	24	0.603022689
1.75	25	0.615457455
2	27	0.639602149
2.25	27	0.639602149
2.5	28	0.651338947
2.75	29	0.662867965
3	30	0.674199862
4	32	0.696310624
5	35	0.728219081
6	38	0.758786911
7	40	0.778498944
8	40	0.778498944
9	41	0.788170109
10	41	0.788170109
12	43	0.807164885
14	46	0.83484711
16	47	0.843872746
18	48	0.852802865
20	48	0.852802865
22	49	0.861640437
24	49	0.861640437
26	49	0.861640437

Fig 4: Results for turbulent boundary layer measurements at manometer reading of 6.6cm.



Graph 2: Graph u/U∞ against y at a manometer reading of 10cm and 6.6cm for the turbulent boundary layer.

Calculations and Discussion:

$$\frac{1}{2}\rho u^2 = \rho l g \Delta h \sin\theta \ where \ \frac{u}{U\infty} = \sqrt{\frac{\Delta h}{\Delta h\infty}}$$

Δh is the height of the manometer column, θ = 5° is the angle of inclination of the manometer, ρ is the velocity of air and ρl = 815 kg/m3, which is the density of the methylated spirits. After arranging the equation, it gives:

$$\frac{1}{2}\rho u_\infty^2 = \rho_l g \Delta h_\infty \sin\theta$$

For the high-speed readings, Δh∞=100mm, and for the low-speed reading Δh∞=66mm. The free stream velocity, U∞ is then 10.78 m/s and 8.76 m/s respectively.

$$Re = \frac{\rho u L}{\mu}$$

The formula of Reynolds number, Re is shown above where ρ is the density of the air and L is the length of the plate, 0.735m and μ is the dynamic viscosity of air, 1.75×10^{-5} kg/(m.s). With the free stream velocity calculated above, Reynold's numbers are 5.43×10^5 and 4.42×10^5 respectively.

The same calculation and results are gained from the turbulent boundary layer because the Δh ∞ is the same as the laminar boundary layer.

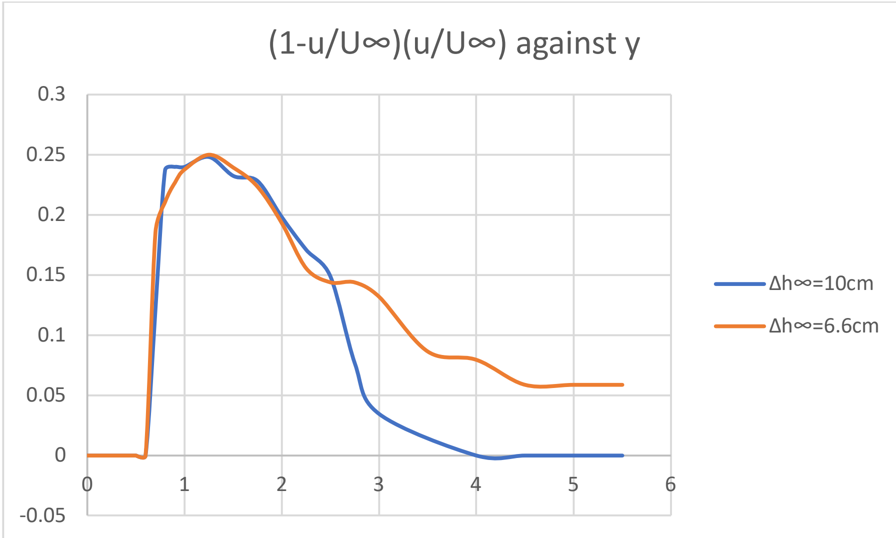
By hearing the microphone's output which has been inserted into the airflow, the turbulent flow has a larger noise with greater fluctuations compared to the laminar flow.

The normalized velocity against distance from the plate surface graph for both laminar flow and turbulent flow with different speed flow are shown in Graph 1 and Graph 2 respectively.

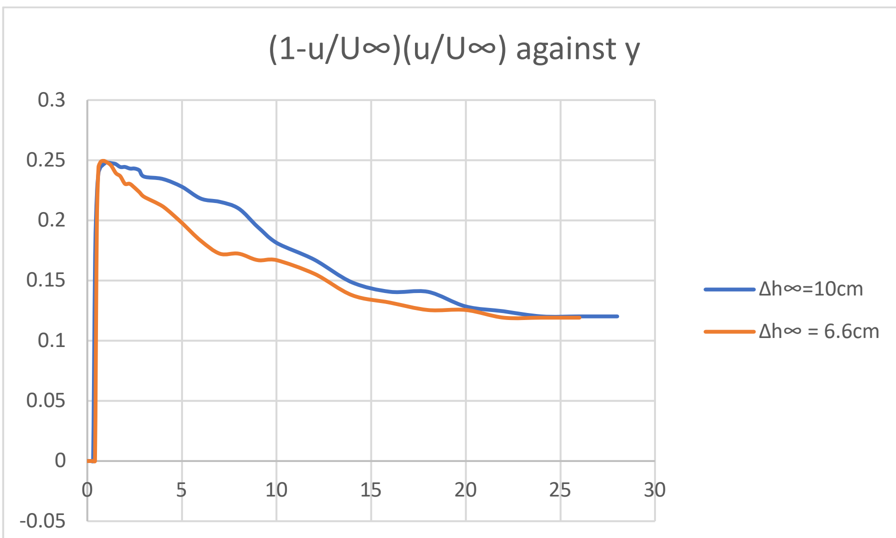
The rate of momentum flux lost across a section dx along the plate across the boundary layer thickness θ is given by :

$$\dot{M} = \int_0^\infty (U_\infty - u)\rho u \, dy = \int_0^\infty \rho U_\infty^2 \left(1 - \frac{u}{U_\infty}\right)\left(\frac{u}{U_\infty}\right) dy$$

The rate of momentum flux lost is equal to the total skin friction drag on one side of the plate.



Graph 3: Graph (1-u/U∞)(u/U∞) against y at a manometer reading of 10cm and 6.6cm for the laminar boundary layer.



Graph 4: Graph (1-u/U∞)(u/U∞) against y at a manometer reading of 10cm and 6.6cm for the turbulent boundary layer.

Graph 3 and graph 4 show the curve of (1-u/U∞)(u/U) for laminar and turbulent flows.

The area under the curve was calculated to estimate the total skin friction. The skin friction drag of both set of values are equal because the area under the curve for Δh∞ = 6.6cm and Δh∞ = 10cm is roughly the same.

The skin friction for laminar flow = 1.2 x 10.78^2 x 2.34 x 10^{-5} = 3.26x10^{-3} N/m

The skin friction for turbulent flow = 1.2 x 8.76^2 x 8.49 x 10^{-5} = 7.81x10^{-3} N/m

The skin friction for the turbulent flow is approximately double the one for laminar flow. This is because of the increased shear stress on the boundary layer.

The shear stress produced by the relative movement of a differential particle in a fluid near the wall is given by:

$$\tau = \mu \frac{\partial u}{\partial y}$$

The shear stress for laminar flow = 1.75×10^{-5} x 202.03 = 3.53×10^{-3}

The shear stress for turbulent flow = 1.75×10^{-5} x 550.48 = 9.63×10^{-5}

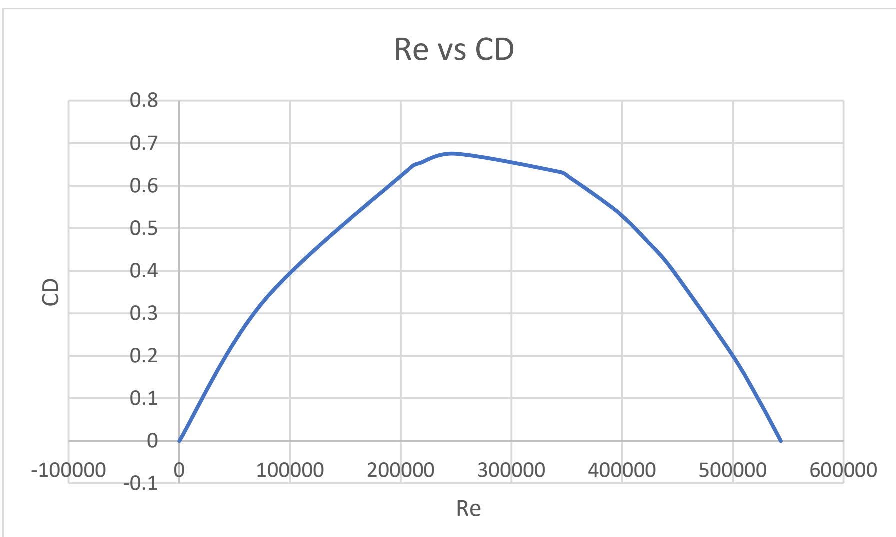
The percentage difference of values of the skin friction calculated by both methods for laminar flow is 8% and 18.9% for turbulent flow, both of which are below 20%. Therefore, it is consistent.

The drag coefficient formula is as below:

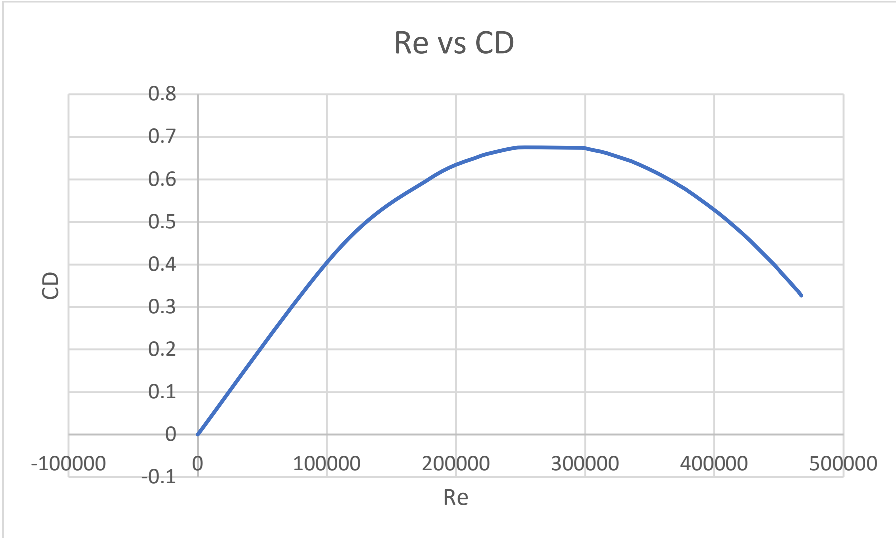
$$C_D = \frac{F_D}{\frac{1}{2}\rho U_\infty^2 L}$$

Combining with the rate of momentum flux lost equation will give:

$$C_D \approx \frac{2\left(1 - \left(\frac{u}{U_\infty}\right)\right)\frac{u}{U_\infty}}{L}$$



Graph 5: Graph Drag Coefficient against Reynolds number at a manometer reading of 10cm for the laminar boundary layer.



Graph 6: Graph Drag Coefficient against Reynolds number at a manometer reading of 10cm for the turbulent boundary layer.

Conclusion:

1) Turbulent flow results in higher skin friction drag compared to laminar flow.

2) There is a maximum drag coefficient at a specific Reynolds number.

3) As the pitot moves further from the wall, the velocity increase rate diminishes in both laminar and turbulent flows.