Design, Development And Validation Of Specialized Fixture For Wind Tunnel To Study Boundary Layer

Bhavesh R. Kataria
Department of Mechanical Engineering, Vishwakarma Institute of Information Technology, Pune-48, Maharashtra, India

Vinayak A. Karkhanis
Department of Mechanical Engineering, Vishwakarma Institute of Information Technology, Pune-48, Maharashtra, India

Abstract

Fluid mechanics is considered as one of the core subjects in mechanical engineering. The concepts of this subject are easy to understand when they are shown practically. One of such important concept in fluid mechanics is boundary layer. It has variety of applications in many fields. In practice to study this phenomenon wind tunnel is used as one can have a good control over the test section environment with this instrument. Wind tunnel is not only useful in getting the concept of boundary layer but also to have study of boundary layer over different geometries for different velocities.

In this project, we have developed a specialized fixture for wind tunnel which can take readings over the different points on flat plate and thus will give the nature of boundary layer.

Keywords: *Boundary Layer, Wind Tunnel, Specialized Fixture, Testing, Simulation, Validation.*

1. Literature Review

1.1. Introduction

Boundary layer is a layer adjacent to a surface where viscous effects are important. When real fluid flows past a solid body or a solid wall, the fluid particles adhere to the boundary and condition of no slip occurs. This means that the velocity of fluid close to the boundary will be same as that of boundary. If the boundary is not moving, the velocity of fluid at the boundary will be zero. Further away from the boundary, the velocity will be increasing gradually and as a result of this variation of velocity, the velocity gradient will exist. The velocity of fluid increases from zero velocity on the stationary boundary to the free stream velocity of the fluid in the direction normal to the boundary.

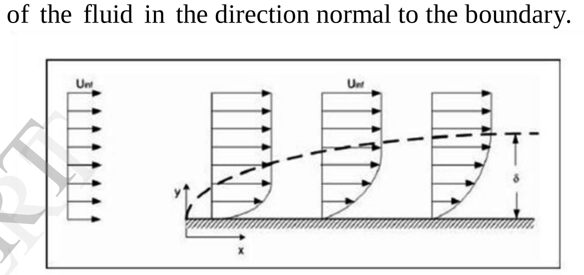


Figure 1. Velocity Variation over Flat Plate

Three main parameters that are used to characterize the size and shape of a boundary layer are the boundary layer thickness, the displacement thickness, and the momentum thickness.

1. The boundary layer thickness (δ)

It is used for a thickness beyond which the velocity is essentially the free-stream velocity (U). The velocity in boundary layer increases towards U in an asymptotic manner.

2. The displacement thickness (δ*)

It is the distance by which the surface would have to be moved parallel to itself towards the reference plane in an ideal fluid stream of velocity (U) to give the same mass flow as occurring between the surface and the reference plane in a real fluid.

$$\delta^* = \int (1 - \frac{u}{u_\infty}) dy$$

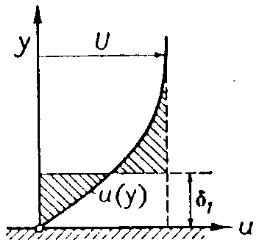


Figure 2. Displacement Thickness over Flat Plate

3. The momentum thickness (θ)

It is the distance by which a surface would have to be moved parallel to itself towards the reference plane in the viscid fluid stream of velocity (U) to give the same total momentum as existing between the surface and the reference plane in a real fluid.

$$\theta = \int \frac{u}{u_\infty}(1 - \frac{u}{u_\infty})dy$$

1.2. Regions of Boundary Layer

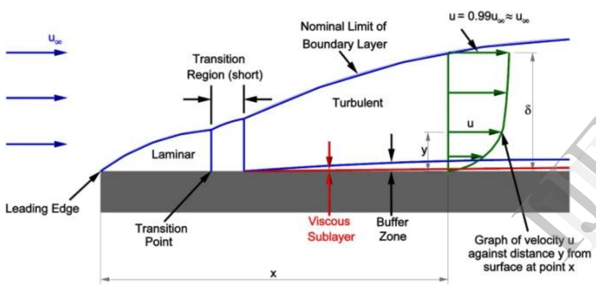


Figure 3. Boundary Layer over Flat Plate (Y Scale Enlarged)

In physics and fluid mechanics, a boundary layer is the layer of fluid in the immediate vicinity of a bounding surface where the effects of viscosity are significant. In other words, it is a thin layer of viscous fluid close to the solid surface of a wall in contact with a moving stream in which (within its thickness δ) the flow velocity varies from zero at the wall (where the flow "sticks" to the wall because of its viscosity) up to U_e at the boundary, which approximately (within 1% error) corresponds to the free stream velocity as shown in the figure.

The boundary layer can be divided into the following three regions:

1. Laminar Flow Region
2. Transition Flow Region
3. Turbulent Flow Region

1. Laminar flow region

A laminar flow is defined as the type of flow in which fluid particles move along a well defined paths or stream line. In this, the fluid layers slide smoothly one over the other adjacent layer. Laminar flow is also referred as stream-line flow or viscous flow.

Reynolds number for this region over a flat plate is less than 3E+05.

Some of the typical examples of laminar flow are flow of a fluid over a plate, viscous liquids (e.g. honey) poured out of bottle, etc.

2. Turbulent flow region

A flow is said to be turbulent flow in which the fluid particles move in a zigzag way. In this case, the fluid particles have the velocity in the transverse direction to the principal direction of flow having variable magnitude of velocity. In turbulent flows, eddies formation takes place which are responsible for high energy loss.

Reynolds number for this region over a flat plate is greater than 5E+05.

Some of the typical examples of turbulent flow are smoke of cigarette, flow of water from a fully opened water tap, etc.

3. Transition flow region

This region lies in between the laminar flow and the turbulent flow. The flow change from laminar to turbulent is not sudden but it changes gradually.

Reynolds number for this region over a flat plate lies between 3E+05 and 5E+05.

1.3. Applications of Boundary Layer

1. Aerodynamics (airplanes, rockets, projectiles)
2. Hydrodynamics (ships, submarines, torpedoes)
3. Transportation (automobiles, trucks, cycles)
4. Wind engineering (buildings, bridges, water towers)
5. Ocean engineering (breakwaters, cables)

2. Test Apparatus

2.1. Wind Tunnel

Wind tunnel is one of the most important apparatus used in the experimental analysis in the field of aerodynamics and fluid flow. Its purpose is to provide a region of controlled air flow into which models can be inserted.

Wind tunnel consists of the following sections:

1. Bell mouth with an air straighter
2. Setting chamber and contraction cone
3. Transparent test section

4. Diffuser section
5. Drive unit section

The tunnel is of simplest tube section open type along which air is propelled. A fan downstream of working section usually provides the propulsion.

Wind tunnel is made in a single mould by using Fiber Reinforced Plastic (FRP) which gives a smooth inner surface and less leakage.

The room containing the tunnel is in fact part of the tunnel, since it provides a path by which air returns from the downstream end to upstream end

Figure 4. Wind Tunnel

1. Bell Mouth and Entry

The entry is shaped to guide the air smoothly into the tunnel. Proper flow separation here would give less turbulence and uniformity in velocity in the working section. An air space of 2 to 2.5 meter is provided.

2. Setting Chamber and Contraction Cone

The bell mouth is followed by a setting chamber that leads to a contraction, which increases the velocity of flow. The function of this section is to make the flow parallel and more uniform. This is connected with working section or test section. The setting chamber usually includes a honey comb and nylon mesh screens to filter and stabilize the incoming air flow.

3. Transparent Test Section

Tunnel has a 300 mm x 300 mm x 1000 mm test section with two windows to insert the models or probes. The test section consists of accessories to hold the instruments and models for facilitating the motion of the model in all directions relative to air stream.

4. Diffuser Section

The test section is followed by a divergent duct. The divergence results in a corresponding reduction in the flow speed. Diffuser reduces dynamic pressure, which leads to reduction in power losses at the exit. Leaving the diffuser, the air escapes into the atmosphere.

5. Drive Unit Section

The drive unit consists of an axial fan and a motor. A five blade fan is coupled to the motor which is fitted on a sturdy mild steel frame. Motor is controlled by a variable frequency drive, which gives a smooth variation of air velocity in test section. An anemometer is provided to read the air velocity and accordingly to set the desired value of air velocity by increasing or decreasing the motor speed.

2.2. Specifications

Table 1. Specifications of Wind Tunnel

PARAMETER	DESCRIPTION
Type	Open Type Wind Tunnel
Test Section	
1. Main duct	Mild Steel with Powder Coating
2. Side glass	Acrylic Sheet- 8mm thick
3. Size	300 mm x 300 mm x 1000 mm
Blower Fan	5 Blades- Aluminum Die Cast
A.C. Motor	3 HP- 2880 rpm
1. Speed Variation	10% to 100% by Frequency Drive Controller
2. Make	Delta
3. Mode	400 V; Class VFS7-4037p; 2.1 kW- VFD
Air Velocity in Test Section	1 to 50 m/s
Duct Material	Fiber Reinforced Plastic (FRP)
Passage for Air Flow	9.5 m
Contraction Ratio	9:1
Lift/Drag Force Sensor	0 to 20 kg Beam Type Load Cell
Load Indicator	0 to 20 kg- 2 Channel/0.01 kg Resolution
Pitot Tube Diameter	7.951 mm
PARAMETER	**DESCRIPTION**
Inclined Manometer	0 to 50 mm Static Head
Multi Tube Manometer	
1. Height	300 mm
2. Number of Tubes	16 Poly Vinyl Chloride (PVC)
Manometer Inclination	0 to 90 degrees

Anemometer	
1. Velocity Range	0 to 30 m/s
2. Display	Digital
Strain Gauge Balance	Two Channel
Capacity	
Lift Force	0 to 20 kg
Drag Force	0 to 20 kg

3. Fixture Design

3.1. Fixture Overview

Table 2. Fixture Overview

COMPONENT	MATERIAL	DIMENSIONS (mm)	QTY
Base			
1. Base plate	Acrylic	235x125x4	1
2. Base strip	Acrylic	200x15x6	2
Slider			
1. Slider plate	Acrylic	485x125x5	1
2. Slider block	Acrylic	71x65x20	1
3. Slider block disc	Mild steel	Ø40x3	1
4. Slider rod	Mild steel	Ø9x135	2
5. Vertical sliding plate	Acrylic	149x49x10	1
6. Vertical static plate	Acrylic	149x49x10	1
7. Micrometer holder	Aluminum	Ø45x20	1
Guideway			
1. Guideway strip	Acrylic	185x25x6	2
2. Guideway limiting strip	Acrylic	155x15x6	1
Stud guide			
1. Detachable stud guide	Acrylic	155x65x15	1
Bush	Acrylic	Ø9x25	2
Pitot tube	Copper	Ø8	1
Micrometer	Mild steel	0 to 5	1
Ball bearing	Mild steel	OD 20 ID 9	2
Stud with knob	Mild steel	Ø8x275	1
Scale and pointer	Mild steel	150	2

3.2. Fixture Model

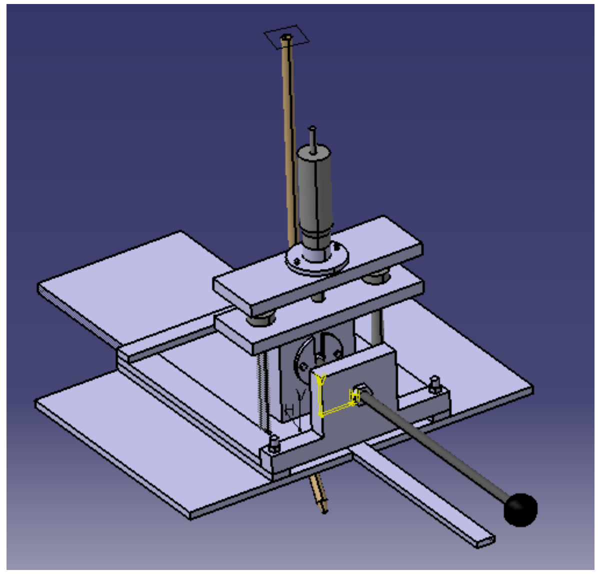


Figure 5. Fixture Model in CATIA V5R20

Figure 6. Fabricated Fixture

4. Test Procedure

1. The flat smooth surface (flat plate) was kept on a stand firmly, at the test section of the wind tunnel.
2. The wind tunnel was set up with the fixture having a pitot tube. The pitot tube was placed at the leading edge and attached to an inclined manometer to get the manometric height.
3. Then the wind tunnel was turned on.
4. Readings were taken at 10 different points within boundary layer gradually increasing Δy (distance measured from the surface) from 0 mm to 5 mm.
5. The manometric height was noted carefully.
6. The test was repeated adjusting the pitot tube at 0, 20, 40, 60, 80, 100, 120, 140, 160, 180,

ISSN: 2278-0181
Vol. 2 Issue 5, May - 2013

200 mm from the leading edge of the flat plate.

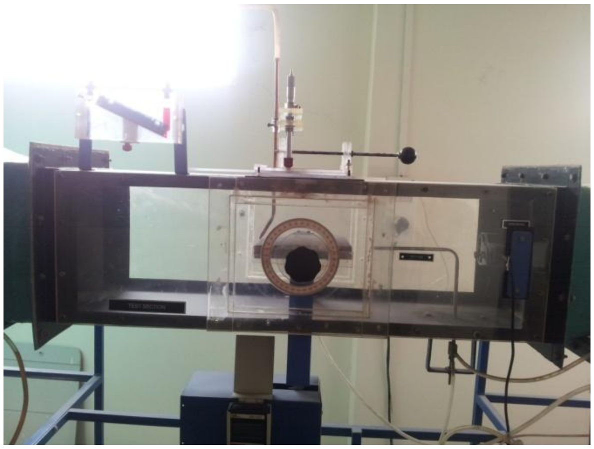


Figure 7. Test Setup

5. Observations and Testing

5.1. Experimental Data

1. Length of plate = 200 mm

2. Free stream velocity = 37 m/s

3. Density of air = 1.225 kg/m^3

4. Dynamic viscosity of air = 1.79E-05 Ns/m^2

5. Velocity at sections can be calculated by using:

$$u = \sqrt{2gh}$$

6. Reynolds number can be calculated by following formula:

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

7. Boundary Layer Thickness is calculated by following formula:

$$\delta = \frac{5L}{\sqrt{Re}}$$

5.2. Assumptions and Nomenclature

5.2.1. Assumptions

The basic assumptions used in the following calculations are:

1. The working fluid, air, was an incompressible fluid as the testing was done in the low speed wind tunnel
2. A standard atmospheric condition of the air is assumed

5.2.2. Nomenclature

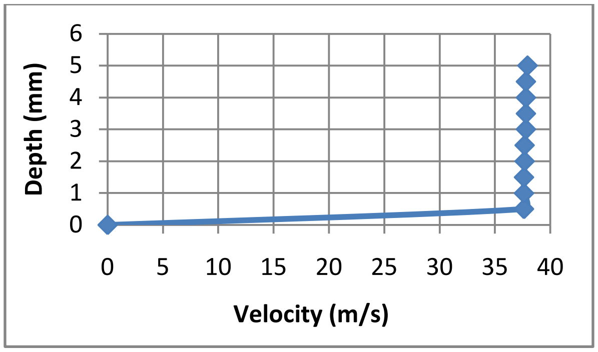
Table 3. Nomenclature

SYMBOL	DESCRIPTION
ρ	Air density
u	Velocity at sections
U	Free stream velocity
μ	Dynamic viscosity
L	Length of the plate
Y	Distance from the surface
Re	Reynolds number
X	Distance from the leading edge
δ	Boundary thickness

5.3. Tables and Graphs

Table 4. Distance of 20 mm from Leading Edge

Distance from surface (mm)	Velocity u (m/s)	u/U
0.0	00.00	0.00
0.5	37.62	0.99
1.0	37.62	0.99
1.5	37.62	0.99
2.0	37.69	0.99
2.5	37.69	0.99
3.0	37.80	1.00
3.5	37.80	1.00
4.0	37.80	1.00
4.5	37.80	1.00
5.0	37.96	1.00



Graph 1. Depth v/s Velocity at 20 mm from Leading Edge

Parameters Calculated:

Boundary layer thickness (δ) = 0.5 mm
Reynolds number (Re) = 51491.06

Similarly the test was repeated adjusting the pitot tube at 40, 60, 80, 100, 120, 140, 160, 180, 200 mm from the leading edge of the flat plate and graphs were plotted.

5.4. Nature of Boundary Layer

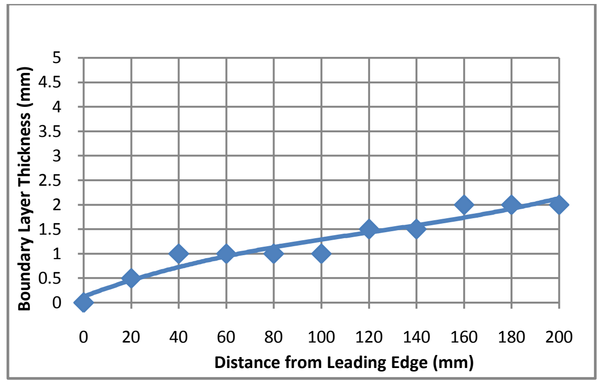
The following table shows the parameters calculated for all the positions of pitot tube from the leading edge of the flat plate.

Table 5. Reynolds Number, Flow Type and Boundary Layer Thickness as Function of x

Sr. No.	x (mm)	Reynolds Number	Flow Type	Boundary Layer Thickness (mm)
1	0	0	Laminar	0.0
2	20	51491.06	Laminar	0.5
3	40	102379.81	Laminar	1.0
4	60	153569.71	Laminar	1.0
5	80	205745.09	Laminar	1.0
6	100	258139.46	Laminar	1.0
7	120	310752.83	Transition	1.5
8	140	362928.20	Transition	1.5
9	160	413680.12	Transition	1.5
10	180	464281.47	Transition	2.0
11	200	514910.20	Turbulent	2.0

5.5. Boundary Layer over Flat Plate

The following graph shows the nature of boundary layer over the flat plate for the above observations made.



Graph 2. Boundary Layer Growth along the Distance from Leading Edge

6. Simulation

We have simulated the test environment conditions in MATLAB to verify the experimental results.

6.1. Simulation Results

For x = 20 mm

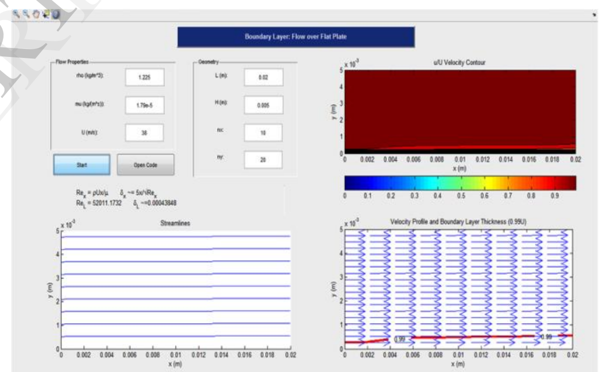


Figure 8. Simulation Result of Distance of 20 mm from Leading Edge

Parameters Calculated:

Boundary layer thickness (δ) = 0.4 mm
Reynolds number (Re) = 52011.17

Similarly the simulation was repeated for x = 40, 60, 80, 100, 120, 140, 160, 180, 200 mm.

6.2. Nature of Boundary Layer

The following table shows the simulation results for all the positions of pitot tube from the leading edge of the flat plate.

Table 6. Nature of Boundary Layer

Sr. No.	x (mm)	Reynolds Number	Flow Type	Boundary Layer Thickness (mm)
1	0	0	Laminar	0.0
2	20	52011.17	Laminar	0.4
3	40	104022.35	Laminar	0.6
4	60	156033.52	Laminar	0.7
5	80	208044.69	Laminar	0.8
6	100	260055.87	Laminar	0.9
7	120	312067.04	Transition	1.0
8	140	364078.21	Transition	1.1
9	160	416089.39	Transition	1.2
10	180	468100.56	Transition	1.3
11	200	520111.73	Turbulent	1.3

6.3. Boundary Layer over Flat Plate

The following graph shows the nature of boundary layer over the flat plate for the simulation results obtained.

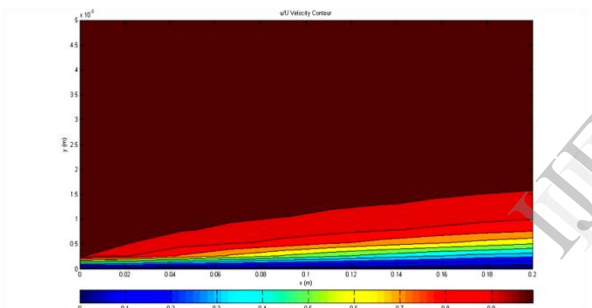


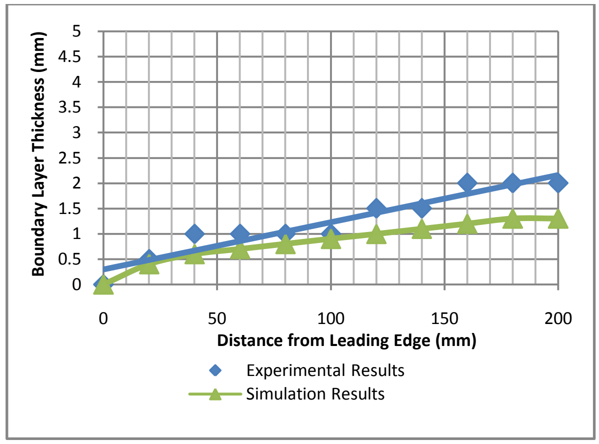
Figure 9. Boundary Layer Growth along the Distance from Leading Edge

7. Validation

Table 7. Validation

X (mm)	Simulation Results			Experimental Results			Error	
	Re	BL	Flow	Re	BL	Flow	Re	BL
0	0	0.0	Laminar	0	0.0	Laminar	0.0	0.0
20	52011.17	0.4	Laminar	51491.06	0.5	Laminar	520.1	0.1
40	104022.35	0.6	Laminar	102379.81	1.0	Laminar	1642.5	0.4
60	156033.52	0.7	Laminar	153569.71	1.0	Laminar	2463.8	0.3
80	208044.69	0.8	Laminar	205745.09	1.0	Laminar	2299.6	0.2
100	260055.87	0.9	Laminar	258139.46	1.0	Laminar	1916.4	0.1
120	312067.04	1.0	Transition	310752.83	1.5	Transition	1314.2	0.5
140	364078.21	1.1	Transition	362928.20	1.5	Transition	1150.0	0.4
160	416089.39	1.2	Transition	413680.12	1.5	Transition	2409.3	0.3
180	468100.56	1.3	Transition	464281.47	2.0	Transition	3819.1	0.7
200	520111.73	1.3	Turbulent	514910.20	2.0	Turbulent	5201.5	0.7

The following graph shows the nature of boundary layer over the flat plate both experimentally and by simulation.



Graph 3. Boundary Layer Growth along Distance from Leading Edge

7.1. Error

Error is calculated by using following formula:

Error = Simulation value – Experimental value

8. Conclusion

The project was to design, develop and validate a specialized fixture for wind tunnel. The objective behind the project was to develop a fixture that would enable us to study boundary layer over a flat plate for different velocities.

The project was split in two phases. The first phase consisted of design and fabrication of a fixture. Later phase involved the validation part.

The nature of boundary layer over a flat plate for different points is studied experimentally as well as by computation. The computation results show that the experimental results are adequate.

References

[1] Dr. R.K. Bansal, *Fluid Mechanics*
[2] Ronald B. Stull, *Introduction to Boundary Layer*
[3] MATLAB help