Design and Development of a Modular Atmospheric Boundary Layer Wind Tunnel

Murukshe Muralidhar, Saneesh C Joy, Akhil Mohammed P and Kannan B T*
Department of Aerospace Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai, Tamilnadu, India

*E-mail: skyinventorbtt@gmail.com; btk@alumni.iitm.ac.in

Abstract. This paper addresses the various design parameters of an atmospheric boundary layer (ABL) wind tunnel and also explains the approach taken to construct the various parts of the wind tunnel. The paper tries to explain the different design stages in the tunnel construction and methods to replicate turbulent boundary layer profiles in it. Rather than using conventional material like wood, a new approach of using aluminum profiles for the basic framework has been used. These profiles have proven advantageous to tweak the dimensions of the tunnel to obtain varying flow profiles.

1. Introduction
The atmospheric boundary layer is the region of the atmosphere where the effects of the earth’s surface is dominant or experienced. This region is part of the troposphere and extends typically from 100 m to 3000m. Due to the earth’s surface, viscous force is imparted to the fluid and thereby creating a region of varying viscosity and velocity profile until the effects are no more felt, this region is the atmospheric boundary layer (refer to figure 1). This layer influences all human lives, beings, and objects. This boundary layer may be laminar, in transition or turbulent depending on the Reynolds number of the flow but mostly turbulent.

Figure 1. Atmospheric Boundary Layer (ABL) & BL velocity profile.
Over the ages, wind tunnels have been used for various studies ranging from automotive designs to climate studies. One of the specialized wind tunnel is the atmospheric boundary layer wind tunnel. The significance of studying the atmospheric boundary layer is great especially in this present age of pollution and global warming. These tunnel helps to study how the turbulent flow behaves in the Boundary layer region, what are its effects and implications. Flow over different models of terrains, flow over-scaled modeled of buildings, cities, etc. can be studied in these tunnels. Different turbulent models can be replicated depending on the turbulence generators used and flow speed. The tunnel maybe even used to study different pollution, dispersion models.

In this paper detailed steps involved in the design and construction of an ABL wind tunnel of 14 – meter length with a test section of cross-sectional dimension 1m × 1m. Highly turbulent flow greater than the order of $10^5$ is obtained in the test section.

2. Design Methodology
The CAD design of the 14 - meter long ABL wind tunnel was done as seen in Figure 2 and 3. The dimensions of each component were found out by calculating the requirements of the flow keeping in mind the space constraint of 8m × 3 m. The project was executed in 7 months by the paper authors.

![Figure 2. Side view of CAD model with dimensions in meter (m).](image)

![Figure 3. Isometric view of CAD model.](image)
3. Wind tunnel construction

3.1. Fan

The fan is one of the major components of the wind tunnel. Fan (refer to figure 4) produces the required airflow in the wind tunnel. The fan must be able to produce a highly turbulent flow after accounting for the losses due to the structure. The losses must be calculated to find the required power rating of the fan motor.

The pressure losses due to friction loss ($\Delta P_f$) of each component was calculated and by the formula below the power required was found out to be 13.5 KW.

$$\text{Power Required} = \Delta P_f \times Q$$

With an added factor of safety of 3 KW, the required motor was found to be the rating of 16.5 KW for obtaining velocity in the range of 7 – 9m/s in the test section. However, due to the non-availability of a fan with the same power rating in the market, the next available rating of 18.5 KW with a variable frequency controller was chosen. The variable frequency controller allows for the bidirectional operation of the fan at different RPMs by preprogrammed settings. An axial fan was selected due to the higher flow rate and lower cost of construction than a centrifugal fan.

![Axial fan of power rating 18.5 KW mounted on base.](image)

3.2. Transition Section

The transition section is the part of the tunnel that connects the fan to the straight part and test section. Care is to be taken as no flow separation takes place in the section as it will lead to disruption of the boundary layer formation. Corner fillets of 45$^\circ$ is sometimes used to reduce the chance of separation.

3.3. Straight Part

The straight part is the longest section of the wind tunnel. The straight part comprises the test section and the fetch. The fetch is the part that makes the incoming flow turbulent by the use of various turbulence generators (refer to figure 6) like elliptical disks, fences, spires, tornado generators, etc. These spires placed ahead or behind fences simulate atmospheric boundary layer by creating large scale turbulent structures with vorticity mainly in the horizontal plane. The boundary layer starts developing in the fetch region and progresses towards the test section.
The ABL may be simulated in a short (4 to 6 m) or long (8 to 10 m) test section as seen in figure 5. However, in a short test section, the boundary layer must be forced by maintaining zero pressure gradient to avoid reverse flow but develops naturally in a long test section wind tunnel. For this reason, the total length of the straight part was designed to be 9 meters.

Figure 5. Straight part (Test section & Fetch).

Figure 6. Spires and Elliptical Disks.

3.4. Settling chamber
The function of the settling chamber is to make the incoming flow of air uniform and to remove fluctuations. It mainly consists of two parts, namely honeycomb, and screens.

3.4.1. Honeycomb. Dampening of lateral fluctuations of the flow by turning the flow parallel to the centerline is the main function of the honeycomb (refer to figures 7 & 8). It is a grid-like structure made of tubes stacked over each other compactly. With increase in cell length of the honeycomb, the pressure loss coefficient increases. Small cell diameter and long cell creates a more uniform flow. The parity between minimum pressure loss and flow straightening is given by
and a cell with a length of 8× that of the cell diameter. The honeycomb was made using cut pieces of PVC pipe.

\[ D_{\text{cell}} = D_{\text{settling chamber}} / 150 \]

Figure 7. Stacked honeycomb.

Figure 8. Closer look at the honeycomb.

3.4.2. Screens. Homogenized velocity profiles are obtained by placing screens (refer to figure 9). They are placed right after the honeycomb structure. It may be placed in combination with multiple screens for the desired result. It is a mesh-like structure made up of wires which provide resistance to the flow. The wires act as obstacle creating a large amount of small vortices of similar size thereby creating an average velocity profile and thus homogenizing the flow. The effects of the screen are not known in advance and are to be calibrated according to required flow parameters.

Figure 9. Screen.
3.5. Contraction cone

The purpose of the contraction cone is to increase the average velocity of the flow and to make it more uniform. Care should be taken so that there is no flow separation in the corners of the cone. As proposed by Bradshaw, the contraction ratio should be in the range of 6 to 9.

In this project, a contraction cone was designed in the CAD design phase however the required average velocity was already achieved in the test section hence the cone was not constructed for the period with a scope of future development if necessary.

4. Experiment

After assembling and calibrating the tunnel, a digital anemometer was placed in the test section to verify the specifications. The fan was operated at different RPMs and velocity noted. It was found to be in the range of $1.6 \text{–} 8.3\text{m/s}$ and the calculated Reynolds number confirmed highly turbulent flow.

5. Results and discussion

5.1. Smoke Flow visualization

With the help of smoke flow visualization, highly random and turbulent flow was observed in the test section region thereby confirming successful boundary layer generation.

5.2. Experimental Results

Reynolds number was calculated at different velocities obtained in the test section. Kinematic viscosity (at $35 \, ^\circ \text{C}$) was found to be $1.655 \times 10^{-5} \text{m}^2/\text{s}$.

\[
Reynolds \, number = \frac{u \times Dh}{\nu}
\]

Where,
- $u =$ velocity in test section (m/s),
- $Dh =$ hydraulic diameter,
- $\nu =$ kinematic viscosity (m$^2$/s)

| RPM of frequency controller | Velocity (m/s) | Reynolds number |
|----------------------------|----------------|-----------------|
| 200                        | 1.6            | 96676           |
| 300                        | 2.6            | 157099          |
| 400                        | 3.5            | 211480          |
| 500                        | 4.4            | 265861          |
| 600                        | 5.5            | 332326          |
| 700                        | 6.4            | 386706          |
| 800                        | 7.5            | 453172          |
| 900                        | 8.3            | 501510          |
The Reynolds number was similar to the theoretically calculated values.

6. Cost of construction
The construction costs consist of the cost of materials only here as man-hours’ work is excluded. Wood is easier to handle for construction and is less likely to drum than steel, hence plywood was chosen for constructing the tunnel.

The framework of the tunnel was done using a market available 40 mm × 40 mm aluminum profiles. This was done to decrease the dependence of wood in the tunnel construction and thereby reduce cost. Glass of 8 mm thickness was used to construct the transparent test section part. Other materials include paint, thinner, sandpaper, Fevicol SR glue, carpet, silica-based sealant, mica sheets, PVC pipes, etc. A concrete foundation base of height 55 cm was built to mount the fan and to dampen the vibrations. The total cost of the project was calculated at around 6 lakhs Indian rupees. This was an appreciably small amount because the fan and the variable frequency controller together contribute nearly half the budget.

7. Conclusion
Certain design parameters are of significance while designing an ABL wind tunnel. They are;
- A full-scale boundary layer can be replicated in the tunnel only if zero longitudinal pressure gradient is maintained. This depends on the quality of the fetch.
- Care should be taken that flow separation does not take place at corners or curves.
- Optimization of a scale-down model is very important, 5 % blockage ratio is the limit of the cross-sectional area of the model.
- Turbulent Reynolds number in the test section confirms turbulent flow in the tunnel.
- Positioning of turbulence generators in the fetch influences the turbulence created in the tunnel. The tunnel should be calibrated for specific experiments.

The velocity profile of the boundary layer follows a logarithmic curve starting from zero at the surface until it reaches free stream velocity $u_{∞}$. This is known as the power-law or log law.

Determination of pressure loss of the structure due to friction is necessary to compute the required mass flow rate of air that compensates these losses and produces the required flow.

A full-scale academic scale atmospheric boundary layer that is fully operational with flow of Reynolds number in the order of $10^5$ has been constructed and tested successfully.

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