Subsonic, Open-Circuit Wind Tunnels: A Real-World Theoretical Analysis, Design, Construction and Testing Case

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Abstract

Wind tunnels are useful for studying air flow conditions, aerodynamic forces and pressure distribution relative to aerodynamic bodies. Following, the assessment of the achieved flow characteristics assists in exploring alternative configurations for the aerodynamic design of examined bodies. Therefore, this study deals with the analysis of subsonic wind tunnels where maximum wind velocity is around 134 m/s. Under this context, the purpose of this work is twofold: (i) to present a theoretical background about wind tunnels and the related technical equipment, and (ii) to present the analysis, design, construction and testing of a low cost, small-scale educational wind tunnel.

1. Introduction

Today, a plethora of computational fluid dynamics (CFD) methods are extensively used in the field of aerodynamics for predicting the generated fluid flow fields around various bodies and structures [1]. Nevertheless, ground testing is a highly inevitable methodology elaborated for the design and physical experimental analyses of the resulting aerodynamic performance of shapes under the occurrence of various fluid flow characteristics and operating conditions [2]. To that end, wind tunnel facilities have been developed to support engineers and researchers in their effort to specifically quantify flow characteristics like aerodynamic forces and pressure distribution relative to aerodynamic bodies. In fact, wind tunnels offer a rapid, economic and accurate means for generating reliable data through simulating realistic fluids' flow conditions past vehicles and hence they assist in validating CFD simulations [3]. Notably, wind tunnels allow the use of models that can be prepared at the early stage in product design cycles, thus supporting the design decision-making process.

Today, all major engineering departments in academia are equipped with wind tunnel facilities to assist students in comprehending the basics of aerodynamics through experimentation, and further motivate them in identifying alternative design approaches that might improve the performance of specific bodies under investigation such as airplanes, cars, and even buildings. Specifically, the practice of low-speed experimental aerodynamics is the cornerstone of educational activities towards the development of a wide range of vehicles that must perform their operational functions in the presence of forces imposed by strong flows of air or water in the subsonic regime.

However, the relatively newly founded Department of Production Engineering and Management, Polytechnic School, Democritus University of Thrace, does not have a wind tunnel facility to support the corresponding courses on fluid dynamics. Specifically, the Department was founded in 2000 and operated for the first time in the academic year 2000-2001. It is housed in the A1 building in the Polytechnic School, Vassilissis Sofias 12, PC 67100, Xanthi, Greece. The Department offers three related courses on its undergraduate curriculum, but at least until 2006, it lacked the necessary laboratory facilities to support the related courses.

Therefore, this study deals with the analysis of subsonic wind tunnels where maximum air flow velocity is around 134 m/s. Under this context, and motivated by the desire to support empirical research and educational services upon applied aerodynamics that is conducted at the Department of Production Engineering and Management, Democritus University of Thrace, the purpose of this work is twofold: (i) to present a comprehensive theoretical background about wind tunnels and the related technical equipment used for fluid characteristics' measurements, and (ii) to present the analysis, design, and construction of a low cost, small-scale educational wind tunnel. Notably, this research is the outcome of the graduate thesis of the author as part of his 5-year engineering diploma studies.

Particularly, a subsonic wind tunnel was finally constructed that facilitates the visualization of the air flow around a specific aerodynamic body. The technical specifications of the constructed wind tunnel are: total length of 3 300 mm, width of 80 mm, maximum height of 114 mm, and weight of 150 kg. Particularly, the dimensions of the wind tunnel test section are 1 000 × 300 × 300 mm. To achieve the necessary air flow, an axial fan with a diameter of 350 mm is employed. The resulting velocity profile along the height and width of the test section is almost linear in nature, excluding the approximately 12% allowance in the four side walls of the test section where boundary layer is formed. The constructed wind tunnel can be used for conducting different tests in the field of aerodynamics for the experimental verification of laminar and turbulent flow phenomena.

The rest of the paper is organized as follows. First, a brief theoretical background of wind tunnel design principles is provided in Section 2. More specifically, the objective of Section 2 is two-fold: (i) to provide a rather generic review of wind tunnels from an informative point of view, and (ii) to document the measuring equipment normally used in such facilities. Following, in Section 3 the design methodology of the constructed low speed wind tunnel within the confines of this research is presented. The successful construction and function of the developed wind tunnel is further illustrated through experimental settings on a scaled car model, and interesting managerial insights are provided (Section 4). Finally, conclusions are discussed in Section 5.

2. Theoretical background

Motivated by the desire to study the effects of air streams around solid objects, researchers and engineers develop wind tunnels as apparatus that can support aerodynamics' investigations [4]. Specifically, wind tunnels assist modellers and engineers in reproducing flows and dispersion phenomena that simulate the aerodynamic flow field of the corresponding atmospheric full-scale phenomena [5]. Nevertheless, due to limitations related to the needed laboratory physical space for wind tunnel facilities and the increased instrumentation cost, engineers usually develop small-scale models and thus employ small-scale wind tunnels following specific scaling relationships [6]. Following, in Section 2.1 we provide a brief analysis of the most common types of wind tunnels, while in Section 2.2 we focus on the basics of open (return) circuit wind tunnels. Section 2.3 summarizes the typical measurement equipment used in experimentations in wind tunnel facilities.

2.1 Types of wind tunnels

Wind tunnels are used to simulate airflow in scientific and research laboratories under controlled conditions. These find vast application in automobile and aircraft industry to test the prototypes for aerodynamic conditions. University laboratories utilize such facilities to study the flow around specific small objects and in various speed ranges. The typical criteria and classification of wind tunnels are presented in Figure 1.

In practise, two basic types of wind tunnels and two basic test section configurations exist [7]. The two basic types are open circuit and closed circuit. Furthermore, the two basic test section configurations are open test and closed test section, although such configurations are now being replaced by slotted wall test sections (for low-speed experimentations) and transonic wind tunnels. Nevertheless, wind tunnel designs follow an ad-hoc approach and are often designated by the special purpose for which such facilities are designed and built.

For example, propulsion wind tunnels raise special requirements for handling the high temperature exhaust from turbine or rocket engines. Furthermore, flow visualization or "smoke" tunnels must also handle the exhaust contaminants that are used in the tunnel. Moreover, wind tunnels that are used to study the stability of aircrafts need to allow the model to move freely within the test section. Following, certain high temperature facilities have been designed to more accurately simulate the high temperature effects of hypersonic flows.

In the academic domain, the most common type of wind tunnel is the open return tunnel due to the low construction cost, and the superior design for propulsion and smoke visualization as there is no accumulation of exhaust products in such a type of tunnel [8]. This type of tunnel is widely used for instructional purposes and for investigations of fundamental flow phenomena.

Criterio #1: Speed Regime

- **Subsonic or low speed wind tunnels** – Maximum flow speed in this type of wind tunnels can be 135 m/s. Flow speed in wind tunnels is generally preferred in terms of Mach number which comes out to be around 0.4 for this case. Wind tunnels of this type are most cost effective due to the simplicity of the design and low wind speed. Generally low speed wind tunnels can be found in schools and universities because of low budget.
- **Transonic wind tunnels** – Maximum velocity in test section of transonic wind tunnels can reach up to speed of sound meaning 340 m/s or Mach number of 1. These wind tunnels are very common in aircraft industry as most aircrafts operate around this speed.
- **Supersonic wind tunnels** – Velocity of air in test section of such wind tunnels can be up to Mach 5. This is accomplished using convergent - divergent nozzles. Power requirements for such wind tunnels are very high.
- **Hypersonic wind tunnels** – Wind velocity in test section of such type of wind tunnels ranges between Mach 5 and Mach 15. This is also achieved using convergent - divergent nozzles.

Criterio #2: Tunnel Geometry

- **Open circuit wind tunnel** – This type of wind tunnel is open at both ends. The chances of dirt particles entering with air are increased; therefore honeycombs (mesh to clean incoming air) are required to clean the air.
- **Closed circuit wind tunnel** – Outlet of such wind tunnels is connected to inlet so the same air circulates in the system in a regulated way. The chances of dirt entering the system are very low. Closed wind tunnels have more uniform flow than in open type tunnels. This is usually a choice for large wind tunnels as these are more costly than open type wind tunnels.

Criterio #3: Working Fluid

- **Air** – In most low speed aircraft wind tunnel testing, air is moved through the tunnel.
- **Water** – In order to visualize shock waves for high speed aircraft, or to study the flow around submarines or boats, water is used as the working fluid.
- **Nitrogen or Helium** – In some hypersonic facilities, nitrogen or helium has been used as the working fluid. Similarly, cryogenic nitrogen has been used for high Reynold's number testing of transonic flows.
- **Ice** – Several wind tunnels around the world use to study ice build-up on aircraft parts. These icing tunnels include refrigeration devices to cool the air in the tunnel and water spray devices to provide liquid droplets in the test section.

Figure 1: Main types and classification criteria of wind tunnels [*Source*: NASA].

2.2 Structure of open (return) circuit wind tunnels

The air flowing through an open circuit wind tunnel follows an essentially straight path from the entrance through a contraction cone to the test section, followed by a diffuser, a fan section, and an exhaust of the air. The tunnel may have a test section with no solid boundaries (open jet or Eiffel type) or solid boundaries (closed jet or National Physical Laboratory type).

Thereafter, three (3) principal components are identified in a wind tunnel structure: (i) the contraction cone or nozzle, (ii) the test section, and (iii) the diffuser section (see Figure 2). Briefly, each of the aforesaid sections serves a particular purpose as described below:

- Contraction Cone or Nozzle – The contraction cone ensures that the airflow is inserted into the test section in a uniform pattern. Typically, in small-scale wind tunnels the contraction ratios range between 6 and 9 [8]. Mainly, the contraction cone reduces both the mean and fluctuating air flow velocity variations to a smaller fraction of the average velocity and further increases the corresponding mean velocity [9].
- Test Section – The test section is the chamber in which the test model is mounted to proceed with observations and aerodynamic measurements of the air flow field around the investigated body. The shape and the size of the test section is basically determined by the testing requirements [7].
- Diffuser – The diffuser is the chamber that allows the fluid pressure to increase with decreasing fluid velocities [10].

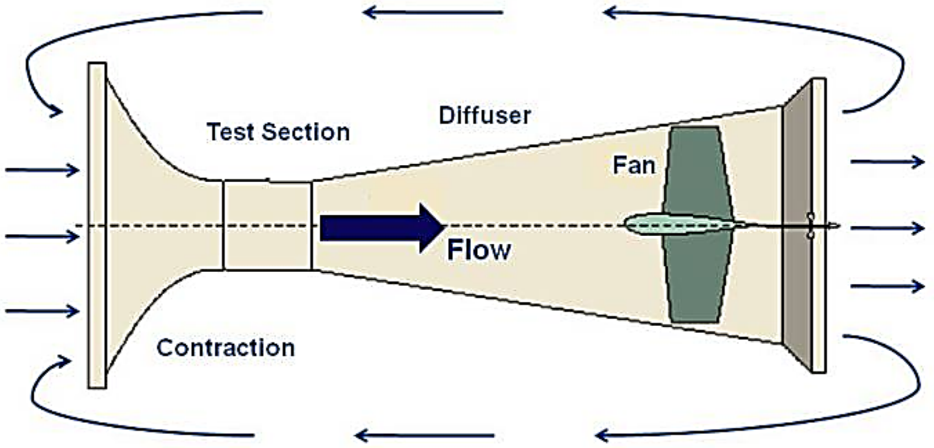

Figure 2: Open return wind tunnel structure and function [*Source*: NASA].

Additionally, two other key sections are typically included in a wind tunnel structure. The air vent or settling chamber (also known as “flow straightener”) is placed at the front-end of a wind tunnel through which the air enters the contraction cone. At the back-end of the wind tunnel is the drive section (fans) that pull the air through the wind tunnel.

2.3 Technical equipment

After the construction of a wind tunnel, it is imperative to determine and assess the resulting fluid flow characteristics. A low speed “steady” air stream is typically defined by the distribution of its temperature, pressure, dynamic pressure, and by its turbulence. To that end, the aforesaid quantities need to be measured through using the appropriate instrumentation. Today, the role of acoustics in aerodynamics is also considered an important factor in accepting a number of vehicles for operational purposes.

An indicative list of technical equipment required for fluid flow measurements in a wind tunnel is presented in brief in Figure 3. Once a wind tunnel is constructed, the first research step is to visually evaluate the flow characteristics around the aerodynamic surfaces under study. The assessment of the flow characteristics assists in motivating novel design approaches for the examined bodies as to achieve optimal aerodynamic design and performance.

The instrumentation list presented in Figure 3 is by no means a rigid inclusion nor is it based on an exhaustive list of all relevant equipment, but rather acts as a synthesis of all equipment that we have identified as part of our research in the work provided by [7].

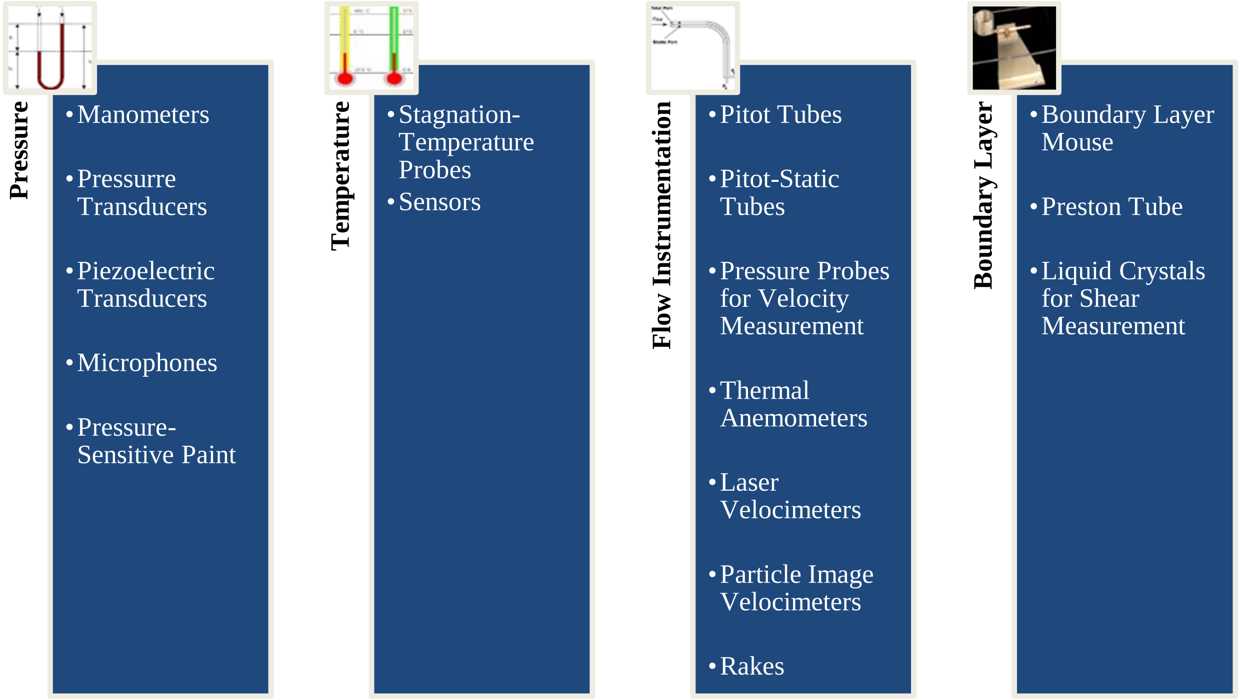

Figure 3: Technical equipment for measurements in wind tunnels.

3. Design Methodology

A wind tunnel is made of distinct sections that need to assemble in order to achieve desired air flow properties. To that end, for the construction of the wind tunnel for instructional purposes we followed three (3) stages: (i) the design, (ii) the procurement and construction of all individual components, and (iii) the wind tunnel assembly. Our aim was to achieve the main objective for wind tunnels, that is, to obtain a laminar flow of air through the test section, meaning a parallel steady flow with uniform speed throughout the section [11].

Designing a wind tunnel for automotive purposes presents several challenges. First, it is the blockage effect on the frontal area. Usually, airflow around automobiles is characteristic of “bluff bodies” as opposed to “streamlined bodies” such as an aircraft wing. Therefore, bluff bodies result in a sizable region of separated flow [7]. To that end, to achieve a smooth parallel flow the aforesaid separated regions of air must converge before they exit the diffuser so that no pressure problems arise inside the test section. Any pressure imbalance causes noise and a large amount of drag after the vehicle [12]. Therefore, the test section needs to have sufficient empty area after the car for the separated flow to join back together as to avoid turbulence. The only source of turbulence in a wind tunnel should be the test model.

Following the above considerations, we produced the designs of each component of the wind tunnel to be constructed. Thereafter, we proceeded to the procurement of the necessary material. A comprehensive list (bill of materials) of the constructed wind tunnel components is inserted in Table 1 in the Appendix. A major limiting factor in the overall effort was that the total cost of the wind tunnel construction as covered by personal financing from the author of this research. The assembly of the wind tunnel was completed on the premises of the Department of Production Engineering and Management, Democritus University of Thrace.

3.1 Contraction cone

The contraction cone is designed to control the air coming into the wind tunnel. For accurate results, it is vital to have a laminar flow of air into the tunnel. A laminar flow is attained via the shape of the contraction cone and a series of screens. In addition, the contraction cone increases the velocity of the air in the test section without creating turbulence in the airflow.

Hence, the entrance of air in the constructed wind tunnel is achieved through a nozzle with an initial section of 600 × 600 mm which ends in a cross section of 300 × 300 mm. The cross section decreases gradually with the length of the contraction cone. Therefore, the acceleration of the air flow is achieved without risking the occurrence of any air stream separation effects on the junction of the sides, which would result in the creation of unwanted turbulence in the flow. For the construction of the nozzle, we used galvanized sheet metal of 0.5 mm in thickness that was formed with a press-brake machine. At the entrance of the nozzle, we placed an anti-turbulence screen that also prevents the suction of foreign bodies inside the tunnel test section. Figure 4 presents the contraction cone or nozzle of the constructed wind tunnel.

Figure 4: Contraction cone or nozzle of the constructed wind tunnel (longitudinal view).

3.2 Test section

The dimensions of the test chamber are the major design criterion for a wind tunnel. Considering the manufacturing and cost constraints, the dimensions of the rectangle test section were selected to be 1 000 × 300 × 300 mm. Therefore, the test model that can be inserted in the test section can have a maximum width of 240 mm. In addition, knowing that the laminar air flow stream is achieved at the centre of the test section, we use a platform at a height of 130 mm from the bottom of the test chamber.

Furthermore, the test section is constructed by polycarbonate material of 5 mm in thickness. Wooden frames are used to mount the test section walls to the overall structure. Among the side walls of the test chamber and the floor, at the edges of the contact points, we deposited silicone that serves a dual role. Firstly, it assists in bonding the different surfaces together. Secondly, silicone ensures the tightness and the insulation of the test chamber, so that no significant pressure or power losses of the air stream occur during the function of the tunnel. The lid of the test cell is attached with two hinges on the wooden frame of the diffuser. Furthermore, a handle was placed on the lid for easy opening of the test chamber to directly observe turbulence phenomena in case of pressure loss in the test section.

Additionally, the area (A) of the surface vertical to the air flow is calculated as: $A = 300 \times 300 = 0.09$ m^2. Therefore, the air supply volume on the rectangular test section is $Q = A \times C$, where A: the area of the incision of the section vertical to the air flow, and C: the velocity constituent vertical to the air flow area. We further assumed that the desired air flow velocity in the wind tunnel test section is 54 km/h (note that 54 km/h = 15 m/s) meaning that we can simulate a car running with 54 km/h. Consequently, the desired axial fan had to achieve a flow of $Q = 1.35$ m^3/sec or 4 860 m^3/h. Figures 5 and 6 present the test section of the constructed wind tunnel.

Figure 5: Test section of the constructed wind tunnel (cross-sectional view).

Figure 6: Test section of the constructed wind tunnel (longitudinal view).

3.3 Diffuser

The length of the diffuser is 1 000 mm (Figure 7). The diffuser dimensions on the entrance are 300 × 300 mm, while the dimensions on the exit are 400 × 400 mm. In order for the easy mounting of the diffuser on each of the wooden frames on both sides (front and rear), we formed laths of 200 mm in width. For the construction of the diffuser section, we used galvanized sheet metal with a thickness of 0.5 mm which was formed with a press-brake machine. Construction wise, on the side panels of the diffuser we can observe the known "nerves" which offer better mechanical resistance to axial loads and render the diffuser structure with robustness during transportation, while they assist in preventing choking effects on the air stream. These nerves stood before folding the sheet metal and completion of construction.

Figure 7: Diffuser of the constructed wind tunnel (longitudinal view).

3.4 Flow fan

Focusing on the primary educational scope of the wind tunnel, we proceeded to the selection of the fan to generate the wind stream. The fan, or power source, is the final critical component in the design of our low speed wind tunnel. An industrial fan was selected, and acquired, to meet specifications made by the test section. We concluded on an axial-flow fan with a diameter of Φ350 mm with cast aluminium axial fan blades which is driven by a compact motor construction of IP 55 protection (Figure 8). Therefore, we rejected the case of the centrifugal pump as their output energy is considered particular big for our experimentation purposes. The IP protection factor refers to the protection provided by the impeller in case of a contact with foreign bodies. The total weight of the fan (impeller, motor, frame) is 2.9 kg.

Based on the calculations in Section 3.2, for a test section with an area of 0.09 m^3 the desired axial fan would be of Φ400 mm for achieving air flow velocity of 15 m/s. However, due to market limitations, we could only procure a fan of Φ400 mm in diameter. With this particular fan, the achieved air flow velocity is 23.35 m/sec. Therefore, the wind tunnel that was designed and constructed as part of this research can actually simulate a vehicle that moves with 44.44 km/hr. Hence, laminar air flow is achieved at a length of 1.75 m from the input of the air stream into the wind tunnel and in a distance of 250 mm from the entrance of the diffuser.

Another parameter that needs to be considered in axial fans is that of the generated noise levels. The selected axial-flow fan generates 54 dB of noise; however, the generated noise level is not confusing. Indicatively, an air-conditioning system in a regular apartment generates noise levels of 60 dB. The reduced noise level is partially due to the fact that the blades are not manufactured by PVC, thus limiting the blade oscillations. The operation of the wind tunnel requires a single-phase power supply with a frequency of 50 Hz.

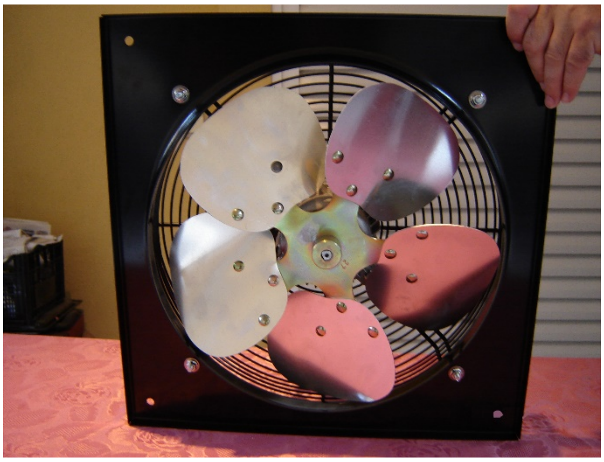

Figure 8: Axial fan of the constructed wind tunnel.

3.5 Assembly

All sections of the wind tunnel were assembled and installed in the premises of the Department of Production Engineering and Management of the Polytechnic School, Democritus University of Thrace. We have to report that at the joints of the test section with the two wooden frames we placed corner vanes, i.e. thin curved blades usually made from sheet metal, to redirect the flow while minimizing pressure loss and boundary layer separation.

The installed wind tunnel after assembly is presented in Figure 9. The constructed wind tunnel has an overall length of 3 300 mm and can be used for flow visualization experiments. The materials' cost of the wind tunnel exceeds the 1 000 € and was entirely covered by personal funds of the author.

Figure 9: Fully fabricated subsonic, open circuit wind tunnel.

4. Model aerodynamics testing

Flow visualization provides a direct and reasonable mental image of a flow about a body and provides a useful understanding of an aerodynamic or hydrodynamic problem [7]. Therefore, following the construction of the referred wind tunnel's components according to the mechanical drawings and designs, the tunnel could be used for conducting experiments. Due to the absence of any funding sources, the experimentations were only limited to the visualization of the air flow in the test section without using any specific electronic sensors such as pressure taps.

4.1 Experimental model

The test section hosts a car model in a transparent enclosure. The car model is on a scale of 1:24 and tufts were attached on its surface (Figure 10). The various air flow patterns about the car model were observed based on the model orientation and the pressure change inside the test section. The model was mounted in the tunnel on a steel plate that can rotate by 360°.

Figure 10: A scaled car model in the wind tunnel.

4.2 Airflow visualization

In order to visualize the airflow around the test model, we had to first select a flow visualization method. As air is transparent, and considering the limited available sources, we decided to use the quantitative flow visualization method based on tufts. Generally, tufts are applied to a model and remain attached during testing as to identify air flow patterns and flow separation phenomena [13]. Furthermore, we placed tufts on the side walls of the test section to get more visually direct flow effects.

4.3 Tests and results

Initially, we rather generically calibrated the wind tunnel through observing the generated airflow stream (Figure 11). With the tufts, you can see the airflow over and around the car model in a very satisfactory level. The platform on which the car model is mounted can be rotated by 360° thus allowing us to demonstrate the flow phenomena that occur on a vehicle in case air moves over a wing and the control surfaces.

Figure 11: Front and rear air flow over the scaled car model.

The very first experiment was to let the air stream run and open the lid of the test section. To that end, we could observe that the tufts exhibited a certain unsteady motion. Furthermore, in the case that the tufts presented the tendency to lift from the surface of the car model, a separated flow regime was indicated. Following, we observed the tufts’ motion when we placed the car model perpendicular to the airflow (Figure 12) as well in an angle of 45° towards the air stream (Figure 13).

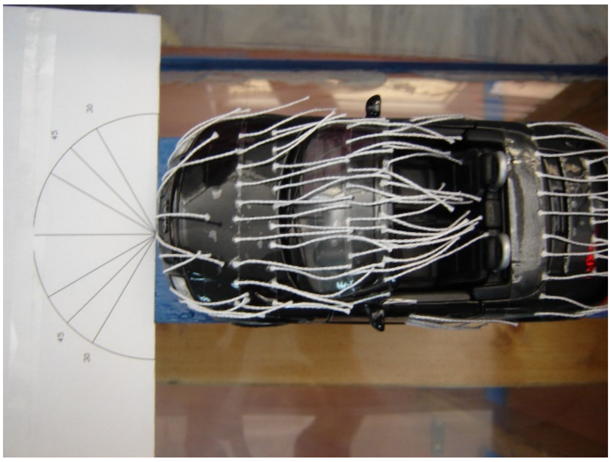

Figure 12: Car model perpendicular to the air flow.

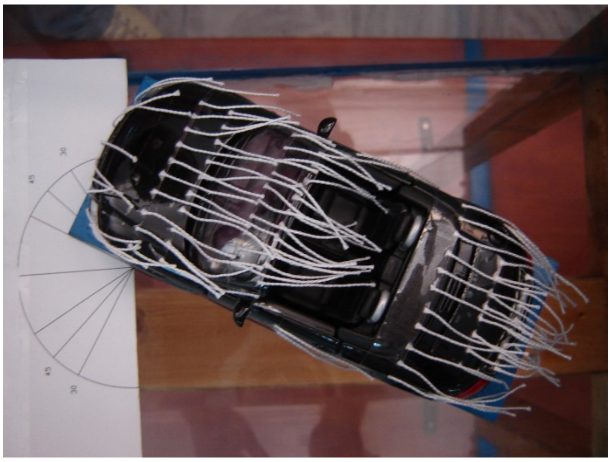

Figure 13: Car model in position of 45^o towards the air flow.

5. Conclusions

The laudable growth over the past three decades in the capabilities of wind tunnels has convincingly highlight their distinctive role as an adjuvant to the design and development efforts in fluid dynamics domain. Specifically, while great advances in theoretical and computational methods have been made in recent years, low speed wind tunnel testing remains essential for obtaining the full range of data needed to guide detailed design decision for many practical engineering problems [7]. Particularly, small-scale low speed wind tunnels are intended mainly for educational uses.

In this project we successfully designed and built a small-scale, low speed wind tunnel and evaluated it for educational purposes. The developed wind tunnel is anticipated to serve the academic purposes of the Department of Production Engineering and Management of the Polytechnic School, Democritus University of Thrace. Specifically, we hope that our flow visualization wind tunnel will act as an indispensable facility that can assist students and researchers at the Department to comprehend the basics of air flow aerodynamics.

The next step is the development of laboratory measurements in a wide range of basic fluid dynamics phenomena, vehicle, building and environmental aerodynamics. Moreover, future research steps at an undergraduate level could include the design, test and validation of many airfoils used in low Reynolds number applications, as such data is readily available online.

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Appendix

Table 1: Bill of materials for the constructed wind tunnel.

	Material	**Dimensions**	**Quantity**
1. 1	Polycarbonate	1 000 × 30 × 35 mm	4
2.	Axial fan	Φ350 mm	1
3.	Insulation sticker (white)		1
4.	Chipboard screws (set of 120 units)		1
5.	Countersunk screws (set of 10 units)	4 × 35 mm	1
6.	Countersunk screws (set of 10 units)	4 × 40 mm	3
7.	Countersunk screws (set of 20 units)	4 × 20 mm	1
8.	Corner shelf bracket		13
9.	Powe switch		1
10.	Planed balk	45 × 95 × 3000 mm	9
11.	Planed balk	19 × 44 × 3 000 mm	1
12.	Wire HQ 5VV-F (white)	3 × 1.5 mm	3
13.	Handle (yellow gold)	96 mm	4
14.	Sheet metal into contraction	60 × 60 into 30 × 30 mm	1
15.	Sheet metal into contraction	40 × 40 into 30 × 30 mm	1
16.	Hinges	25 × 20 mm	2
17.	Car model	1:24	1
18.	Chipboard (yellow), 50 units	3 × 16 mm	1
19.	Chipboard (nickel), 8 units	6 × 50 mm	4
20.	Chipboard (nickel), 25 units	4 × 30 mm	1
21.	Melamines DPF	3 660 × 800 × 26 mm	1

	Material	Dimensions	Quantity
22.	Galvanized nuts M3, 50 units		1
23.	Galvanized nuts M4, 50 units		1
24.	Solid lath (rectangular)	13 × 28 mm	1
25.	Knobs (INOX)		1
26.	Potentiometer		1
27.	Machinery wheel		6
28.	Width washers, 20 units	6 × 18 mm	2
29.	Width washers, Grover set, 250 units		1
30.	Window latch	60 mm	1
31.	Tube	1 150 × 20 mm	1
32.	Bolt	3 × 10 mm	1
33.	Felts sticker, 2 units		2
34.	Beacon		1
35.	Schuko plug (Grey)		3