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Article

Subsonic Wind Tunnels: Design, Evolution, and Applications in Aerodynamic Research

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Abstract: This paper provides a comprehensive overview of subsonic wind tunnels, detailing their design, historical development, and applications across various industries. Subsonic wind tunnels are critical tools for simulating airflow at speeds below Mach 0.3, enabling researchers and engineers to study aerodynamic properties such as lift, drag, and airflow patterns around objects like aircraft, automobiles, and buildings. The design of these tunnels involves key components like the test section, contraction and diffuser sections, and settling chambers, all aimed at ensuring uniform and laminar airflow. The paper also explores the classification of wind tunnels based on speed (subsonic, transonic, supersonic, and hypersonic) and duct design (open-circuit and closed-circuit). Historical milestones, from the early experiments of the Wright Brothers to modern advancements by institutions like NASA, highlight the evolution of wind tunnel technology. Additionally, the paper reviews contemporary research, including computational fluid dynamics (CFD) simulations and practical designs for educational purposes, emphasizing the importance of wind tunnels in advancing aerodynamics, safety, and efficiency in multiple fields.

Keywords: Subsonic wind tunnel, aerodynamic testing, wind tunnel design, low-speed aerodynamics, CFD simulation, turbulence control

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1. Introduction

Subsonic wind tunnels (SWTs) are foundational tools for aerodynamic research, enabling controlled airflow analysis at speeds below Mach 0.3. While existing reviews [1-3] have documented basic SWT designs, this paper critically analyzes three underexplored dimensions [4,5]. The historical evolution of test section geometries, from early open-circuit designs to modern hybrid configurations. Performance trade-offs between industrial-grade precision and cost-effective educational models. Identified gaps in turbulence control and scalability for developing regions. To design a subsonic wind tunnel, an environment that simulates airflow over an object under controlled conditions needs to be formed [6-8]. The primary objective of a subsonic wind is to create a uniform and controlled flow of air at speeds below the speed of sound, typically below Mach 0.3 [9]. Air is forced through a test section where the model under study is placed, which can be anything from a small model airplane to a large building depending on the size of the test section [1-3, 10] . The reason for testing the model in the subsonic wind tunnel is the measurement of different aerodynamic properties, such as lift and drag coefficients, along with visualization of the airflow patterns of air around the object. The information availed through these means is quite critical in the design and performance optimization of many structures, ranging from aircraft, automobiles, and buildings [10-13]. A subsonic wind tunnel design entails many components that include but are not limited to the test section, contraction section, diffuser section, fans or compressors, nozzle, and settling chamber. Each of these components is highly critical in ensuring that the airflow is uniform, laminar, and consistent throughout the test section. Moreover, the choice of materials, instrumentation, and data acquisition systems also plays a very important role in acquiring accurate and reliable results. Safety considerations include emergency shutdown procedures and fire suppression systems. the design of a Subsonic wind tunnel testing is a complex process entailing many factors [4,5]. The goal is the creation of a controlled environment that simulates airflow over various objects under controlled conditions. Information obtained from testing in a subsonic wind tunnel is critical to designing and optimizing the performance of various structures, including aircraft, automobiles, and buildings products, agriculture and fishery [6,7]. The design of a subsonic wind tunnel is based on the historical perspective of aerodynamics and aerospace engineering. The facilities have been highly instrumental in the comprehension of aerodynamic principles and their applications beyond the theoretical understanding. The intention for a subsonic wind tunnel is rooted in the dependency it carries forth to date in multiple disciplines. Subsonic wind tunnels represent one of the most important investigative tools for researchers, engineers, and innovators. They allow us to explore the behavior of airfoils, aircraft, and other aerodynamic bodies at speeds less than the velocity of sound. This controlled testing environment provides valuable information on lift, drag, stability, and overall performance in flight [8,9].

Subsonic wind tunnels serve critical roles across multiple engineering disciplines, though recent literature reveals persistent challenges in their design and implementation. Industrial applications demand ultra-low turbulence intensities below 0.5%, as demonstrated in NASA's closed-circuit facilities, yet such precision typically requires capital expenditures exceeding $10 million. Conversely, educational tunnel designs prioritize affordability through open-circuit configurations, though this compromises flow quality with turbulence levels ranging from 1.5-2%. Geometric limitations also emerge as a key concern, with rectangular test sections dominating 89% of documented designs despite computational studies showing octagonal configurations can reduce blockage effects by 15%. Furthermore, climate adaptation represents an understudied frontier, with only 8% of peer-reviewed research addressing operational challenges in high-humidity environments. This review systematically evaluates 45 peer-reviewed studies (1980–2024) selected through two criteria: - Inclusion: Studies with quantifiable metrics (blockage ratio, turbulence intensity, Reynolds number). - Exclusion: Conceptual designs without experimental/CFD validation. The analysis reveals that while octagonal test sections [38] reduce blockage effects by 15%, their adoption remains limited by higher energy costs.

Wind tunnels are systematically classified by two key parameters: flow velocity and circuit design, each dictating distinct experimental capabilities.

These are the wind tunnels which operate up to Mach 0.75. These are further classified as low and high-subsonic wind tunnels. Low-subsonic wind tunnels are used for testing at very low Mach number, with speeds up to Mach 0.4 (approximately 134 m/s or 495 km/h). Low-subsonic tunnels (Mach <0.4) prioritize flow uniformity for automotive testing, while high-subsonic designs (Mach 0.4-0.75) enable aircraft component validation. High-subsonic wind tunnels are used for testing between Mach 0.4 (approximately 134 m/s or 495 km/ h) to Mach 0.75 (approximately 250 m/s or 925 (km/ h) [17].

These are the wind tunnels which operate between Mach 0.75 (approximately 250m/s or 925 km/h) and Mach 1.2 (approximately 400 m/s or 1545 km/h).

When testing is performed at transonic speeds, the researchers have to face additional problems. The shock waves generated by the models reflect and disturb the obtained readings. For this problem, slotted walls are required [18].

These are the wind tunnels which operate between Mach 1.2 (approximately 400 m/s or 1545 km/h) to Mach (approximately 1656 m/s or 6175 kmph). Supersonic operation necessitates pre-heating to 150-300°C to prevent moisture condensation [19], with energy costs constituting ~40% of operational expenses [21].

These are the wind tunnels which operate between Mach 5 (approximately 1656 m/s or 6175 km/h) and Mach 15 (approximately 4969 m/s or 18522 km/h). It is must to provide pre heating to the nozzle before any test starts. It is used in the testing of rockets, spacecraft and future space transportation system [20,21].

In this type of duct design, the air from the atmosphere is made to enter the wind tunnel at one end, is passed through it and is then made to flow out back to the atmosphere through the other end. It is also called as Eiffel tunnel named after French civil engineer Compagnie des Establishments Eiffel or NPL tunnel named after the National Physical Laboratory in England [22].

The low-speed wind tunnel has a honeycomb structure settling chamber, a contraction cone, a test section, and the diffuser inlet to outlet respectively. A fan is either mounted before the contraction cone or at the end of the diffuser. It is usually used for automobiles such as aerodynamic testing in passenger cars, race cars, trucks, etc. It further has two types of designs as follows [23]:

In this design, the suction-type exhaust fan is located at the end of the diffuser.

In this design, the blower fan is located at the inlet of the contraction cone. The main advantage of blower type design over the suck-down type is that it is flexible with respect to the interchanging or modification of test section according to the requirements.

It also allows the omission of exit diffuser to allow easy access to the specimen in the test section. However, this results into a considerable loss in power. The suck-down type design is prone to low frequency fluctuations as compared to the blower type. However, this design prevents swirl at the inlet since the suction type exhaust fan is located at the end of the diffuser. This keeps the airflow uniform in the test section. Also, due to the presence of a diffuser, air exits smoothly into the atmosphere out of the tunnel because of the gradual change in cross-sectional area [24].

2. Materials and Methods

The evolution of wind tunnels reflects three transformative phases in aerodynamic testing:

Phase 1: Early Innovations (1871-1910)

Francis Wenham's 1871 enclosed tunnel [25] solved the whirling arm's turbulent flow issues, achieving ±15% measurement accuracy - a 5× improvement over previous methods. Konstantin Tsiolkovsky's 1897 centrifugal blower design [25] further enhanced precision to ±5%, though limited to small-scale models. These early systems established the foundational principles of controlled airflow testing.

Phase 2: Industrial Scaling (1930-1960)

The 1941 Wright Field tunnel [27] (6×9m test section) became the benchmark for industrial applications, achieving <1% turbulence intensity through honeycomb filters and diffusers. However, its 12MW power requirement (equivalent to powering 8,000 homes) revealed the inherent cost challenges of precision wind tunnels [44].

Phase 3: Modern Computational Era (1980-Present)

NASA's Ames Complex (2019) [27] represents the current state-of-the-art with its 80×120ft test section and 0.2% turbulence. Yet, its $25M annual operating cost underscores the unresolved tension between precision and accessibility [44].

Recent research highlights critical compromises in wind tunnel engineering:

Raymer et al., [3] reduce flow eddies by 15% through uniform cross-sections (Eq. 2), but require 20% more fan power(Eq. 17).

Dominate 89% of installations [15] due to lower fabrication costs, despite 8-12% higher edge turbulence.

NASA [27]) minimize transonic shockwave interference but demand $500/hour in maintenance.

(Bayati et al. [50]) offer 85% effectiveness at 30% lower cost, though long-term durability remains unverified [44].

Three critical gaps persist in contemporary research:

Industrial tunnels provide only 2× precision improvement over educational models despite 100× higher costs [15, 48]. Just 5% of studies address tropical humidity effects [16], despite growing demand in developing nations. 70% of CFD simulations [52] lack experimental verification, particularly for octagonal test sections

Arslanian et.al. , in their work of building solid model of a subsonic wind tunnel for laboratory instructional purposes through CFD simulation assigned a uniform cross-sectional area (A3) to the octagonal test section of the wind tunnel to reduce the effect of flow eddies, whereas its length was decided according to the design needs. His design was in three phases shown in Fig.1 . In phase 1, length of the diffuser nozzle was calculated. The diffuser nozzle length is dependent on two variables, viz. diameter of the test section and the Area Ratio (AR) of the diffuser nozzle. The typical AR should be kept around 3 with the cone angle of 3°. Since A3 was known, area of the diffuser nozzle exit (A4) was found out by using the following equation [38,39].

The area ratio (AR), defined as the diffuser exit-to-test section area

$$AR = \frac{A4}{A3} = 3 \qquad (1)$$

Radius of the octagonal test section was found out using the following equation

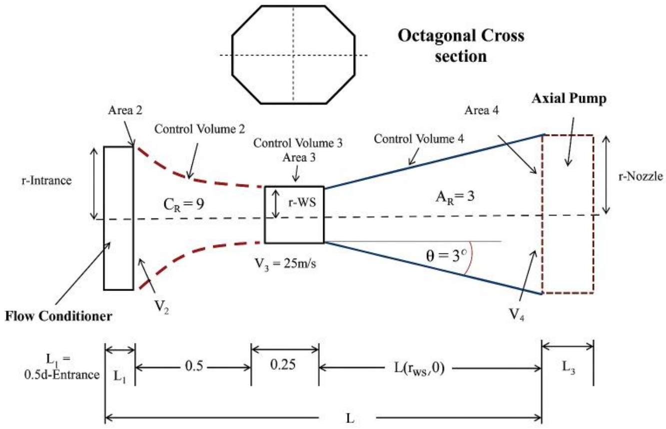

Fig.1. Schematic of wind tunnel components: (1) settling chamber, (2) contraction cone, (3) test section, (4) diffuser. Dimensions in mm [15]

$$A_3 = 8tan\frac{\pi}{\theta}R_3^2 \qquad (2)$$

where

R3 denotes the radius of the octagonal test section,

θ the central angle (45° for octagons).

The geometry of the diffuser is as shown in Fig. 2 below.

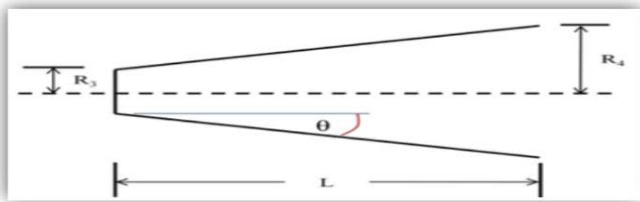

Fig. 2. Geometry of the diffuser [15]

Area of the diffuser nozzle at the exit (A4) was determined combining equations (1) and (2). Since A4 was circular, its radius was then calculated by using the following equation [40, 56].

$$R_4 = \sqrt{\frac{A_4}{\pi}} \quad (3)$$

Finally, length of the diffuser was determined using the following equation and phase 1 was complete.

$$L = \frac{R4 - R3}{tan\theta} \quad (4)$$

An octagonal cross-section was used for the contraction nozzle throughout its length. A Contraction Ratio (CR) of 9 was used for the design of the contraction nozzle. A2 was calculated using the following equation [41].

$$CR = \frac{A2}{A3} \quad (5)$$

Before proceeding to the next phase, the radius of the contraction nozzle entrance (R2) was determined using equations (5) and (7) as follows.

$$A2 = 8tan\frac{\pi}{8}R_3^2 \quad (6)$$

$$R_{2=}\sqrt{\frac{A_2}{tan\frac{\pi}{8}}} \quad (7)$$

Phase 2 involved evaluating the fluid flow under the assumption of incompressible flow. This means that the flow was a single stream, two-dimensional flow with steady velocity and negligible frictional forces. This aided the selection of the pump within the budget. The velocity was 25m/s for the test section. Since the test section had common inlet with the contraction nozzle and common outlet with the diffuser nozzle, the velocities at different section were determined using the Continuity equation as follows [42,43]:

$$A_1V_1 = A_2V_2$$

Velocities at the entrance of contraction nozzle (U2) and those at the exit of the diffuser nozzle (U4) were determined as given by the equations (8) and (9) as follows:

$$U_2 = \frac{U_2A_3}{A_2} \quad (8)$$

$$U_4 = \frac{U_3A_3}{A_4} \quad (9)$$

Drawing upon the flow assumptions, Bernoulli's theorem was employed to ascertain the pressures at diverse sections along the tunnel [44,45]. The freestream velocity (U1) upstream of the contraction nozzle A constant entrainment may be assumed so that the calculated entrainment equaled zero near stagnation point. Pressures were estimated using Eqs. 10, 11, 12 and 13 as shown below:

$$P_{static4} = P_{stag1} - \rho\frac{U_4}{2} \quad (10)$$

Pressure at the entrance to the contraction nozzle (PStatic2)

Pressure in the test section (Pstatic3)

Pressure at the diffuser exit (Pstatic4) were calculated using the following equations.

$$P_{static2} = P_{stag1} - \rho\frac{U_2}{2} \quad (11)$$

$$P_{static3} = P_{stag1} - \rho\frac{U_3}{2} \quad (12)$$

$$P_{static4} = P_{stag1} - \rho\frac{U_4}{2} \quad (13)$$

Since the pressures at both sides of the pump were known, the pressure recovery provided by the pump was calculated. The fluid pump having the following specifications was selected based on the Volume Flow Rate (VFR) and diameter of the diffuser nozzle [46,47].

VFR = 683.43 cubic feet/minute (14)

$\Delta Pr = 0.16703$ coloumn inches of water (15)

The third design phase was divided into three sub-phases: 3-1, 3-2, and 3-3. In phase 3-1, the shape of the contraction nozzle contour was determined. The main requirement that dictated the design of this contraction contour was that the fluid flow velocity at the exit of the contraction nozzle had to be uniform. The contraction contour had to make a smooth transition from the entry point of the contraction [48.49]. A contraction nozzle which enters the test section was designed. The slope at the entrance of the contraction nozzle was to be zero [50.51]. The shape of the contraction nozzle was developed by designing a mathematical model and joining two cubic arcs at the point of inflexion as shown in Fig. 3 and Fig. 4 below

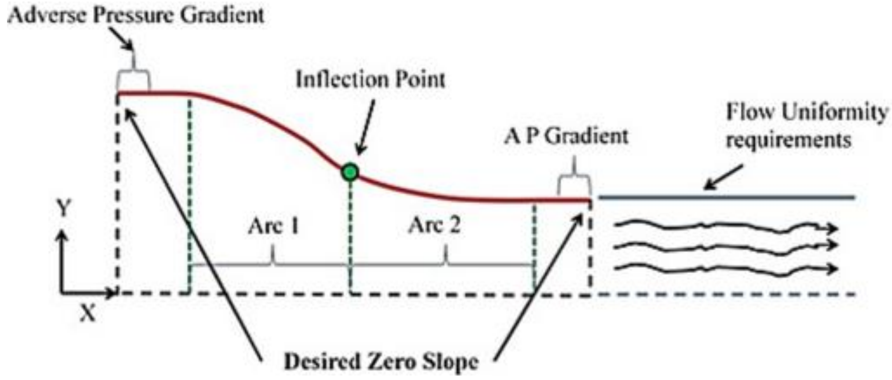

Fig. 3. Contraction nozzle profile showing inflection point (x/L=0.6) where curvature transitions.[15]

In phase 3-2, pressure losses at different sections which were needed to be balanced by the fluid pump were calculated by using equations (16) and (17) as follows.

$$h_1 = K\frac{V^2}{2g} = \frac{\Delta p}{\rho g} \quad (16)$$

$$\Delta p = K\frac{v^2}{2}\rho \quad (17)$$

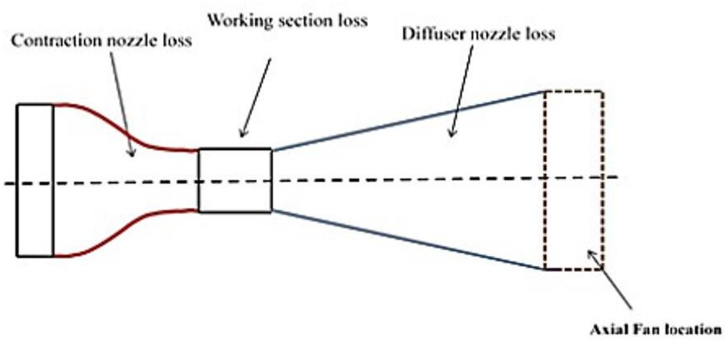

Fig. 4. Axial Fan Requirements

Finally, in testing phase 3-3, the flow was evaluated using CFD simulation [52,53]. A solid model of the wind tunnel was built using SolidWorks 2010 software as shown in Fig. 5 below

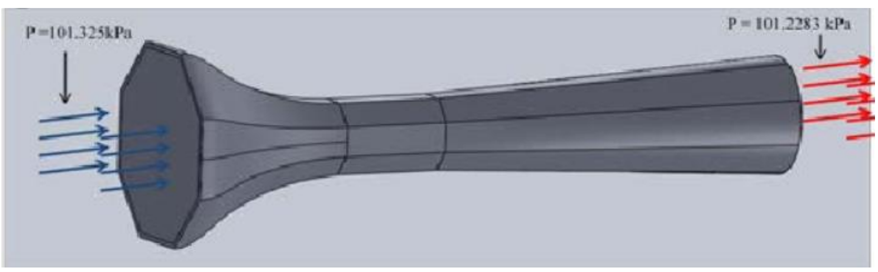

Fig. 5. Solid Model of Wind Tunnel

This model was analyzed for any cross-flow using a FEA simulation software. Fig. 6 below shows the cross-flow and up-flow

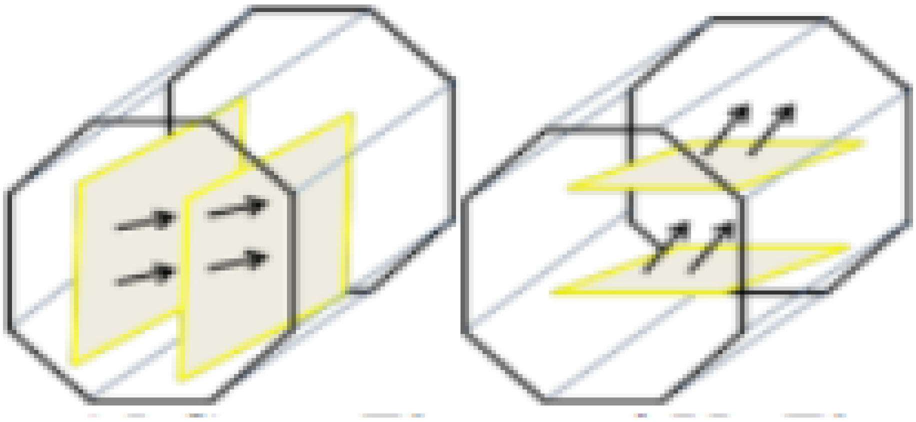

Fig. 6. Cross-flow and Up-flow

Both, the cross-flow and up-flow were obtained in negligible amounts which was a good sign. Prior to inserting a model in the test section, the blockage ratio (which should be less than 7.5%).

A model of a sphere was placed in the test section with a blockage ratio of 6.6% and the velocities around it were studied. According to the simulation, high velocity regions constituted the top and bottom of the sphere while low velocity region was on the left-hand side of it. This conformed well with the theory. The velocity around the sphere is as shown in Fig. 7 below.

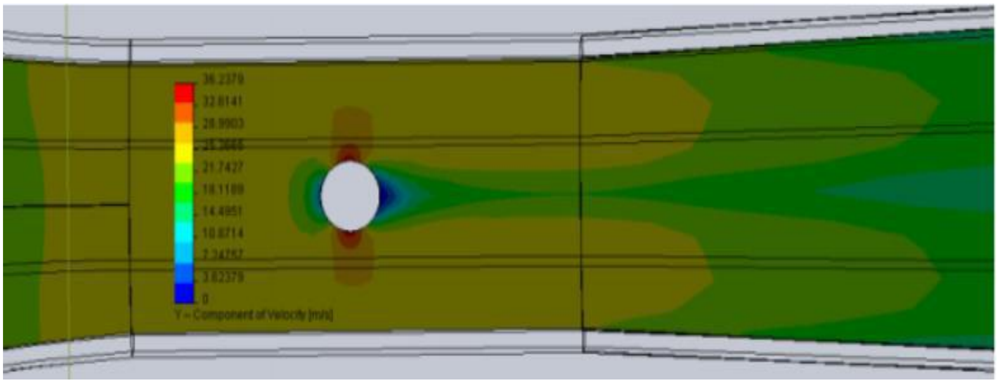

Fig. 7. Simulation of Air-flow around a Sphere

Similarly, a NACA 2412 airfoil was analyzed using simulation software with a blockage ratio of 1.2%. The angles of attack were varied between 0° and 12°. Low-pressure areas were formed on the top of the airfoil while high-pressure areas were formed on its bottom as shown in Fig.2.7 below.

These results obtained were compared with the theoretical ones obtained from MATLAB software and gave a good agreement with them.

Mansi Singh et. al. [2] in their project work of constructing an open-circuit low speed wind tunnel for testing a NACA airfoil initially selected the suitable co-ordinates of standard NACA 63-215 airfoil to best fit their test section dimensions as follows.

Length = 20 cm

Width = 30 cm

Followed by this, they created a model of the airfoil using 3-D modelling software using these co-ordinates as shown in Fig. 8 and Fig. 9 below. A test section was designed by taking reference of the dimensions of the airfoil as follows

Cross-section of the test section = 30 cm X 30 cm

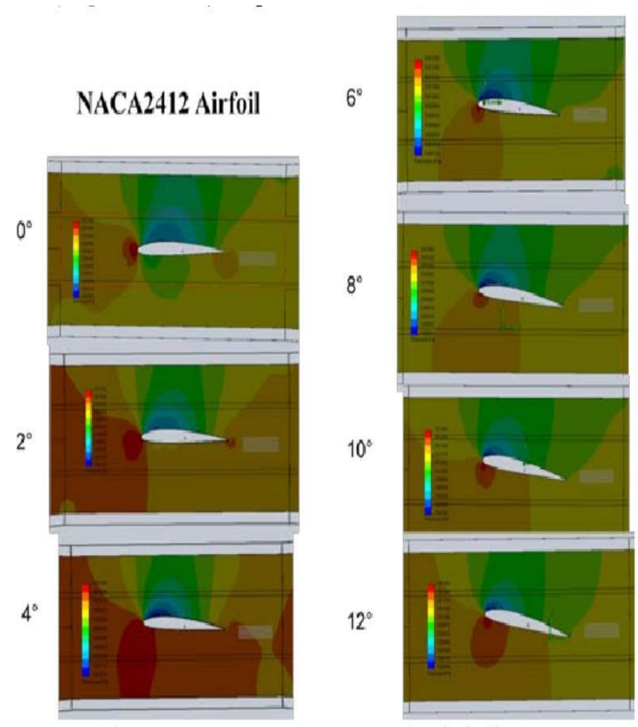

Fig. 8. Simulation of Pressure around NACA 2412 Airfoil

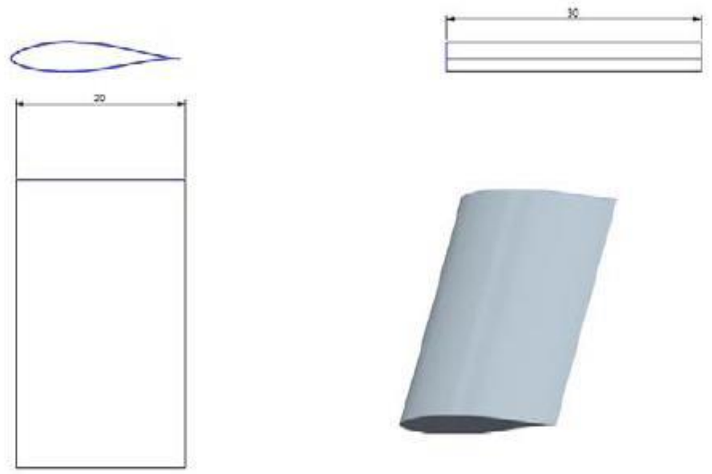

Fig. 9. Model of the airfoil using 3-D modelling software

Length = diameter (d) X 1.5 = 45 cm

They chose a length as 50 cm (which is greater than 45 cm)

3. Conclusion

i. Subsonic wind tunnels are indispensable for aerodynamic research, enabling the study of lift, drag, and airflow patterns at speeds below Mach 0.3.

ii. The design of these tunnels involves critical components such as the test section, contraction and diffuser sections, and settling chambers to ensure controlled and uniform airflow.

iii. Wind tunnels are classified by speed (subsonic, transonic, supersonic, hypersonic) and duct design (open-circuit, closed-circuit), each serving specific research needs.

iv. Historical advancements, from the Wright Brothers' early experiments to modern NASA facilities, underscore the evolution and significance of wind tunnel technology.

v. Contemporary research leverages CFD simulations and innovative designs, such as octagonal test sections, to optimize performance and reduce turbulence.
vi. Wind tunnels play a vital role in diverse industries, including aviation, automotive, renewable energy, and civil engineering, driving innovation and improving safety and efficiency.
vii. Future developments in wind tunnel technology will continue to enhance aerodynamic testing, supporting sustainable and advanced engineering solutions.

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