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Design and Construction of a Low Reynolds Number Subsonic Wind Tunnel

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ABSTRACT

This paper delivers a description of modeling and constructing a small, low Reynolds number, open loop, subsonic wind tunnel. It also briefly discusses a process to generate smokes for visualizing the invisible air while passing over a bluff body. This work mainly aims at understanding the factors influence the design of a wind tunnel, pointing out what errors might have associated with the experimental data during the experiment, and getting practical knowledge on the factors needs to be considered while constructing a fluid machinery. In this wind tunnel, when the air is sucked by an induced draft fan and started passing over the solid bluff body placed inside the tunnel, an electrically heated metal tip vaporizes glycerin in order to create dense smoke for visualizing the flow fields and streamline around the body. In this wind tunnel, the maximum useful speed of the air is 7.1 m/s at a Reynolds number of 1065.

Key words: Wind tunnel, Reynolds number, Flow visualization, Fluid machinery, Design Criteria

INTRODUCTION

The wind tunnel is an indispensable apparatus for conducting an experimental investigation of fluid flow problems. Wind tunnel refers to an apparatus used for producing an airstream of known velocity passing over the small scale test models of aircraft, buildings, etc., in order to anticipate the effects of the wind on the full-size object. Visualizing flow fields over a model is an important part of the experimental investigation by using a wind tunnel for examining the flow patterns around a body or over its surface and getting an idea of the streamline and turbulence of the flow for the particular model. Flow visualizing is a qualitative measurement scale to analyze flow behavior [1]. In this work, we only concentrate on the qualitative analysis of fluid flow. On the other hand, quantitative analysis requires measuring properties of fluids at a particular point in the flow field. Although the quantitative analysis is critical for getting a complete idea of flow fields, due to lack advanced apparatus and technology (such as Particle image velocimetry or particle tracking velocimetry) in campus premises, we had to keep our scope limited to getting ideas about the streamline. Our primary objectives involve understanding the factors that influence a wind tunnel design, accumulation of experimental data of flow problem from wind tunnel property, working out the errors and acquisition of knowledge considered while designing and fabricating a fluid machinery.

The wind tunnel usually consists of several distinct sections: the settling chamber or plenum, the contraction cone, the test/working section, the diffuser and the draft fan. Several considerations have to be made for these specific sections in order to achieve a wind tunnel with the required properties and below these main design criteria are listed according to Telev et al [2].

- Open wind-tunnel and good flow quality (mean flow variation, turbulence intensities & temperature variation).
- The test section is square and the maximum test section length possible in the available space.
- Maximum flow speed in the test section of 40 m/s and Contraction ratio, CR, of 8.
- Low noise level and low cost.

Zingg (1951a) proposed seven practical guidelines to consider when designing and building a portable wind tunnel for field use [3]. He further suggests using commercially available equipment when possible. These criteria are listed below:

1. The wind tunnel must be capable of producing an air stream free of general rotation and unsteady characteristics.
2. It must provide smooth and positive control of a range of wind velocities and forces common to the natural wind.
3. It must be durable.
4. It must be safe to use.
5. It should have sufficient size to afford free movement and representative sampling of eroding materials over field surfaces.
6. It must have ready portability.
7. It should be light in weight and amenable to quick and active assemblage and dismantling.

An open wind tunnel draws air from the outside of the tunnel into the test section and then exhaust back to the outside again. In order to obtain meaningful data, the flow similarity parameters of Mach number and Reynolds number must match the desired flight conditions [4]. Both Mach and Reynolds number rely on the velocity and gas density inside the tunnel. In the case of academic and educational purposes, the requirements related to flow quality may be relaxed, but for research and aeronautical applications, the flow quality becomes very essential, resulting in more expensive construction and higher operational costs. The aerodynamic properties of an object cannot all remain the same for a scaled model [3]. However, by observing certain similarity rules, a very satisfactory correspondence between the aerodynamic properties of a scaled model and a full-size object can be achieved. The choice of similarity parameters depends on the purpose of the test, but the most significant conditions to satisfy are usually:

- Geometric ratio: all dimensions of the object must scale proportionally;
- Velocity: the ratio of the airspeed to the speed of sound should be identical to the scaled model and the actual body (having identical Mach number in a wind tunnel and around the actual body is -not- equal to having identical airspeeds)
- Reynolds number: the ratio of inertial forces to viscous forces should be maintained. This parameter is challenging to satisfy with a scaled model and has led to the development of pressurized and cryogenic wind tunnels in which the viscosity of the working fluid can be considerably changed to compensate for the reduced scale of the model.

Mike Raupach and John Leys (1990) suggested six aerodynamic criteria that should be considered in addition to Zingg's practical criteria [5]. Their aerodynamic criteria are listed below:

1. The flow must reproduce the logarithmic wind speed profile in the natural atmosphere, thus ensuring realistic aerodynamic forces on saltating grains.
2. The surface shear stress must scale correctly with the wind speed above the surface so that realistic aerodynamic forces act on grains of all sizes at the surface.
3. The vertical turbulence intensity and scale in the region close to the ground must be realistic, ensuring that vertical turbulent dispersion of suspended grains is adequately modeled.
4. The flow must be spatially uniform to avoid local scouring by anomalous regions of high surface stress.
5. Gusts should be simulated in the tunnel due to the fact that higher shear stress is required to initiate erosion than to sustain it.
6. A portable wind tunnel simulation of erosion should allow for the introduction of saltating grains at the beginning of the working section if more than the very upwind area of an eroding field is to be simulated.

DESIGN AND CONSTRUCTION

Wind-tunnel design is a process where research goals are first set then these goals are assessed to find the design criteria. According to our research goal, the design typically involves fabrication, cost, space, and other conflicting constraints, the process is iterative. More significantly, the design criteria are strongly linked with the specifications and requirements and those must be in accordance with the wind tunnel applications. We also try to follow the instruction given in [2,3,5] while constructing and designing our wind tunnel.

Wind tunnel are typically circular since it provides smoother flow than the square cross-sectional tunnel because of the viscous effect [6]. In the corner of the square tunnel, the flow faces more constriction which introduce turbulence in the flow. Though circular duct provides a better environment for streamlined laminar flow, we have to use rectangular duct since its design simpler than circular duct and convenient for inspecting test specimen in the trial section.
The mass flow rate inside the wind tunnel is governed by the continuity equations for ideal gasses [7].

$$Q = A_1V_1 = A_2V_2 \quad (1)$$

Where, Q represents flow rate, A and V denote cross sectional area and velocity at a certain point respectively.

The Reynolds number can be measured by the following equation.

$$Re = \rho v d/\mu \quad (2)$$

Equation (2) can be rewritten as,

$$Re = vd/k \quad (3)$$

Where, kinematic viscosity, $k = \mu/\rho$ and for air k = $1.5\times10^{-5}m^2/s$ at 25ºC
The laminar flow of air inside a tube or pipe transformed into turbulent flow at Reynolds number of 2300. A cross-sectional area of $225cm^2$ is enough to test a small scaled model. So the speed should be less than 15 m/s according to equation (2) for laminar flow in the test section of cross-sectional area of $225cm^2$.

According to the manual given with the blower, the maximum flow rate at which the centrifugal blower can suck the air is 0.6 m^3/s and diameter of the throat this blower is 10cm. By using an anemometer, we measure the maximum speed of air at the exit of the blower is 60m/s. Hence now the maximum volume flow rate at the exit is $0.47m^3/s$. According to equation (1), with this blower, highest achievable speed in the test section is 20 m/s. However, we will keep the speed less than 15 m/s while taking data in our wind tunnel.

At first, we have designed a wind tunnel in a CAD software according to the specification described above. Then we have simulated the flow in that wind tunnel at various speeds. After retrieving satisfactory results in our simulation, we started the construction in the university workshop.

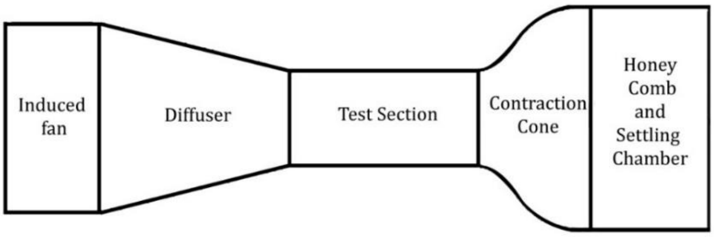


Fig. 1: A simple diagram of open channel wind tunnel

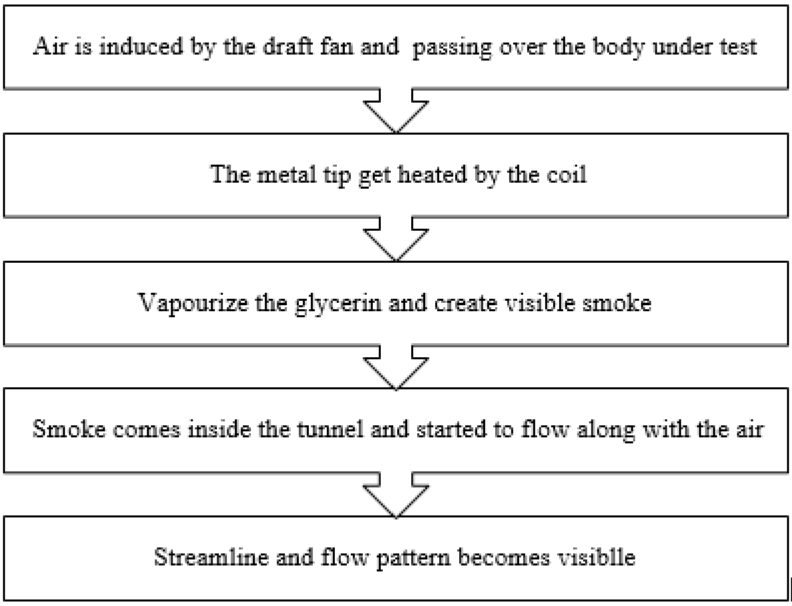


Fig. 2: Process of generating smokes in wind tunnel

Smoke Generation

Flow fields in a wind tunnel can be visualized in many ways: Smokes or fog, Tufts, neutrally buoyant particles, helium bubbles, surface powders/oils and smoke plumes are widely used for subsonic tests and Schlieren, birefringence, and interferometric techniques cover the supersonic regime [8]. Among them, the most convenient and inexpensive way is using smoke where invisible air visualized by injecting smokes into the airflow and capturing the image of the flow under ample lighting while the smoke is flowing over the body. Please note that the techniques mentioned earlier are quite accurate than this one. The smoke follows the air currents, allowing the observer to see the flow. Among several methods of producing and injecting the smoke into the tunnel, we have selected vaporization of glycerine since it creates a dense smoke because of its higher cohesion bonding. The metal tip along with the coil of a soldering iron is detached for the soldering iron, and this detached part is used as heat source for vaporizing the glycerine. Here the power required for the coil is 60 W, and it is heated 220V A.C. current. The tip is coated with rapeseed oil, and its head is placed inside an insulated box full of glycerine. This box is placed below the middle of the tunnel and connected with the tunnel through a plastic pipe. The created smoke pass through this pipe and reach the desired destination. Then this smoke flows over the body under test. In this way, we only can understand and analyze the laminar flow. For turbulent flows, this way of visualizing air won't work properly because of substantial mixing of air and glycerine particle. In the advanced method of visualizing like particle tracing technique, the smoke particles can be generated and injected this way and then can be analyzed for measuring fluid properties. The sole purpose of this work is to capture the flow pattern over a bluff body. In this work, we don't measure aerodynamic forces, pressure distribution and other aerodynamic characteristics which are also some important uses of wind tunnel testing. The toxicity of vaporized glycerine was also not severe [9].

In this wind tunnel, air is sucked by the centrifugal blower of the tunnel which acts as an induced draft fan. When the air is started to flow inside the tunnel, it will also take the smoke in the test section through the pipe connected to the box. Due to vaporization of the glycerine, there is already a positive pressure which forces out the glycerine smoke through the pipe. Then smoke follows the streamline of the flow of air. This visible smoke enables the observer to get the idea of streamlines and patterns of the flow-particle over the body.

Wind Tunnel Components and Measurements

The test section's dimension is 20cm×10cm×10cm. It is made of 2 mm thick mild steel sheet and has three acrylic viewing windows. Each end of the test bed has drilled a hole to bolt to the other sections.

The second section of the wind tunnel designed is the contraction cone. The size of the large end, nearest the settling chamber was set at 30cm×30cm. The small end of the contraction cone was set at 10cm×10cm to fit directly onto the test section. The contraction cone made of sheet metal also has drilled holes on each side to bolt together with the other sections the settling chamber's cross section dimensions are 30cm×30cm, and match up with the dimensions of the contraction cone. It is made of 2 mm thick mild steel sheet and has drilled holes to bolt it to the contraction cone. Its length is 15cm to accommodate three different flow straightening devices. The first of the flow straightening devices is the honeycomb. In the inlet, before reaching the subject of testing smoothing out of turbulent airflow is done by closely spaced vertical and horizontal honeycomb-like air vanes. The second and third flow-straightening devices are screens. The two screens are approximately 3.75cm apart from each other and is placed 3.75cm behind the honeycomb.

The diffuser is 45cm long and is connected to the test section with bolts. The dimensions of the front opening of the diffuser are 10cm×10cm, and the dimensions of the end opening are 16.5cm×16.5cm. The blower or power source is the final critical component in the design of our low-speed wind tunnel. Here a centrifugal blower was used with a 10cm diameter, maximum power of 250 w and maximum volume flow rate of $0.6m^3/s$ so that it can pull enough air to reach desired speed in the test section. A switch was also used for controlling and allowing for a free range of wind velocity. A different number of nets was held for various velocities. The velocities at the inlet and inside the test section were measured by a digital anemometer.

Interior Lighting

The lighting method designed for this experiment is to illuminate almost all the space of the test section. It should be noted that, for a better result, the light should not illuminate the background or the wall in the test section facing the camera. To achieve a satisfying lighting condition, colourful flashlights were aligned parallel to the smoke filament plane.

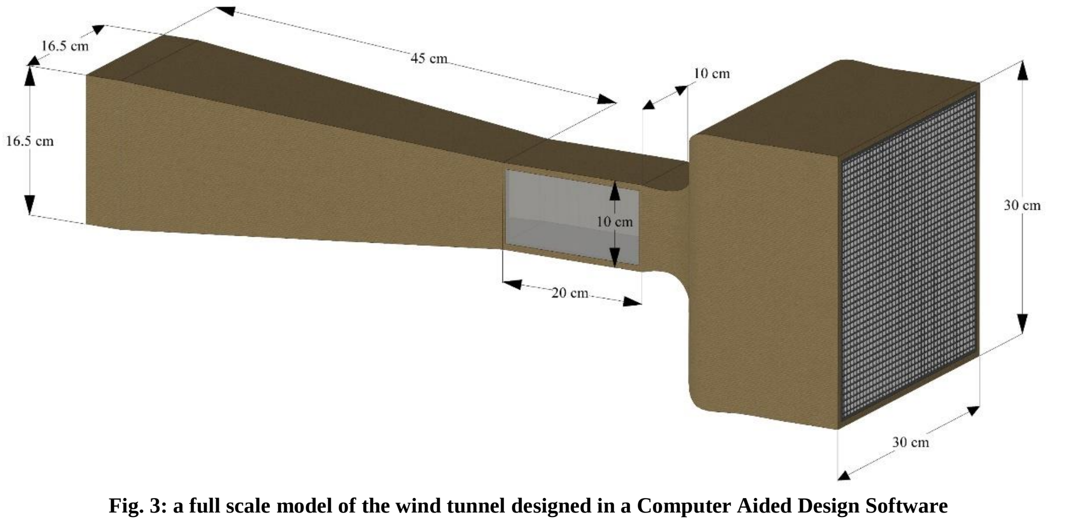
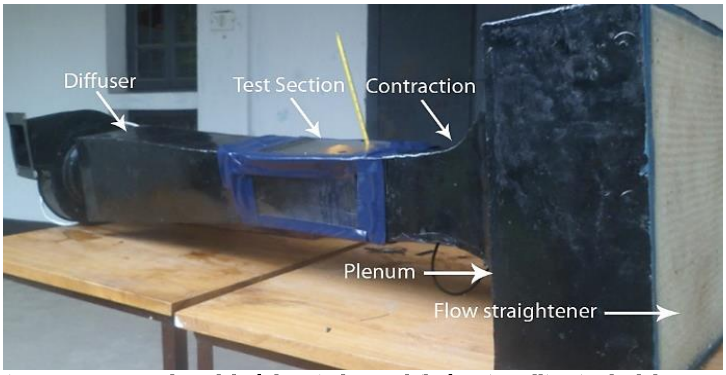


Fig. 3: a full scale model of the wind tunnel designed in a Computer Aided Design Software



. **Fig. 4. Constructed model of the wind tunnel (before installing in the laboratory)**

Table - 1 Description of Flow Generated at Different Velocities

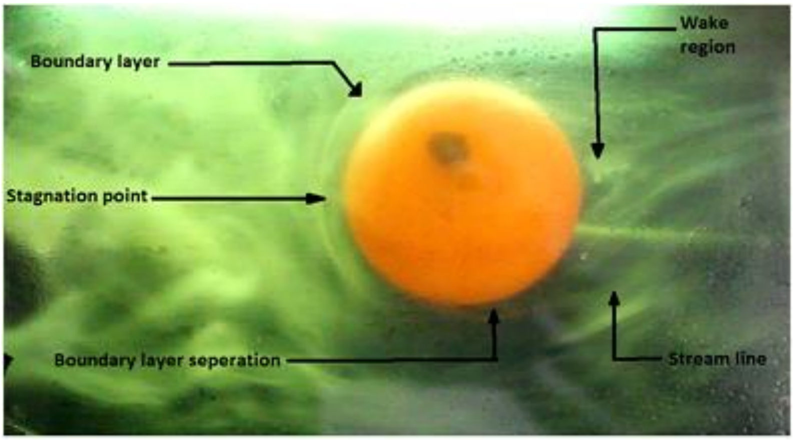
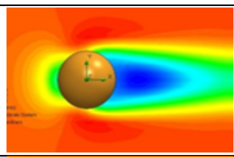
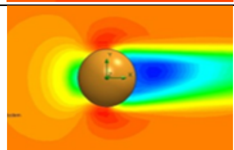
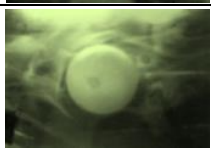
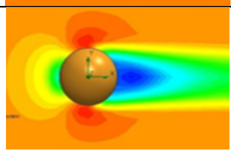
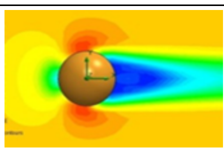
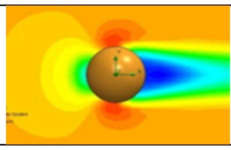


Fig. 5 illustration of flow-fields around the bluff body at a velocity of 2.1 m/s

Theoretical velocity at test section, *v* (m/s)	**Experimental velocity at test section, *v* (m/s)**	***Re* in test section**	**Experimental Results**	**Simulation Results**	**Remarks**
1	0.81	121.5			Uniform streamline was depicted over the body. Some random smokes flowing in a chaotic manner which was created due to the buoyancy of the glycerin smokes.
2.5	2.1	315.7			These conditions gave the best results. Easily recognizable white and uniform streamline was generated. Flow pattern could be easily visualized.
5	4.3	645.4			Flow pattern could be visualized at this speed as well. Smoke was quite dense and clear at this speed. Buoyancy still dominates here.
7.5	7.1	1065.0			The smoke stayed condense in most of the regions in the test section which indicates the flow was laminar then. Buoyancy had become weaker.
10	10.9	1635.0			At this speed, the smoke had become a bit mixed and blurred because of the introduced turbulence.

RESULTS AND DISCUSSION

We chose a sphere of 40mm diameter for analyzing flow in our wind tunnel. It was observed in our experiments that the flow fields and streamlines in this wind tunnel could only be visualized and identified when wind velocities stayed below 7.5 m/s and Reynolds number below 1010. Although air speed of 10m/s is well below the maximum limit of laminar flow, we depicted some turbulence and non-uniform streamlines. This deviation might result from design errors such as lack of smooth internal surface and lack of symmetry. Some eddies, turbulences, and vortex also produced in the flow because of the pipe we used to inject smokes in the flow. Thus it became difficult to recognize the streamline properly. Up to these velocities and Reynolds number mentioned above, the flow stays uniform and streamline can be identified.

The flow fields and the streamline around an object are shown in the Fig. 5 when the air is passing from left to right at 2.1 m/s. Smokes are moving along a curved line around the object, and this line indicates the streamline around the object. It can be seen that the stagnation point, at which the flow velocity is locally zero, forms in front of the object. However, at some points on the back side, the boundary layer separates from the object's surface to form a wake region. The wakes that form in downstream the spherical body lower the pressure and, therefore, results in a difference in pressure between the front and rear faces. This difference eventually creates a drag on the body.

CONCLUSION

The primary objective has accomplished in this works: assessing the crucial factors that manipulate the design of a wind tunnel, identifying the aspects of the design of wind tunnel which will lead to significant errors and developing practical knowledge over the construction of fluid machinery. In wind tunnel design, the finishing of the interior surface is a vital factor even for a low-speed wind tunnel. Irregular surface will lead to unnecessary turbulence. The contraction cone should be as long as possible since most of the turbulences are created in the contraction cone at higher speed. The glycerin smoke generation technique is quite useful to visualize streamlines in a low-speed wind tunnel. One flaw of the glycerin smokes is that it is very light. The smoke tends to move upward rather than follow the direction of the wind. If the buoyant force of the smoke dominates the flow, it becomes a bit harder for the observer to recognize the flow pattern. Another problem of vaporized glycerin is that it condenses to liquid form quickly at room temperature. Further improvement of this setup will make it more applicable to study of fluid mechanics and conduct experiments. Some recommendations are mentioned below:

- Use of High-Speed Camera can capture the movement of the particles more accurately.
- The mixture of Glycerin with colored dye will create colored smoke -create a better chance for the observer to identify streamlines.
- Pressure, drag, etc. measuring equipment should be introduced.

To reduce the surface drag and turbulence, the inner surface of the tunnel should be as smooth as possible. Such drag and turbulence may cause inaccuracy while experimenting. Open tunnel has advantages related to the closed return tunnel which are –

- Efficient construction cost
- Superior design for propulsion and smoke visualization. There is no accumulation of exhaust products in an open tunnel.

Though open return tunnel has some positive vantage, it carries some disadvantages too which are-

- The corner of the bell mouth requires flow straighteners. Otherwise, it may face poor flow quality.
- The tunnel will produce asymmetries to the bell mouth if it is kept near walls, desks, etc.
- Tunnel exposed to outside atmosphere, winds and weather may cause an effect on data.
- This type of tunnel needs high operating costs in contrast to close type tunnel. Because the fan continually accelerates flow through the tunnel.

Acknowledgements

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