Indian Journal of Science and Technology, *Vol 9(30), DOI: 10.17485/ijst/2016/v9i30/99195, August 2016*
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Design of Low Cost Open Circuit Wind Tunnel – A Case Study

Mahesh K. Panda* **and Amiya K. Samanta**

Department of Civil Engineering, National Institute of Technology Durgapur - 713209, West Bengal, India; mahesh26119@gmail.com, aksnitd@gmail.com

Abstract

Objectives: This paper elucidate the entire procedure to design an open circuit subsonic wind tunnel which will be used to study the wind effect on the different prototypes of structural elements. **Method:** The existing guidelines and findings of the previous research works were followed for design calculation of different parts of the wind tunnel. Three design trials have been performed so as to achieve a velocity of 25 m/s at the test section. The final trial has been discussed in the body of the paper. **Findings:** The design includes a square test section of side 500 mm, to accommodate the model and required instrumentation in it, for force and pressure measurement. A straight section before the test chamber is provided to allow the output of contraction section to stabilize before it reaches the test section. Instead of using a curved wall shape a straight contraction profile with larger contraction length is used. The diffuser extends from the test section and its cross section changes from a square test section to an octagon of 311 mm side. The pressure drop and power required for the designed wind tunnel are calculated and tunnel performance curve is plotted. **Application:** The design being purely empirical, it requires computational validation before commencement of the construction of the wind tunnel. The investigators have actually made an attempt to design the same in the existing setup, which may be useful for different research purpose.

Keywords: Design of Open Circuit Wind Tunnel, Loss in Contraction Section, Power Requirement, Pressure Drop in Diffuser, Stilting Section, Tunnel Performance Curve

1. Introduction

The wind tunnel is a tool to study fluid flows around a body and the forces generated by the fluid-structure interaction. Using such tool, it is possible to measure global and local flow velocities, as well as pressure and temperature around the body. A wind tunnel experiment provides the force and pressure values on the model and the flow visualization. It is a critical instrument in the quick and thorough design process of anything that involves fluid dynamics. Based on the flow through the tunnel circuit, the wind tunnel is of two types, open type and closed type. In open type, ambient air enters from one side and exits to the atmosphere after flowing through the tunnel. In closed type wind tunnel, a constant volume of air is allowed to pass through the tunnel circuit continuously Figure 1.

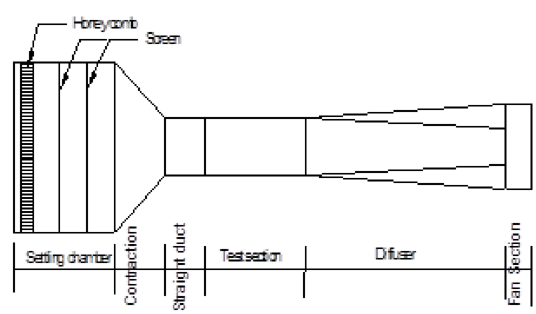

Figure 1. Schematic diagram showing different parts of wind tunnel.

** Author for correspondence*

The main goal of wind tunnel design is to have uniform flow within the test chamber. Test chamber dimension depends on the type of test to be performed and the size of the model to be tested. The wind tunnel's overall dimensions are key factors in its construction and running costs. The trade-off is required between the opposing needs to get a suitable design of the wind tunnel, satisfying the test requirements, space and budget constraints[1]. The design process starts by defining the test chamber dimensions and shape, after that the rest part of the wind tunnel is designed by keeping in view the dimensions of the test chamber.

Principal parts of an open type wind tunnel are the test section, contraction, diffuser, settling chamber and driving unit (Fan). This paper deals with the design of an open type wind tunnel to have minimum construction cost and the running cost.

2. Design Methodology

The open circuit wind tunnel is made of several distinct sections, the settling chamber, the contraction cone, the test section, the diffuser and the fan. Different parts are described as follows:

2.1 Test Section

The wind tunnel design starts with deciding the test section keeping an eye on the accessibility and installation of the test model and instrumentation. From the experimental investigations, it has been found that the blockage has an almost negligible effect on test results when it is about 10%[2]. The test chamber length has to be in the range of 0.5-3 times its hydraulic diameter[3,4]. The test chamber is being designed to test the scaled model of a silo with length 250 mm and minimum L/D ratio 1. In order to have a blockage ratio less than 10% a square test chamber of 500 mm side is chosen Figure 2. The test will be carried out at a flow speed of 25 m/s. The pressure loss coefficient goes on increasing with increase in the test section Figure 3. So the length of test section should be as small as possible. The length of the test chamber was set to 1.25 m i.e. 2.215 times the hydraulic diameter of the test section.

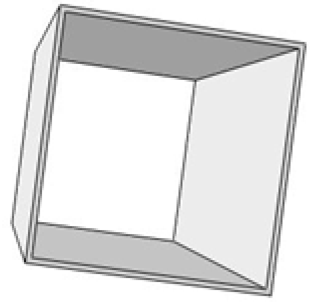

Figure 2. Test section.

2.2 Contraction Cone

The contraction accelerates the flow to the test section, further reducing any variations in velocity. A contraction design satisfying all criteria will be such that the separation is just avoided and the exit non-uniformity is equal to or less than the maximum tolerable level for the desired application in shortest possible length[5]. The contraction starts with the selection of contraction ratio[6]. For smaller tunnels the contraction ratio should be in between 6 to 9. The length of the contraction should be in between 0.15 R to R. R being the hydraulic radius of the contraction section inlet. Too large contraction section avoids flow separation[7]. As shown in Figure 4, the pressure drop coefficient values go on decreasing with increase in CR, so the maximum allowable contraction ratio 9 is chosen. To avoid flow separation, a contraction of length of 900 mm is used, which is 20% longer than the maximum recommended value. For easier and cheaper construction a straight contraction shape is used instead of solving complex equations to get the wall shape. The nozzle exit cross section dimensions and shape are identical to the test chamber.

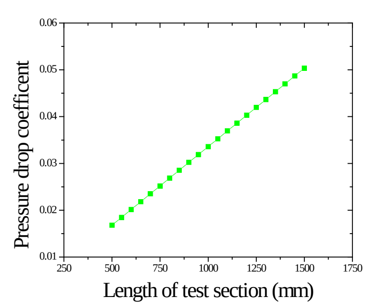

Figure 3. Plot to show the pressure loss in a constant area section.

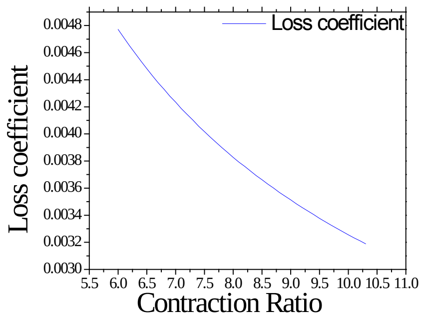

Figure 4. Contraction section pressure loss coefficient with contraction ratio.

2.3 Straight Section

Inserting a small settling duct before the test section can reduce the turbulence level to an acceptable level, for non-streamlined shape of contraction wall[8]. A straight section of length 0.5 m has been inserted after the contraction, with an area of cross section equal to the testing chamber size. Figure 5 shows the straight section attached to the contraction cone.

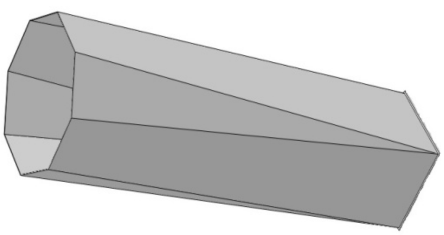

Figure 5. A diagram showing the contraction cone with a straight section.

2.4 Diffuser

The diffuser is mainly used to reduce the velocity of flow in the shortest possible distance to reduce the load on drive system. The flow through the diffuser depends on its geometry defined by area ratio (ratio of outlet area to the inlet area) and diffuser angle (2θ), wall contour and diffuser cross-sectional shapes. The area ratio of the diffuser should be less than 2.5 and diffuser angle should be 5° – 7° for controlling flow separation. The minimum length of diffuser can be found from Equation,

$$\theta_e = \tan^{-1}\left(\frac{1}{2}\frac{\sqrt{AR}-1}{L/D_{h1}}\right). \quad (1)$$

Where, D_{h1} is the inlet sections hydraulic diameter and θ_e is the half of the included angle of the diffuser cone.

Assuming minimum diffusion angle (θ_e) i.e. 5^0 and solving for L, the maximum of the minimum length of the diffuser is found to be 2.38 m, hence a diffuser of 2.5 m length is provided. An octagonal outlet is chosen with side 310 mm Figure 6. The diffuser area ratio is calculated as 1.86, which falls in the no stall region in Figure 7 with a diffusion angle 5.03^0.

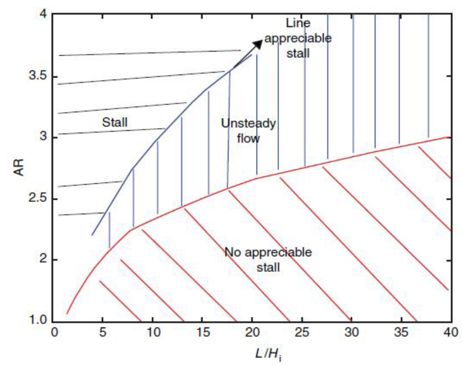

Figure 6. A diagram showing the diffuser.

2.5 Settling Chamber

The aim of a settling chamber containing honeycombs and screens is to reduce the flow turbulence before it enters the cone. A selection of honeycomb and screens for a wind tunnel is very much dependent on the test type to which the tunnel is intended[8]. The settling chamber cross-sectional area matches the dimensions of contraction cone inlet i.e. 1.5 m x 1.5 m with a length equal to 1.25 m is used.

2.6 Honeycomb

The honeycomb removes the swirl from the incoming flow and minimizes the variation in both mean and fluctuating velocity[9]. It should have sufficient flexural rigidity to withstand applied forces during operation without significant deformation. The primary design parameter for honeycomb is the ratio of length to cell hydraulic diameter (L/D) and porosity (flow area upon total area). Recommended L/D ratio for honeycomb is 6 to 8 with porosity nearly 0.8. A square shaped honeycomb, 3 mm thick and 27 mm size and 150 mm length is provided with a porosity value of 0.82. Figure 8 shows an arrangement of Honeycomb and screens in settling chamber.

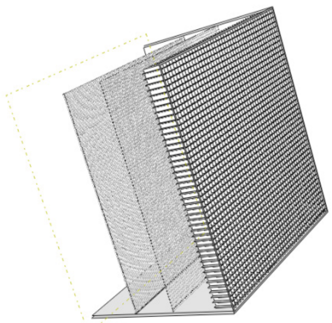

Figure 8. Diagram showing the arrangement of honeycomb and screen.

2.7 Screens

Tensioned screens are placed in the settling chamber for the reduction of turbulence level of incoming flow, this breaks up the large scale turbulent eddies into a number of small scale eddies that subsequently decay. To be effective in reducing turbulence a screen must have porosity in the range 0.58–0.8[9]. Screen porosity values over 0.8 are not suitable for good turbulence control while values below 0.58 lead to flow instability[10]. A clearance of 0.2 times the settling chamber diameter is required between the screens. Experimentally it is found that better turbulence control can be achieved when the finest screen is placed farthest downstream[11–13].

So a screen with 2 mm wire and porosity 0.69 is placed at a distance 340 mm from the start of the contraction i.e. 0.2 times the hydraulic diameter of the settling chamber and the 3 mm wire screen mesh with porosity 0.76 is placed at the same distance from the first screen.

2.8 Drive System

The drive system compensates the loss in the circuit and determines the movement of the fluid through the test section. For an air tunnel, two primary drive systems are a compressor and fan. In our case, an Axial fan will be used as these are high efficient and produce air flow with less turbulence. After the maximum required fan static pressure and volume flow rate have been estimated the maker's performance chart can be consulted to choose a fan with optimum efficiency, RPM and required power[14].

3. Losses in Wind Tunnel Circuit

For loss calculation, the tunnel can be divided into sections. The pressure loss in a tunnel section is defined as the mean loss of total pressure sustained by the stream, in passing through the particular section. The energy loss of each section can be written in dimensionless form as pressure drop coefficient $k_i = \frac{\Delta P_i}{q_0}$ (2)

Where, q_0 is test section dynamic pressure given as

$$q_0 = \frac{1}{2}\rho_0 V_0^2 \quad (3)$$

The losses in different parts of wind tunnel can be calculated as below:

3.1 Pressure Losses in Constant Area Sections

Considering a constant-area section (A), the pressure loss (p) along the duct is proportional to its length (L), hydraulic diameter (D_h), fluid density (ρ) and constant of proportionality is the friction factor (f). The loss coefficient is given by, $k_l = f\frac{L}{D_h}$. (4)

The friction loss coefficient can be determined by using universal law of friction to determine the friction factor in 4 to 6 iterations with an initial value of 1. In Equation is given as: $f_{i-1} = \left[2\log_{10}\left(R_e\sqrt{f_i}\right) - 0.8\right]^2$ (5)

3.2 Pressure Loss in Diffuser

Pressure loss in the diffuser is due to the skin friction loss and the expansion loss. The main parameters are equivalent conical expansion angle (θ_e) and the ratio between inlet and outlet cross section areas (A_r). The loss coefficient is the sum of the two loss factors, the first relates to friction and the second to expansion

$$k_d = k_f + k_{exp} \quad (6)$$

For one dimensional flow, the frictional loss coefficient is given as $k_f = \left(1 - \frac{1}{A_r^2}\right)\frac{f}{8\sin\theta_e}$ (7)

and the expansion loss is calculated by the empirical relationship $k_{exp} = k_e(\theta_e)\left(\frac{A_r - 1}{A_r}\right)^2$ (8)

The term $k_e(\theta_e)$ can be expressed as a geometrical function depending upon the expansion angle and the cross section shape of the diffuser. In our case $\theta_e > 5^0$, so $k_e = A3 + B3\theta_e$, (9)

for circular section the values of A3 and B3 are -0.0966 and 0.04672 respectively. For square section the values of A3 and B3 are -0.0132 and 0.05866 respectively. Figure 9 shows the variation of pressure loss coefficient with area ratio for different diffusion angle.

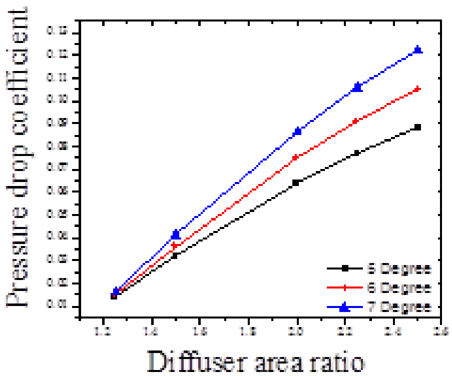

Figure 9. Plot showing the pressure drop for various diffusion angle.

3.2 Contraction Section Loss

The pressure loss in contraction is due to skin friction. The loss coefficient in the contraction is given by[15]:

$$k_c = \frac{f}{4}\frac{L_0}{D_i - D_0}\left(1 - \frac{D_0^{\,4}}{D_i^{\,4}}\right) \quad (10)$$

Where, L_0 is the length of contraction, D_0 the test section diameter, D_i the inlet cone diameter, and f is friction coefficient.

3.2 Stilting Section Loss

The losses in the settling chamber are primarily due to the honeycomb and screens used for turbulence reduction. The loss in the honeycomb can be calculated from the formula

$$k_h = \lambda_h\left(\frac{L_h}{D_h} + 3\right)\left(\frac{1}{\beta_n}\right)^2 + \left(\frac{1}{\beta_n} - 1\right)^2 \quad (11)$$

Where

$$\lambda_h = \begin{cases} 0.375\left(\frac{\Delta}{D_h}\right)^{0.4} R_{e\Delta}^{\;-0.1}, & R_{e\Delta} < 275 \\ 0.214\left(\frac{\Delta}{D_h}\right)^{0.4}, & R_{e\Delta} > 275 \end{cases} \quad (12)$$

The screen loss coefficient can be calculated

$$k_m = k_{mesh} k_{Rn} \sigma_s + \frac{\sigma_s^{\,2}}{\beta_s^{\,2}} \quad (13)$$

σ_s Is screen solidity and β_s is the screen porosity. k_{mesh} is the mesh factor equal to 1.0 for new metal wire , 1.3 for average circular metal wire, and 2.1 fir silk thread and k_{Rn} is given as

$$k_{Rn} = \begin{cases} 0.785\left(1 - \frac{R_{ew}}{354}\right) + 1.01, & 0 \le R_{ew} < 400 \\ 1, & R_{ew} \ge 400 \end{cases}$$

(14)

From the Equations it is clear that the pressure drop through the honeycomb and the screen depends only upon the characteristics of the same and becomes constant when the Reynolds number values exceed some critical value. Honeycomb loss depends on L/D ratio of honeycomb and porosity while the pressure drop through the screen is dependent on the type of wire and the porosity.

4. Power required in Wind Tunnel

Power required for maintaining a steady flow through the wind tunnel is equal to the total losses occurring in the flow through the tunnel. These losses are due to kinetic energy being dissipated by vortices and turbulence. The loss in kinetic energy, which appears as a decrease in total pressure must be compensated by a pressure rise, usually provided by a fan. Thus if the power input to the fan is P (i.e. the motor shaft output) and the fan has an efficiency η the equation balancing the energy input to the stream to the energy losses in the tunnel is $\eta P = \Sigma circuit\ loses$

(15)

The required power for a given section size and flow conditions depends on the sum of the pressure drop coefficient (k_i) in the individual tunnel sections. The pressure loss equation for subsonic flow in wind tunnel is given as $\eta P = \frac{1}{2}\rho_0 V_0^{\,3} A_0 \Sigma k_i$ (16)

In the designed tunnel the various loss coefficient are given in Table 1, for a speed of 25m/s at the test section.

Speed at fan section: = (25*0.5*0.5)/ (0.25*3.142*.75*.75)

= 14.144 m/s

The pressure loss in the tunnel circuit is equal to:

= $(\frac{1}{2}\rho_0 V_0^{\,2})$ Σk_i + loss at fan section (17)

= 0.5*1.225*25^2*1.3553 + 0.5*1.225*14.144*14.144

=641.36 Pa

Table 1. Tunnel pressure loss coefficient at test section velocity 25 m/s

Wind Tunnel Section	Loss coefficient
Honeycomb	0.2200
Screen 1	0.4117
Screen 2	0.6049
Contraction	0.0037
Straight section	0.149
Test Section	0.372
Diffuser	0.0629
Total	**1.3553**

The power required by the tunnel is equal to:

$$= Q * \Delta Pa = (A*V)* \Delta Pa \quad (18)$$

$$= (0.25*3.142*0.75^2*14.144)*641.36 = 4008.5 \text{ Watt}$$

The power required for given flow in the wind tunnel test section is calculated and the same is plotted as the tunnel performance curve. Figure 10 shows the tunnel performance curve for the designed wind tunnel. Fan performance curves, which are supplied by the fan manufactures, can be plotted on the tunnel performance curve and the fan with maximum efficiency that intersects the tunnel performance curve is to be chosen for use in the tunnel.

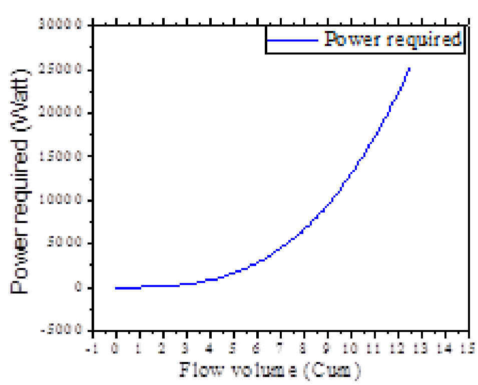

Figure 10. Tunnel performance.

5. Conclusion

The fan/motor to be fitted in the tunnel should be chosen conservatively to have desired flow velocity in the wind tunnel test section to cater the unseen losses in the tunnel. Further due to the purely empirical design of wind tunnel, as per the guidelines of the previous researchers, the design is required to be verified computationally as well as experimentally. First the tunnel design is to be tested for the desired flow quality and pressure loss in the tunnel computationally through any high-end simulation software (ABAQUS or ANSYS) if satisfactory results are found then the wind tunnel can be built. Before carrying out any experiment, the wind tunnel performance is to be tested and calibrated.

To ensure good performance of the structures subjected to wind loads, their behavior must be anticipated in advance by the design engineer[16]. Model studies through wind tunnel facilitate the same for the intended structure. So it is a useful tool in wind engineering.

6. References

1. Cattafesta L, Bahr CJ, Mathew J. Fundamentals of wind-tunnel design. Encyclopedia of Aerospace Engineering; 2010 Dec. p. 1–10.
2. Roy S, Saha UK. An adopted blockage factor correlation approach in wind tunnel experiments of a Savonius-style wind turbine. Energy Conversion and Management. 2014; 86(6):418–27.
3. Arifuzzaman, MM. Design construction and performance test of a low cost subsonic wind tunnel. IOSR Journal of Engineering. 2012 Oct; 2(10):83–92.
4. Barlow JB, Rae WH, Pope A. Low-speed wind tunnel testing. 3rd Ed. Wind Tunnel Design. United States of America: John Willey and Sons Publ; 1999.
5. Abdalhamed AS, Yassen YEl-S, Elssaka MM. Design optimization of three dimensional geometry of wind tunnel contraction. Ain Shams Engineering Journal. 2015 Mar; 6(1):281–8.
6. Fang FM, Chen JC, Hong YT. Experimental and analytical evaluation of flow in a square to square wind tunnel contraction. Journal of Wind Engineering and Industrial Aerodynamics. 2011 Mar; 89(3-4):247–62.
7. Mehta RD, Bradshaw P. Design rules for small low speed wind tunnels. The Aeronautical Journal. 1979 Nov; 83(827):443–9.
8. Building a wind tunnel: It will blow your mind. 2008. Available from: http://www.tomcarlone.com/Wind TunnelProject/WindTunnelReport.pdf
9. Gharbanian K, Soltani MR, Manshadi D. Experimental investigation on turbulence reduction in subsonic wind tunnels. Aerospace Science and Technology. 2011 Mar; 15(2):137–47.

10. Mehta RD. Turbulent boundary layer perturbed by a screen. AIAA Journal. 1985 Sep; 23(9):1335–42.
11. Quiterio PR, Velazquez MT, Eslava GT, Eslava RT, Florencio SS, Francis JA. Wind tunnel at LABINTHAP (Updated). Energy and Power Engineering. 2011 Sep; 3(4):565–73.
12. Groth J, Johansson AV. Turbulence reduction by screen. Journal of Fluid Mechanics. 1988 May; 197:139–55.
13. Gharbanian K, Soltani MR, Manshadi MD. Experimental investigation on turbulence reduction in subsonic wind tunnels. Aerospace Science and Technology. 2011 Mar; 15(2):137–47.
14. Bleier FP. Fan handbook: Selection application and design. New York: McGraw Hills Publications; 1998.
15. D Space. 2016. Available from: https://en.wikipedia.org/wiki/DSpace
16. Kumar BD, Swami BLP. Wind effects on tall building frames-influence of dynamic parameters. Indian Journal of Science and Technology. 2010 May; 3(5):583–7.