Chapter 7

On Aerodynamic Analysis of Wind Tunnel Component Design

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Abstract: This paper deals with a procedure for the design of low speed wind tunnel and aerodynamic analysis. Closed circuit wind tunnel is designed with a test chamber of (500mm×500mm) square cross section in which flow velocity is about 30m/s along its axis. Test chamber dimensions, maximum wind speed and Reynolds number are calculated after defining the design targets. Both open and closed test section configurations are used to perform best circuit and axial fan matches. The possible wind tunnel running conditions are predicted by the matching procedure.

Keyword: Adapter, flanges, honeycomb, Mesh factor, porosity, Reynolds number, vane number, wind tunnel

I. INTRODUCTION

Criteria for wind tunnel design and implementation to specific case study is presented in this paper. To study aero foil aerodynamic analysis, closed loop wind tunnel is designed with definitive dimensions of 10.49m x 3.65m. It consists of a square test chamber of (500mm x 500mm) four corners and two diffusers. An axial fan is used for mass flow rate and balance the pressure loss in whole circuit.

To eliminate any transverse flow, a settling chamber (SC) with a honeycomb is used and to reduce turbulence, a series of ever-finer mesh screens is used. To accelerate the flow in test chamber, a nozzle is used.

Wind tunnels are major tools to study gas flows around a body and forces generated by the gas body interaction. Air is used for most parts in wind tunnels. With the advent of such tools now it became possible to measure global and local flow velocities, pressure and temperature around the body. Components of wind tunnel are designed in such a way to ensure the chamber as much as possible uniform in space and remains independent of time air flow.

Global dimensions of wind tunnel is primarily depends on the type of testing. As a result Reynolds number can be calculated. Wind tunnel components are designed in accordance to test chamber dimensions and wind tunnel test type.

Wind tunnels can be bifurcated into:
- Open circuit wind tunnel (OCWT)
• Closed circuit wind tunnel (CCWT)
  Also wind tunnel test section can be divided into
• Open WTTS
• Closed WTTS

A straight path is followed by the air flowing in an OCWT. The air recirculates continuously with no air leakage in a closed return wind tunnel. Open return wind tunnel requires low construction costs and can visualize the flow using smoke without needing to purge the tunnel. Disadvantages of OCWT include high noise level, more energy and to mount extensive screens to obtain high quality flow which in turn can also cause environmental problems. But CCWT are independent of weather conditions and other activities involved in building. Also it has high quality flow. Moreover, it requires less energy in comparison to OCWT and creates less noise. But it has disadvantages also like high construction costs, purging after flow visualization with the help of smoke and requires heat exchanger. Open test section gives best results with CCWT.

**DESIGN OF CCWT**

The first step of wind tunnel design is closely related to the shape of the chamber and dimensions used for the chamber which in turn depends on the type of intended tests. Wind tunnel dimensions depends on the cross section of test chamber. Bigger the test chamber cross-section, greater will be the wind tunnel dimensions. Necessary fan power is acquired by the dimensions of the test chamber, air velocity and type of wind tunnel. All these factors paly key role in the design of CCWT.

**Primary objective**

The main objective of WT design is to obtain the uniform flow in the test chamber. It can be possible with a big test chamber with very high air velocity. The main components of a CLWT are depicted in fig -10. In wind tunnel, the key dimensionless parameter is Reynolds number. For models exhibiting dynamic similarity, the forces and moments on full scale models can be obtained by scaling the force and moment data. Thus it is forced to accept the largest Reynolds number which can be achieved in the test section. Reynolds number also depends on the experiment of interest, which may or may not harm the validity of the result. A closed circuit facility is used when working fluid is not the ambient fluid, for instance, pressurized air, or water and properly sealed to avoid leakage.
Components of wind tunnel

In this case, a square test chamber of 0.5m with an air velocity of 30m/sec is used. Hydraulic diameter is calculated form the testing section as –
Where “a” denotes the cross-section area

Length of test chamber is 0.5-3 times of its hydraulic diameter. Advantage of taking this value is that the air flow existing the nozzle needs 0.5 times hydraulic diameter to become completely uniform.

In order to increase the boundary layer thickness, a long test chamber of more than 3 times the equivalent hydraulic diameter can be used which can detach the boundary layer at the test chamber exit. In the present case, length of testing chamber is taken twice the hydraulic diameter of testing section. Sharp edges of test chamber should be rounded off to avoid air velocity reduction and increase in boundary layer thickness. To introduce measuring tools and allow sample observations, test chamber with flanges and windows are used.

**Test chamber nozzle**

Nozzle is used to accelerate the flow from the settling chamber to the test section. The most difficult component of wind tunnel whose design is very difficult is “nozzle”. Reason being flow velocity and its uniformity directly depends on the design of nozzle within the test chamber cross section. Cross section dimensions of nozzle and shapes are similar to the test chamber because they are joined together. Nozzle also consists of 45° chamfers.

Inlet cross section can be predicted by knowing the nozzle exist cross section dimensions and shape. To reduce the total pressure loss through the screen, it is placed between the SC and nozzle. Furthermore the nozzle area should be very large. Generally, range of 6-10 is preferred for nozzle inlet/outlet cross section area ratio. If area ratio greater than 10 is chosen, then it leads to excessive inlet dimensions while less than 6 area ratio leads to high pressure loss through the screens.

In the present study, area ratio of 7 is taken. The nozzle silhouette with the inlet and outlet nozzle cross section is defined by fifth order Bell-Metha polynomials.

Mathematically it can be represented as

\[
y = ax^5 + bx^4 + cx^3 + dx^2 + ex + f \tag{2}
\]

Where \( x = \frac{x}{L} \) and \( L \) is the total axial nozzle length and \( y = h \), where \( h \) = half of the cross section side length \( (value\ of\ x\ lies,\ 0 \leq x \leq L) \)

Boundary conditions are used to determine the Bell Metha polynomial coefficients as

\[
x = 0 \rightarrow y = y_0 \\
x = 1 \rightarrow y = y_1
\]
\[ x = 1 \rightarrow \frac{dy}{dx} = 0 \]
\[ x = 0 \rightarrow \frac{d^2y}{dx^2} = 0 \]
\[ x = 1 \rightarrow \frac{d^2y}{dx^2} = 0 \]

Fig. 5.2 Shape of nozzle

**Shape of nozzle**

Total length and double semi side length of nozzle inlet cross-section should be equal to as depicted in fig3.

\[ \frac{L}{2y_0} \approx 1 \quad (3) \]

It has been shown experimentally that the \[ \frac{L}{2y_0} \] ratio less than 0.667, detach air flow close to the nozzle exit, where as boundary layer thickness is increased by a value greater than 1.79. In the present case ratio of \[ \frac{L}{2y_0} \] is set to 0.91 to obtain a nozzle length of 1.3. Sharp edges of nozzle’s outlet should be rounded off with 45° chamfers, in order to connect the testing section. Under construction nozzle is shown in fig.3.
Design of diffusers

To design second diffuser, it is necessary to find out the inlet cross-section area and exit should be equal to the nozzle inlet cross section area. Fan dimensions decides the second diffuser inlet cross section area. Hence it is necessary to design the fan in the beginning.

As it is well known that the ratio between the fan cross section area $a_f$ and the test chamber cross section area $a_{ts}$ should be in the range of 2-3.

Value greater than 3 is not preferred because it can create irregular flow velocities at the fan entrance. Value less than 2 is also not favorable because it can increase overall wind tunnel dimensions which in turn causes higher wind tunnel construction costs.

Ratio value of 2 is best suited to maintain low wind tunnel dimensions and costs. In this case, ratio 2 is used.

Air velocity at the fan exit can be determined by using equation (4) as

$$v_f = \frac{1}{2} v_{ts} \tag{4}$$

Diameter of fan cross section can be estimated from the area ratios which is 0.800m in the present case. Inlet cross section area of second diffuser is equal to the cross section area of fan and outlet cross section area of diffuser is equal to the nozzle’s inlet. While designing the process, these values should be known.

The equivalent cone expansion angle can be find out using the hydraulic diameters of the inlet and outlet diffuser cross-section as

$$\phi = \arctan \left( \frac{\sqrt{\frac{a_r-1}{a_i}}}{d_{hi}} \right) \tag{5}$$

where $d_{hi}$ = hydraulic of inlet section

Value of cone expansion angle is chosen 3° to avoid a very long diffuser. Solution of equation (5) for L helps to calculate the minimum diffuser length. In this test case this value is 6.58m.
As it is clear from the fig. (5) that the cross-section of diffuser is circular and similar to fan’s cross section but outlet cross section is square. Furthermore, second diffuser acts as a shape adapter.

To connect the second diffuser with other wind tunnel parts, flanges are used. To match the fan and other wind tunnel components with small corner, another shape adapter is connected to the fan inlet section. Shape adapter of length 0.3 m is used between the fan and smaller corner.
Fig. 5.5 3D fig. of shape adapter

Shape and inlet cross section area of first diffuser are already known because they are equal to the test chamber’s and outlet cross section area is equal to the inlet fan cross section area. To determine the side $l_{out}$ of the outlet cross section equation (6) is used because the fan inlet cross section is round and first diffuser’s is square.

$$l_{out} = \frac{\theta L}{2} \sqrt{\pi}$$  \hspace{1cm} (6)

This value comes out to be 0.710 m in this case. The first diffuser length equals to 3.32 m with a maximum total cone angle of 4°.
Design of small and large corners:-

In this CLWT, flow is deflected with an angle of 90° four times at the four corners with minimum turbulence. This is the reason why corners are equipped with blades or bent flat plates which comes out to be more economical.
Dimensions of corner matches with the related wind tunnel components. Hence corners are made equal in pairs.

Cross section of corners one and two are equal to the cross section outlet of first diffuser. At leading edges, the bent flat plates are set to 5° and the trailing edges to 0°. So the bent flat plate’s chord is determined for 85° as shown in fig.(8). Value of chord can be calculated by the ratio between the corner section width and the choice of corner division.

A vane number of 25 gives appropriate results. A vane gap \( V_g \) of \( 2.84 \times 10^{-2} \) m is obtained by using the first diffuser outlet cross section where \( l = 0.710 \) m

\[
V_g = \frac{l_{out}}{25} (7)
\]

Chord ratio of vane gap should be less than 0.25 and the minimum chord value can be determined using the equation given below –

\[
c_r = \frac{V_g}{0.25} \quad (8)
\]

and value of \( c_r = 0.1136 \) obtained.

The minimum bent flat plate radius can be determined using equation (9) as

\[
r_c = \frac{c_{r_{min}}}{2}, \frac{1}{\sin^2 \theta} \quad (9)
\]

where \( c_{r_{min}} \) represents chord

\( r_c \) = radius of bent flat plate curvature.

\( \theta \) = Central angle subtended by the chord.

24 blades are needed for cleaning and maintenance and could be installed on a removable frame.
Corners and blades are shown in fig (a) and (10) respectively.

Fig 5.8, 3D corner

Fig 5.9 3D turning vanes
Large corners 3 and 4 can be designed by making use of criteria of corners one and two. They have a square cross section. Equation (20) can be used to calculate vane gap with ¾ side length as 1.320m in the case.

A vane number of 25 is also appropriate in the ¾ corner design

\[ h_{3,4} = \frac{l_{out}}{25} \]  

(10)

In the case study, value of vane gap obtained is 5.28 \(10^{-2}\) m with ¾ corner data.

Using equations (11) & (12) the minimum chord value and minimum blade curvature radius can be calculated as in corners one and two

\[ C_{r_{3,4,min.}} = \frac{h_{3,4}}{0.25} \]  

(11)

\[ r_{c_{1,2}} = \frac{c_{r_{3,4}}}{2} \cdot \frac{1}{\sin^2 \theta} \]  

(12)

Considering the overall dimensions, value obtained are

\[ C_{r_{3,4}} = 0.211\text{m} \]

\[ r_{c_{1,2}} = 0.156\text{m} \]

**Constant cross sectional settling chamber (SC)**

The main objective of settling chamber is to degrade the flow turbulence before entering the nozzle. Joined with fourth corner, there is a settling chamber with a constant cross sectional area.

![Fig.5.10, 3D settling chamber](image)

Cross sectional area of settling chamber matches with the dimensions of other components of wind tunnel to which it is joined. Whereas length of settling chamber is designed to fit the
gap between the components that are close to the wind tunnel loop. In the present case, total length of settling chamber is 2.070m and it is capable of containing one honeycomb and three screens

**Reduction in fluctuating variations**

Honeycomb is used to reduce the fluctuating variations with its cells aligned in flow direction in transverse velocity. As the pressure drop through a honeycomb is small so the honeycomb has less effect on stream wise velocity.

**Key factors in the honeycomb design:**

- Length
- Cell hydraulic diameter
- Porosity

Honeycomb porosity = actual flow cross section/total cross section area

\[ h_p = \frac{A_a}{A_t} \] (13)

In wind tunnel honeycomb design two main criteria which are to be verified:-

\[ \sigma \leq \frac{L_h}{d_h} \leq 8 \]
\[ h_p \geq 0.8 \]

Where \( L_h \) = length
\( d_h \) = Hydraulic diameter

**Table 9 Characteristics of honeycomb:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
<th>UOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell diameter</td>
<td>( d_h )</td>
<td>9</td>
<td>Mm</td>
</tr>
<tr>
<td>Sheet metal thickness</td>
<td>( s_h )</td>
<td>0.06</td>
<td>Mm</td>
</tr>
<tr>
<td>Roughness</td>
<td>( \Delta )</td>
<td>15</td>
<td>Mm</td>
</tr>
<tr>
<td>Length</td>
<td>( L_h )</td>
<td>62</td>
<td>Mm</td>
</tr>
</tbody>
</table>
Fig. 5.11 Structure and symbol of hexagonal honeycomb

Cell side of honeycomb can be calculated by eqn. (16) as in fig. (12)

\[ l_{ch} = \frac{d_h}{2\sin\frac{\pi}{2}} \]  

(16)

Calculation of external cell side can be done as,

\[ l_{eh} = l_{ch} + \frac{2s_h}{\tan60^\circ} \]  

(17)

Sheet divisions (z) of the metal can be determined with eqn. (18)

\[ z = 2l_{ch} + l_{eh} \]  

(18)

A single division is taken into consideration while calculating the honeycomb’s area. A single division comprises of two twin area parallelograms and two twin area trapezes as shown as in fig.(12) and the area can be find out using equations (19) & (20)

\[ A_{\text{paral.}} = l_{ch}S_h \]  

(19)

\[ A_{\text{trap.}} = \frac{(l_{ch} + l_{eh})S_h}{2} \]  

(20)

In context to measure the honeycomb porosity, number of divisions according to height and length must be calculated firstly. Former and latter is given by the area ratios as:-

\[ N_z = \frac{L_1}{2} \]  

(21)

Where \( L_1 \) = height of settling chamber cross-section and the latter is given by the ratio settling chamber cross section width \( L_2 \) and the sum of \( \frac{d_h}{2} \) and \( s_h \) as,

\[ N_{\text{sheet}} = \frac{L_2}{\frac{d_h}{2} + s_h} \]  

(22)

Value of \( L \) should be equal to \( L_1 \) and \( L_2 \) for a square cross-section. Honeycomb metal sheet cross section area can be evaluated as

\[ A_{\text{sheet}} = 2(A_{\text{paral.}} + A_{\text{trap.}})N_zN_{\text{sheet}} \]  

(23)

Solidity of honeycomb is given by,

\[ \sigma_{hs} = \frac{\text{cross section area occupied by the metal sheet}}{\text{cross − section area of settling chamber}} \]

\[ \sigma_{hs} = \frac{A_{\text{sheet}}}{A_{\text{total}}} \]  

(24)

As it clear that eqn. (13) and (24) are complementary to each other their sum is an identity.

\[ h_p + \sigma h_s = 1 \]  

(25)

Criterion of equation (14) can be verified by calculating the honeycomb cell hydraulic diameter starting with the honeycomb cell area.
Imposing the same area of equivalent circle, the honeycomb cell hydraulic diameter can be calculated as –

\[ \pi D_{hs}^2 = \frac{3 d_h^2}{2 \sqrt{3}} \]  \hspace{1cm} (27)

\[ D_{hs} = d_h \sqrt{\frac{6}{\pi \sqrt{3}}} \]  \hspace{1cm} (28)

**Table 10. Main parameter of test case honeycomb**

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>SYMB</th>
<th>VAL</th>
<th>UOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honeycomb cell side</td>
<td>( l_{ch} )</td>
<td>5.20</td>
<td>Mm</td>
</tr>
<tr>
<td>External cell side</td>
<td>( l_{eh} )</td>
<td>5.26</td>
<td>Mm</td>
</tr>
<tr>
<td>Divisions</td>
<td>( Z )</td>
<td>15.66</td>
<td>Mm</td>
</tr>
<tr>
<td>Divisions height-wise</td>
<td>( N_z )</td>
<td>84.3</td>
<td>-</td>
</tr>
<tr>
<td>Divisions width-wise</td>
<td>( N_{sheet} )</td>
<td>289.47</td>
<td>-</td>
</tr>
<tr>
<td>Honeycomb solidity</td>
<td>( \sigma_{hs} )</td>
<td>1.75</td>
<td>-</td>
</tr>
<tr>
<td>Honeycomb porosity</td>
<td>( h_p )</td>
<td>0.9825</td>
<td>-</td>
</tr>
<tr>
<td>Cell hydraulic diameter</td>
<td>( Z_h )</td>
<td>9.45</td>
<td>Mm</td>
</tr>
<tr>
<td>Length – hydraulic diameter ratio</td>
<td>( \frac{L_h}{D_h} )</td>
<td>6.56</td>
<td>-</td>
</tr>
</tbody>
</table>

**Main parameter of test case honeycomb**

Equation (24) is verified because the value of length/hydraulic diameter ratio lies in between 6 and 8. Criterion of equation (25) is also verified because value of honeycomb porosity is
greater than 0.8. In this way, verified criteria shows that the chosen honeycomb is best suitable for the designed wind tunnel.

**Mesh density and porosity of screens**

As it is well known that a series of screens with different mesh qualities like coarse and medium etc. is more efficient in comparison to only one five screen. Stream wise velocity fluctuations are greatly reduced by the screens with little impact on flow direction. For effective screen porosity range should be 0.58 to 0.8.

\[
0.8 \leq h_s \leq 0.8 \quad (29)
\]

If the value of screen porosity is greater than 0.8, then it is not suitable for turbulence control and if the value is less than 0.58, then it may cause the flow instability. It is clear that for cleaning and maintenance purpose, screens could be installed on a removable frame.

Area possessed by the screen wire can be evaluated as

\[
n_m l d_w + n_m l d_w - n_m (n_g d^2 w) \quad (30)
\]

Where

\[d_w = \text{diameter of wire}\]

\[n_m = \text{generic wire number in mesh}\]

\[l = \text{Side of settling chamber cross section}\]

![Sample of screen](image)

**Fig.5.12 Sample of screen**

We know that

\[
h_s = \frac{A_g}{A_t} = \frac{t^2 - 2n_m l d_w + n_m^2 d_w^2}{t^2} = 1 - 2n_m \frac{d_w}{l} + \frac{n_m^2 d_w^2}{l^2} \quad (31)
\]

\[
h_s = (1 - \frac{n_m d_w}{l})^2 \quad (32)
\]

It is well known that mesh density is given by
\[ \rho_m = \frac{n_m}{l} \]  
(33)

Screen mesh density in a region is defined as the ratio between the mesh wire number and the cross-section side of the chamber. Screen mesh division is the inverse of mesh density as depicted in fig. 13 and given by equation (34) as

\[ W_m = \frac{1}{\rho_m} \]  
(34)

Porosity in terms of screen mesh density is given by

\[ h_s = (1 - d_w \rho_m)^2 \]  
(35)

The main screen characteristics for the present case is shown in table-3

**Table. 11 Characteristics of main screen**

<table>
<thead>
<tr>
<th>Description</th>
<th>SYMB</th>
<th>UOM</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh wire diameter</td>
<td>(d_w)</td>
<td>Mm</td>
<td>0.7</td>
<td>0.56</td>
<td>0.15</td>
</tr>
<tr>
<td>Mesh divisions</td>
<td>(W_m)</td>
<td>Mm</td>
<td>3.2</td>
<td>2.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Screen porosity</td>
<td>(h_s)</td>
<td>-</td>
<td>0.61</td>
<td>0.60</td>
<td>0.61</td>
</tr>
</tbody>
</table>

**Wind tunnel (WT) pressure:** -

In the study of closed loop wind tunnel (CLWT), each wind tunnel section is considered separately. Pressure losses in wind tunnel occurs due to pressure loss in different sections. Net pressure loss of closed loop wind tunnel becomes equal to the pressure gain due to the fan.

Pressure loss (\(\Delta P_j\)) for a wind tunnel component \(j\) can be defined as the product of dynamic pressure at the entrance of the component and constant \(K_j\) as,

\[ k_j = \frac{\Delta P_j}{\frac{1}{2} \rho \bar{C}_j^2} \]  
(36)

Where \(\bar{C}_j\) = mean flow velocity in the wind tunnel section. Pressure loss along the duct in a constant area of section is given by

\[ \frac{\Delta P}{\rho} = \frac{f L}{d_h} \left( \frac{C^2}{2} \right) \]  
(37)

Where \(\Delta P = \) pressure loss

\(d_h = \) hydraulic diameter

\(\rho = \) density

\(L = \) length,

\(C = \) mean flow velocity

\(f = \) friction factor
Using equations (36) & (37), relation of loss coefficient to the duct geometry is given by.

\[ K_L = f \frac{L}{d_h} \]  

(38)

Where \( K_L \) = loss coefficient

Prandtl universal law is more suitable at high Reynolds number for smooth pipes to calculate the friction factor,

\[ f_{i+1} = \left\{2 \log_{10} \left(Re \sqrt{f_i} \right) - 0.8 \right\}^2 \]

Where \( Re \) (Reynolds no.) = \( \frac{\rho c d_h}{\mu} \)

**Calculation of pressure loss in diffusers:**

In calculation of pressure loss in diffusers, loss of energy due to friction must be taken into consideration.

Main parameters:-

1). Conical expansion angle
2). Ratio of inlet and outlet cross-section area

In the present study, loss coefficient can be expressed as the sum of two terms,

\[ K_D = K_F + K_{\text{expansion}} \]  

(40)

Where \( K_F \) = loss coefficient due to friction

\( K_{\text{expansion}} \) = Loss coefficient due to expansion.

Constant friction factor and density is produced with the stream in one dimensional flow and given by

\[ K_F = \left(1 - \frac{1}{\pi r}\right) f \frac{\sin(\varepsilon_e)}{\sin(\varepsilon_e)} \]  

(41)

Where \( A_r \) = ratio between inlet and outlet cross-section areas. To calculate expansion loss coefficient, the empirical expression used is,

\[ K_{\text{expansion}} = K_e(\varepsilon_e) \left(\frac{A_f-A_r}{A_r}\right)^2 \]  

(42)

Where \( K_e(\varepsilon_e) \) represent geometrical function. W.T. Eckert proposed the value of \( K_e \) for circular and square cross-section as given in table 5.4

\[
(K_e)_{\text{circular}} = \begin{cases} 
 a_1 + b_1 \varepsilon_e & \text{if } 0 \leq \varepsilon_e \leq 1.5^\circ \\
 a_2 + b_2 \varepsilon_e + c_2 \varepsilon_e^2 + d_2 \varepsilon_e^3 + e_2 \varepsilon_e^4 + f_2 \varepsilon_e^5 + g_2 \varepsilon_e^6 & \text{if } 1.5^\circ \leq \varepsilon_e \leq 5^\circ \\
 a_3 + b_3 \varepsilon_e & \text{if } \varepsilon_e > 5^\circ 
\end{cases}
\]
Corner pressure loss:-

Two ways to minimize the pressure loss

- Using efficient blade section
- Using appropriate chord to gap ratio

Corner loss coefficient can be calculated as:

\[
(K_e)_{square} = \begin{cases} 
  a_1 + b_1 \varepsilon_e & \text{if } 0 \leq \varepsilon_e \leq 1.5^\circ \\
  a_2 + b_2 \varepsilon_e + c_2 \varepsilon_e^2 + d_2 \varepsilon_e^3 + e_2 \varepsilon_e^4 + f_2 \varepsilon_e^5 + g_2 \varepsilon_e^6 & \text{if } 1.5^\circ \leq \varepsilon_e \leq 5^\circ \\
  a_3 + b_3 \varepsilon_e & \text{if } \varepsilon_e > 5^\circ 
\end{cases}
\]

Screen and Honeycombs pressure loss (HPL)

For security purpose, screen is placed just before the fan section in wind tunnels. As this is a high velocity section, so it affects the pressure loss greatly. All screens are treated equally in terms of energy loss.

Screen loss coefficient depends on

- Porosity
- Reynolds number with wire diameter
- Mesh factor

Screen loss coefficient can be calculated as:

\[
K_s = K_{mesh} K_{Rn} \sigma_s \left( \frac{\sigma_s^2}{h_s^3} \right) \tag{46}
\]

Where

\[
K_{Rn} = \begin{cases} 
  0.785 \left( 1 - \frac{Re_w}{354} \right) & 0 \leq Re_w < 400 \\
  1.0 & Re_w \geq 400
\end{cases}
\]

To calculate pressure loss in honeycomb it is necessary to calculate the three main parameters:

- Stream wise length to cell hydraulic diameter ratio
- Porosity
- Reynolds number with cell hydraulic diameter

Relation used is

\[
K_{honey} = h \left( \frac{L_h}{dh} \right) \left( \frac{1}{h_p} \right)^{2} \left( \frac{1}{h_p} - 1 \right)^{2} \tag{47}
\]
\[ h = \begin{cases} 
0.375 \left( \frac{\Delta}{d_h} \right)^{0.4} Re_{\Delta}^{-0.1} & \text{if } Re_{\Delta} \leq 275 \\
0.214 \left( \frac{\Delta}{d_h} \right)^{0.4} Re_{\Delta} & \text{if } Re_{\Delta} > 275 
\end{cases} \]

Where \( Re_{\Delta} = \) denotes the Reynolds number depends on material roughness & \( d_h = \) cell hydraulic diameter.

**Nozzle pressure loss:**

Skin friction is responsible for pressure loss. Nozzle pressure loss comprises of 3% of total loss. As the errors evaluating are less significant in comparison with high velocity and tunnel sections, so the approximate expression used is,

\[ K_n = 0.32 f_{avg.} \left( \frac{L_n}{d_n} \right) \]

Where \( K_n = \) Nozzle pressure loss & \( L_n = \) nozzle length & \( d_n = \) hydraulic diameter of settling chamber & \( f_{avg} = \) average friction factor.

**Losses in case study:**

Pressure drop is responsible to produce the total pressure drop which is 141.50 Pa in present case and must be compensated by the fan of wind tunnel. Pressure drop corresponding to each wind tunnel component is depicted in table 5.4.

**Table 12 Circular and square cross- sections \( K_e \) parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Circular</th>
<th>Square</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_1 )</td>
<td>0.1033</td>
<td>0.09623</td>
</tr>
<tr>
<td>( b_1 )</td>
<td>-0.02389</td>
<td>-0.004152</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>0.1709</td>
<td>0.1222</td>
</tr>
<tr>
<td>( b_2 )</td>
<td>-0.1170</td>
<td>0.04590</td>
</tr>
<tr>
<td>( c_2 )</td>
<td>0.03260</td>
<td>0.02203</td>
</tr>
<tr>
<td>( d_2 )</td>
<td>0.001078</td>
<td>0.003269</td>
</tr>
<tr>
<td>( e_2 )</td>
<td>-0.0009076</td>
<td>-0.0006145</td>
</tr>
<tr>
<td>( f_2 )</td>
<td>-0.0001331</td>
<td>-0.0000280</td>
</tr>
<tr>
<td>( g_2 )</td>
<td>0.0001345</td>
<td>0.00002337</td>
</tr>
<tr>
<td>( a_3 )</td>
<td>-0.09661</td>
<td>-0.01322</td>
</tr>
<tr>
<td>( b_3 )</td>
<td>0.04672</td>
<td>0.05866</td>
</tr>
</tbody>
</table>

**Table 13 Pressure loss of components at test section air speed of 30m/sec.**

<table>
<thead>
<tr>
<th>Components</th>
<th>( \Delta P ) (Pa)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed test Section</td>
<td>12.531</td>
</tr>
<tr>
<td>First Diffuser</td>
<td>33.429</td>
</tr>
<tr>
<td>Smaller Corner</td>
<td>22.33</td>
</tr>
<tr>
<td>Constant –Area Section</td>
<td>2.064</td>
</tr>
<tr>
<td>Smaller Corner</td>
<td>22.33</td>
</tr>
<tr>
<td>Adapter</td>
<td>0.616</td>
</tr>
<tr>
<td>Fan Screen</td>
<td>1</td>
</tr>
<tr>
<td>Fan Constant-Area Section</td>
<td>1.808</td>
</tr>
<tr>
<td>Second Diffuser</td>
<td>4.6</td>
</tr>
<tr>
<td>Larger Corner</td>
<td>1.965</td>
</tr>
<tr>
<td>Constant-Area Section</td>
<td>0.0215</td>
</tr>
<tr>
<td>Larger Corner</td>
<td>1.965</td>
</tr>
<tr>
<td>Settling Chamber</td>
<td>0.2134</td>
</tr>
<tr>
<td>Honeycomb</td>
<td>2.76</td>
</tr>
<tr>
<td>First Screen</td>
<td>10.25</td>
</tr>
<tr>
<td>Second Screen</td>
<td>10.86</td>
</tr>
<tr>
<td>Third Screen</td>
<td>11.31</td>
</tr>
<tr>
<td>Nozzle</td>
<td>1.47</td>
</tr>
<tr>
<td>Total pressure loss</td>
<td>141.5</td>
</tr>
</tbody>
</table>

Ideal pressure values without energy loss and real pressure values with energy loss in wind tunnel section can be estimated by taking into account the loss coefficient, pressure drop in wind tunnel section and assuming null relative pressure in the testing section as,

\[ P - P_0 = \frac{1}{2} \rho (u_0^2 - u^2) \]

\[ P - P_0 = \frac{1}{2} \rho (u_0^2 - u^2) - \Delta P \]

Where \( \Delta P \) is denotes the pressure loss between the inlet and outlet cross-section of components correlated to \( K_t \) factors.
Fig. 5.13 Wind tunnel relative static pressure

Fig. 5.14 Wind tunnel cumulative static pressure

Fig (5.14) shows the ideal and real static pressure variations while incremental pressure loss is shown in fig. (5.15).

It is clear from the fig. (5.14) that in real case, pressure values are lower up to the fan section. Due to the energy gap in the fan section, real pressure curve becomes greater than the ideal one when fan is on. In the wind tunnel it balances the pressure losses.

Mostly losses takes place in the first section of diffuser and contribution of wind tunnel in pressure loss is shown in fig. (5.16) as,
Wind tunnel energy ratio (WTER)

The ratio between flow power in testing section and loss in power along the circuit due to pressure loss in all wind tunnel components is known as energy ratio.

Expression for energy ratio is given by,

\[
E_{ratio} = \frac{1}{\sum K_i \left( \frac{Q_i}{Q_{te}} \right)^2}
\]

Graph of energy ratio versus testing section air speed is plotted in fig. 17

Fig.5.16 Air speed in test section (m/s) versus ratio of energy

How wind tunnel energy efficiency depends on energy ratio can be explained by above mentioned graph. It is well known that energy ratio measures the wind tunnel energy efficiency and for CCWT, its value lies in between 3 and 7. The greater will be the energy ratio, the better will be the wind tunnel energy efficiency

Wind tunnel axial fan:

To generate the air motion within the wind tunnel circuits, fans are used and they are installed at the exit of the second corner as shown in fig. 1. The 1st mechanical characteristics of wind
tunnel in testing section is overall pressure drop as a function of air velocity. By making use of mass conversation equation, air velocity can be expressed as a function of the fan’s air flow rate in the test section. Mechanical characteristics are calculated for closed and open test section as depicted in fig. (5.18).

![Fig 5.17 Mechanical characteristics of wind tunnel](image)

Value obtained for friction factor \((f)\) is 0.08 for an open testing section. Axial fan mechanical characteristics are shown in fig 5.18.

![Fig 5.18 Mechanical characteristics of axial fan](image)

In this fig.5.18, pressure gain is a function of flow rate and for each specific fan rotational speed, different curves are drawn.

When both mechanical characteristics are combined on the same graph, then right fan matches the wind tunnel circuit by intersecting the curve as shown in fig. (5.19)
Fig. 5.19 Fan matching in wind tunnel

**Most suitable fan includes:**

- Efficiency of fan
- Flow rate
- Air velocity
- Cost

Volumetric flow rate and fan pressure gain can be determined by the intersection of different graphs.

To calculate air velocity corresponding to each rotational speed, mass conservation equation is used to control the electric current frequency and consequently the fan motor’s rotational speed and in this way the desired air velocity can be obtained.

From fig. (20), it is clear that the axial fan chosen for case study provides efficiency greater than 70% in wind tunnel. Imposing the matching conditions, an axial fan of 5.5 Kw with 1430 rpm is chosen for the present case as shown in fig. 5.20
In closed testing section air velocities 0 to 37m/sec. can be obtained from 0 to 1430 rpm and 0 -3 for open testing section.

To obtain CLWT, all the designed wind tunnel components are joined together in sequence as shown in fig. 5.21

**Conclusion:** In this paper much effort has been made to design a low velocity wind tunnel for the analysis of aerodynamics. CCWT with square test section of 500mm × 500mm along average flow velocity of about 30m/sec along its axis is used.
Components of wind tunnel are:-

- Square testing chambers
- Two diffusers (to slow down the flow)
- Corners with turning vanes
- Axial fans
- Settling chamber with honeycomb
- A series of mesh screens
- Nozzle

Following steps are followed in the design procedure:-

- To define the dimensions of test section
- Define desired flow velocity by test type using the criteria of test section.
- Calculation of components pressure loss in wind tunnel
- For both open and closed loop test section calculate the pressure loss as a function of flow velocity.
- Calculate the case study losses and energy ratios.

All components of wind tunnel are designed according to case study. More attention is paid in the design of nozzle because it affects the quality of flow like velocity, turbulence level and uniformity of velocity etc. Thus detailed designed work is carried out using Bell- Mehta polynomials and specific data is provided for the test case.

Proper fan choice can be made by following the design of components, pressure loss and energy considerations which are also necessary for matching procedure.

The matching procedure also provides the detailed information of wind tunnel behavior at different flow velocity. For the prediction of internal characteristics, flow velocity from 0 to 50 m/sec. is used in the present case.

For a desired flow velocity to establish the fan speed inverter and running condition of wind tunnel, matching procedure is taken into account. Wind tunnel build data are in excellent agreement with design procedure.

Efficacy and usefulness of the design process is also confirmed by the wind tunnel build data.

**LIST OF ABBREVIATIONS:**

CCWT- Closed Circuit Wind Tunnel
CLWT - Closed Loop Wind Tunnel
CWT – Components of Wind Tunnel
HPL – Honeycomb Pressure Loos
OCWT – Open Circuit Wind Tunnel
SC – Settling Chamber
WT – Wind Tunnel
WTTS – Wind Tunnel Test Section
WTER – Wind Tunnel Energy Ratio