Wind Tunnel Power Loss Calculation

Loss Calculation ①

Losses in a constant area section

For a fully developed pipe flow

$$\Delta P = f \cdot \frac{L}{D_h} \cdot \frac{1}{2}\rho V^2, \quad D_h = 2\sqrt{A/\pi}$$

= hydraulic diameter

f = friction factor

$= 4 c_f$.

∴ ~~Ko~~

The loss coefficient

$$K_0 = \frac{\Delta P}{q_t} = f \cdot \frac{L}{D_h} \frac{V^2}{V_t^2} = f\left(\frac{L}{D_h}\right) \cdot \left(\frac{V}{V_t}\right)^2$$

For Test section, $V = V_t$

$$\therefore \boxed{K_0 = f \cdot \frac{L}{D_h}} \quad \text{for test section.}$$

The magnitude of skin friction coefficient or friction factor, f, depends on

1. Nature of B.L
2. Reynolds number
3. Surface roughness

$$\therefore \quad c_f = f(Re, \text{roughness})$$
$$= f(Re) \quad \text{for smooth walls}$$

for smooth pipes at high Reynolds number, the prandtl universal law of friction

$$\frac{1}{\sqrt{f}} = 2\log_{10}\left(R_e\sqrt{f}\right) - 0.8 \qquad \text{—— ①}$$

where $R_e = \dfrac{\rho V_{cs} D_h}{\mu}$; V_{cs} is the mean speed in the section.

From eq^n (1) it can be observed that

$f = 0.013$ for $Re = 500,000 = 0.5 \times 10^6$

$f = 0.010$ for $Re = 2,500,000 = 2.5 \times 10^6$

$f = 0.007$ for $Re = 30 \times 10^6$

friction factor decreases with Re.

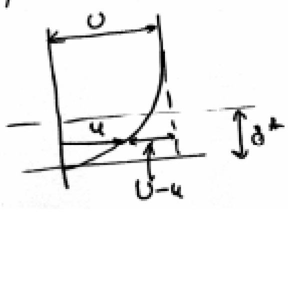
Losses in the test section

Test section is generally of constant area cross-section** and short length $\left(\frac{L}{D} \simeq 1.5\right)$ for general purpose wind tunnel. However, $\frac{L}{D}$ could be large for a special purpose wind tunnel, like Boundary layer tunnel.

**[If the velocity is to be uniform along the length of the working section of a closed throat tunnel, the cross sectional area must increase gradually to allow for the growth of the boundary layer on the walls. The outward divergence of each wall should be everywhere equal to the displacement thickness of the boundary layer (δ^*). Generally this divergence is about $\frac{1}{2}^\circ$.

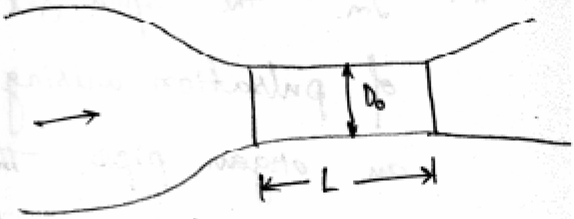
Displacement thickness (δ^*) is defined as the distance by which the external potential flow is displaced outward as a consequence of the decrease in velocity in the boundary layer

$$\rho U \delta^* = \int_0^\infty \rho (U-u)\, dy$$



L = Length of the T.S.

D_0 = Equivalent dia of the T.S. →

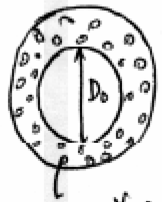


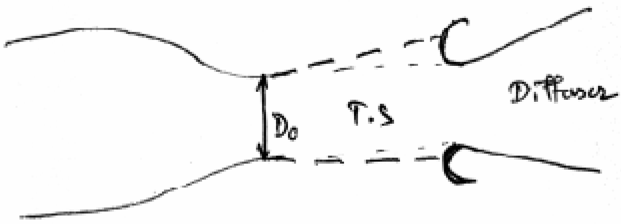
Then, $K_0 = \dfrac{\Delta H}{q_0} = \lambda\left(\dfrac{L}{D_0}\right)$

a) For smooth wall closed jet, λ is very small (0.008 approx.)

$\therefore$ for $\dfrac{L}{D_0} \simeq 1.5$, $\boxed{K_0 = 0.012}$

b) For the case of open jet, the value of λ is found to be very high (0.08 approx) from expt.





$\boxed{**}$ ↑ removes pulsation from jet.

$\therefore$ $\dfrac{L}{D_0} \simeq 1.5$, $\boxed{K_0 = 0.12}$

The loss due to open jet is nearly 10 times greater than that of ~~the~~ due to closed jet. This is about 12% of total loss.

Advantages of using open jet.

① – The velocity of air on the model is same as read by manometer.

– In the closed jet the velocity of air on the model is more than that indicated by the manometer.

② there is no static pressure gradient.

Power Loss in the Diffuser

If there were no losses, then

$$d\left(\frac{U^2}{2}\right) + \frac{dp}{\rho} = 0$$

i.e for a decrease of a K.E. $d\left(\frac{U^2}{2}\right)$ per unit mass there is a corresponding increase in pressure energy $\frac{dp}{\rho}$.

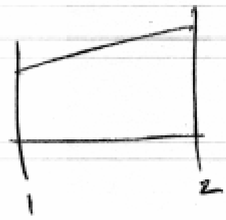
Pressure gradient along the wall of a diffuser is necessarily adverse, and it is difficult to avoid local separation or rapid thickening of the boundary layer. Thus, diffuser is never completely efficient. At low-speed it is seldom possible to recover more than from 80% to 90% of the available K.E.

Estimate - 1 :

using diffuser efficiency.

If η_d is the diffuser efficiency, then we can write,

$$\eta_D \, d\left(\frac{U^2}{2}\right) + \frac{dp}{\rho} = 0$$



or, $$\eta_D = \frac{P_2 - P_1}{\frac{1}{2}\rho U_1^2 - \frac{1}{2}\rho U_2^2}$$

From continuity equation : $U_1 A_1 = U_2 A_2$

$$\eta_D = \frac{P_2 - P_1}{\frac{1}{2}\rho U_1^2 \left[1 - \left(\frac{A_1}{A_2}\right)^2\right]}$$

$\therefore$ Loss of total head

$$\Delta H = \frac{1}{2}\rho U_1^2 - \frac{1}{2}\rho U_2^2 - (P_2 - P_1)$$

or, $$K_0 = \frac{\Delta H}{q_0} = (1 - \eta_D)\left[1 - \left(\frac{A_0}{A_2}\right)^2\right]$$ [note: $A_1 = A_0$]

Note : diffuser efficiency include both frictional & expansion losses.

Method - 2

Total loss = Friction loss + Expansion loss.

a) friction loss.

Loss of total head due to skin friction

$$\Delta H = \int_0^L c_f \, \frac{1}{2}\rho v^2 \, \frac{c}{A} \, dx$$

Let

D_1 = Equivalent dia at entry

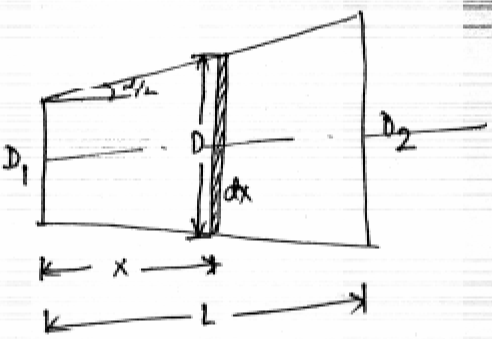
D_2 = - - - - exit

α = divergence angle

D = average diameter

V = average velocity

λ = average friction coefficient for the diffuser.



$$\Delta H = \int_0^L C_f \, \tfrac{1}{2}\rho V^2 \, \frac{C}{A} \, dx$$

$$D^2 V = D_1^2 V_1 \Rightarrow V = V_1 \left(\frac{D_1}{D}\right)^2$$

$$D = D_1 + 2x \tan\frac{\alpha}{2}$$

$$\therefore dx = \frac{dD}{2\tan\frac{\alpha}{2}}$$

$$= C_f \cdot \frac{\rho}{2} \int_{D_1}^{D_2} V_1^2 \left(\frac{D_1}{D}\right)^4 \cdot \frac{\pi D}{\frac{\pi}{4} D^2} \cdot \frac{dD}{2\tan\frac{\alpha}{2}}$$

$$= 4C_f \frac{\rho}{2} \int_{D_1}^{D_2} V_1^2 \, \frac{D_1^4}{D^5} \cdot \frac{dD}{2\tan\frac{\alpha}{2}}$$

$$= \lambda \frac{\rho}{2} V_1^2 D_1^4 \frac{1}{2\tan\frac{\alpha}{2}} \int_{D_1}^{D_2} \frac{dD}{D^5}$$

$$= \frac{\lambda}{8\tan\frac{\alpha}{2}} \left[1 - \left(\frac{D_1}{D_2}\right)^4\right] \left(\tfrac{1}{2}\rho V_1^2\right)$$

$$\therefore K_{0_f} = \frac{\Delta H_f}{q_0} = \frac{\lambda}{8\tan\frac{\alpha}{2}} \left[1 - \left(\frac{D_1}{D_2}\right)^4\right] \left(\frac{D_0}{D_1}\right)^4$$

If $D_1 = D_0$, then we have

$$K_{0_f} = \frac{\lambda}{8\tan\frac{\alpha}{2}} \left[1 - \left(\frac{D_0}{D_2}\right)^4\right] \Leftarrow \text{Due to friction.}$$

b) Expansion loss

According to Fliegner, expansion loss is given by

$$\Delta H_{exp} \simeq \frac{1}{2}\rho V_1^2 \left(0.6 \tan\frac{\alpha}{2}\right)\left[1-\left(\frac{D_1}{D_2}\right)^4\right]$$

$$\therefore K_{o_{exp}} = \frac{\Delta H_{exp}}{q_o} \simeq 0.6 \tan\frac{\alpha}{2}\left[1-\left(\frac{D_1}{D_2}\right)^4\right]\left(\frac{D_o}{D_1}\right)^4$$

If $D_1 = D_o$, then we have

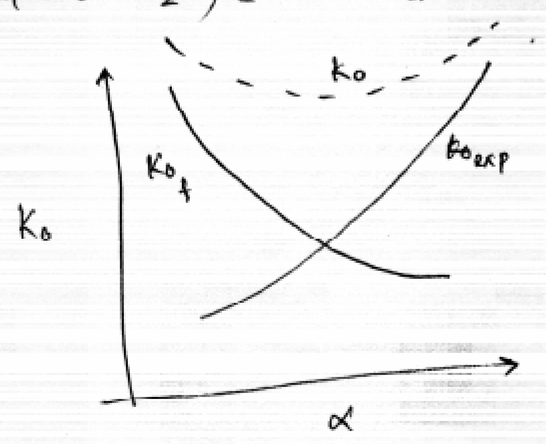
$$K_{o_{exp}} = 0.6 \tan\frac{\alpha}{2}\left[1-\left(\frac{D_o}{D_2}\right)^4\right]$$

$\therefore$ Total loss in the diffuser:

$$K_o = K_{o_f} + K_{o_{exp}}$$

$$= \left(\frac{\lambda}{8\tan\frac{\alpha}{2}} + 0.6\tan\frac{\alpha}{2}\right)\left(1-\left(\frac{D_o}{D_2}\right)^4\right)$$

For losses to be minimum, K_o must be minimum



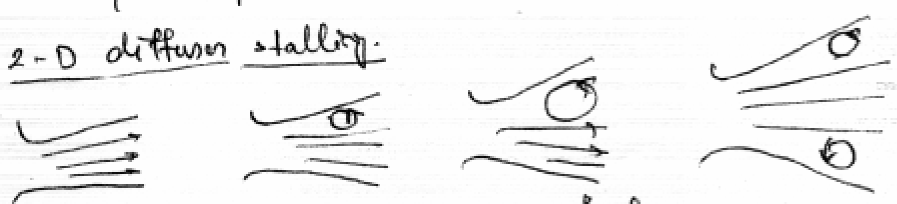
This gives:

$$\boxed{\tan\frac{\alpha}{2} = \sqrt{\frac{\lambda}{4.8}}}$$

For reasonable values of λ $(4c_f \simeq 0.01)$, the most efficient divergence is therefore about 5°. However, space limitation for the tunnel as well as the cost of construction may dictate a slightly larger divergence be employed at an increased in cost of operation.

Diffuser could be 2-D, conical, axisymmetric or 3D. The fluid flow has to advance in an adverse pressure gradient. In which case, it is very likely that the flow on one wall or both walls of a 2-D diffuser will separate, creating region of recirculating flow. After the separation point the static pressure remains constant, so no further pressure recovery is possible.

2-D diffuser stalling.



$2\theta \leq 7^\circ$ unstalled.

$2\theta \simeq 15^\circ$ transient 3-D stall

$2\theta \simeq 17^\circ - 23^\circ$ steady fully developed stall

$2\theta \simeq 30^\circ$ Jet flow, separation from both the wall

Parameter affecting stalling in 2-D diffuser

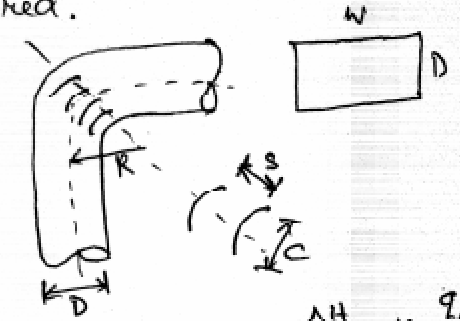
1. Angle of divergence, 2θ
2. $\frac{L}{D}$ ratio
3. Initial turbulence level, B.L. thickness at the diffuser inlet.
4. Free stream turbulence level, higher turbulence level is beneficial.

Method of fixing poor diffuser

1. Splitter plate: essentiall reduces effecting angle of divergence
2. Vortex generator: tip. pump high energy fluid to the B.L.
3. B.L. control: using suction or blowing.

Losses in the corners with turning vanes

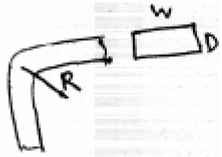
Most of the time, turning vanes turn the flow by 90°. Thus for a closed circuit tunnel 4 corners with turning vanes are required.



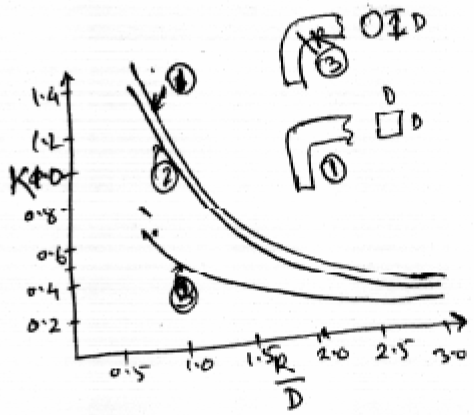
There are ~~four~~ five parameters that characterizes a corner with turning vanes.

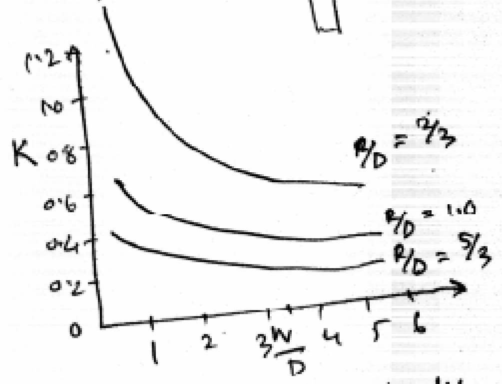
$$K = \frac{\Delta H}{\frac{1}{2}\rho V^2} = g\left(\frac{R}{D}, \frac{W}{D}, \frac{S}{C}, R_e, \text{shape}\right) \; ; \quad K_0 = \frac{\Delta H}{q_0} = K \cdot \frac{q_a}{q_0} = K\left(\frac{U}{U_0}\right)^2$$

If the cross-section is circular or square $(W = D)$, then



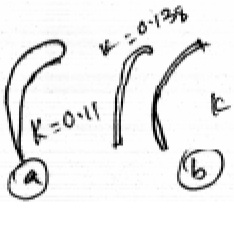
$$K = g\left(\frac{R}{D}, \frac{S}{C}, R_e, \text{shape}\right)$$

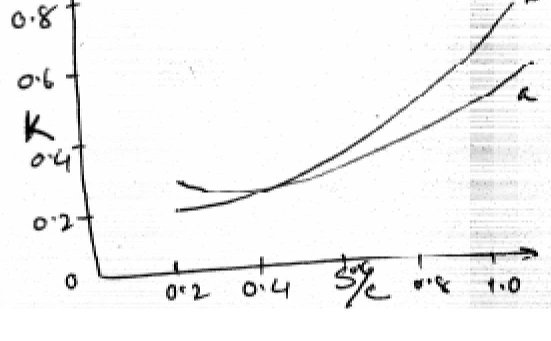




In general K decreases with increase in $\frac{R}{D}$ and $\frac{W}{D}$

~~Acceptable values are~~





Acceptable values are

$$\frac{R}{D} \geq 1.0 \; ; \quad \frac{W}{D} \geq 2.0 \; ; \quad \frac{S}{C} \simeq 0.25 - 0.4$$

Pope Gives: following empirical relation

$$K_0 = \left(0.10 + \frac{4.55}{(\log_{10} R_e)^{2.58}}\right) \frac{D_0^4}{D^4}$$

[This is based on $K = 0.15 = \frac{\Delta H}{q}$ at $R_e = 50,000$

D = equivalent dia of the tunnel at the entry of the corner

R_e = Reynolds number $\left(R_e = \frac{Uc}{\nu}\right)$

c = chord of the guide vanes

U = velocity at the entry.

Loss in the Settling chamber

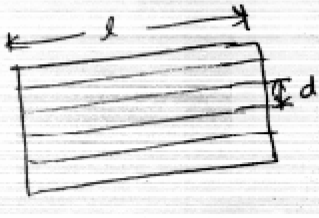
Same as the test section

Honey Comb:

Employed to remove swirl and to reduce the lateral mean velocity variations.

$$K = \frac{\Delta H}{\frac{1}{2}\rho U^2} = g\left(M, \frac{l}{d}, R_e, \text{Geometry}\right) \; ; \quad R_e = \frac{Ud}{\nu}$$

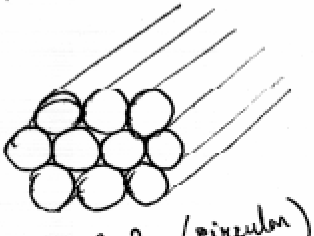
Mesh size



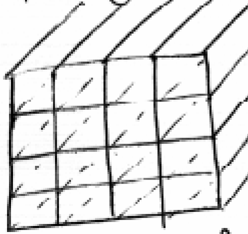
Very little systematic information is available on honeycombs. However, it is important to keep in mind that reasonable length of settling chamber should.

be provided after the honeycomb, which permits the decay of turbulent eddies generated by the honeycomb, before the flow enters the contraction cone.

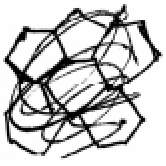
Available known data (from pope & Harper) L.S.W.T testing.

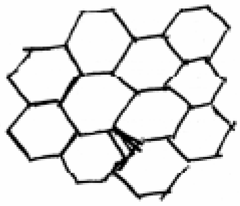


$K = 0.3$ (circular)



$K = 0.22$ (square)





$K = 0.20$ (hexagonal)

Note ~~C_{p_c}~~ K

$$K_0 = K\left(\frac{D_0}{D}\right)^4$$

where D = diameter of tunnel at honey com section.

$K = C_{p_c}$

acceptable : $\frac{l}{D} \simeq 6-8$.

Roughly speaking the loss in a honey comb is usually less than 5% of the total tunnel loss.

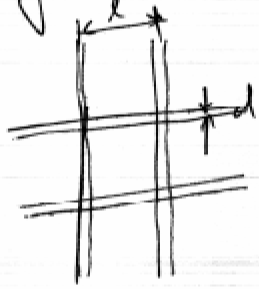
Screens:

Employed to reduce the turbulence level of free stream.

Mechanism: wake behind the screens produce high levels of turbulence, this means effectively breaking down medium size eddies to smaller eddies, and the smaller eddies have higher dissipation rate. thereby overall turbulence level is reduced.

<u>Limitations:</u> Screens can not remove large scale eddies

Screens are made of wires forming meshes, a typical section is as shown



Define a blockage (or porosity factor) coefficient

$$\beta = \left(\frac{l-d}{l} \right)^2$$

Then $K_0 = f_2\left(\beta, \frac{Ud}{\beta\nu}\right)$; $\frac{Ud}{\beta\nu}$ is Reynolds number

Mesh (M) = no. of openings per linear inch.

Empirical data on pressure loss coefficient and reduction of turbulence by screens

Source: Bradshaw & Pankhurst.

	Mesh size	d	β	U fps	K_0 (C_{D_s})	$\frac{u_2}{u_1}$ rms	$\frac{U_2}{U_1}$ rms
	16	0.0148	0.58	30	1.25		
1		"	"	12	1.6		
2	"				1	0.45	0.66
3	"	———			2	0.36	0.54
4	"	———			3	0.31	0.45
5	"	———			4	0.28	0.40
6	"	———					

Dryden and Schubauer (1947) have suggested that the mean intensity of turbulence is reduced by the screen in the ratio

$$\frac{u_2'}{u_1'} = \frac{1}{\sqrt{1+K}} \quad \text{— (1)}$$

This expression has been found in good agreement with experimental data.

Batchelor have shown that it is best to use a number of successive screens rather than a single screen of equivalent pressure drop coefficient. Thus, if the total pressure drop coefficient is nK, it is possible to use either a single screen of this pressure drop or n screens of coefficient K for the same power consumption.

Expression (1) can be written as

for a single screen with pressure drop coefficient, nK

$$\frac{u_2'}{u_1'} = \frac{1}{\sqrt{1+nK}} \quad (A)$$

For a n screen with pressure drop coefficient, K

$$\frac{u_2'}{u_1'} = \frac{1}{(1+K)^{n/2}} \quad \text{— (B)}$$

for example: $K = 0.85$
$n = 4$

Then, $\left.\frac{u_2'}{u_1'}\right)_A = 0.477$

$\left.\frac{u_2'}{u_1'}\right)_B = 0.292$

The full advantage of more than one screen can only be realized, if they are properly spaced. Sufficient distance downstream should be provided so that turbulence has decayed to a reasonably low level.

An approximate criterion is 500d, where d is the diameter of the screen wire.

for $M = 16$; $d = 0.0148''$; $K \doteq 1.6$

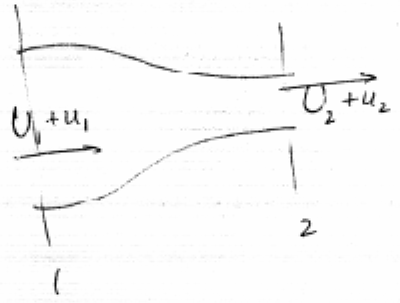
$$\text{spacing} = 0.0148 * 500 = 7.5''.$$

Contraction Cone:

It converts pressure energy into kinetic energy (just like a convergent nozzle). It also helps in obtaining good flow in the test section by reducing the velocity fluctuations.

It was shown before that

$$\frac{u_2}{U_2} = \frac{U_1^2}{U_2^2}\frac{u_1}{U_1}.$$



If the contraction ratio is n

then $$\frac{u_2}{U_2} = \frac{1}{n^2}\left(\frac{u_1}{U_1}\right)$$

$\therefore$ reduction in u-component fluctuations and thus an improvement in the uniformity of the flow.

Losses in the contraction cone is due to the skin friction loss. It is estimated in the same way as for the test section.

$$\Delta H_c = \int_0^{L_c} f \cdot \frac{dx}{D_c} \frac{1}{2} \rho V_c^2$$

L_c = Length of the contraction cone
$D_c = D_c(x)$, hydraulic dia "
V_c = Local velocity "

$$K_{0_c} = \frac{\Delta H}{q_0} = \frac{1}{\frac{1}{2}\rho V_0^2} \int_0^{L_c} f \cdot \frac{dx}{D_c} \cdot \frac{1}{2}\rho V_c^2$$

From continuity, $V_c^2 = V_0^2 \left(\frac{D_0}{D_c}\right)^4$

$$\therefore K_{0_c} = \int_0^{L_c} f \cdot \frac{dx}{D_c} \cdot \left(\frac{D_0}{D_c}\right)^4 = \int_0^1 f \cdot \left(\frac{L_c}{D_0}\right) \cdot \left(\frac{D_0}{D_c}\right)^5 \cdot d\left(\frac{x}{L_c}\right)$$

$$= f_{avg} \cdot \left(\frac{L_c}{D_0}\right) \int_0^1 \left(\frac{D_0}{D_c}\right)^5 d\left(\frac{x}{L_c}\right)$$

$$\boxed{K_{0_c} \simeq 0.32\, f_{avg} \cdot \frac{L_c}{D_0}}$$

$f_{avg} \simeq 0.005$

It is reasonable to take the friction factor as the average of the values for contraction cone entrance and exit Reynolds numbers. Typically, losses in the contraction cone is ~~less than~~ of the order of 3% of total losses in the circuit.

The exact nature of the turbulence changes produced by a contraction cone is not clear from the experimental data. In view of the paucity of information concerning the influence of a contraction on the flow, it is safest to assume that the value of u' is not altered. (However, $\frac{u'}{U}$ is decreased, because of increase in U). In general, it is assumed that all the three components, u', w', v' are unchanged in the contraction cone.

Pope gives that the pressure loss in the contraction cone is approximately 3% of the total loss.

Old tunnels have nominal contraction ratio of 4

for low turbulence tunnel C.R. $\geq$ 10.

Ref: R. Jordinson - Design of 2-D wind tunnel contractions - Aircraft Engineering - Oct 1961 pp. 294.

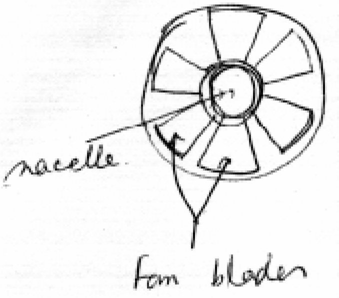
Fan Assembly:

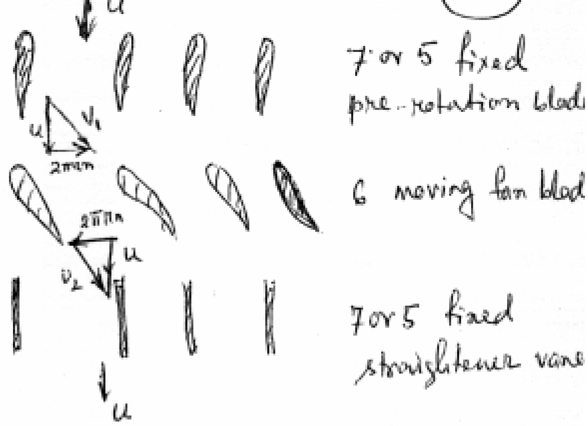
A complete fan assembly consists of three elements:

i) Fixed pre-rotation vanes - to provide equal and opposite initial swirl.

ii) Fan blades

iii) Fixed straightener vanes.





However, several wind tunnels may have just the fan blades, others may have fan blades and fixed straightener vanes.

Function: . To provide static pressure rise across the fan (similar to the pressure rise across the propeller blades of an aircraft), which is sufficient to balance the total power loss in the wind tunnel circuit.

Types of fans for low speed wind tunnels

i) Axial flow fan (IITK 5D and 3D smoke tunnel)

ii) Propeller type fan (IITK LTWT)

iii) Blower or centrifugal type fan (I.I.T. K Cascade tunnel,

For designing the fan, following methods are used :

i) Axial flow fan : Cascade design methods similar to the design of various stages of an axial flow compressor. (Ref: Axial flow fan – R.A. Wallis, 1961

ii) Propeller type fan: Aircraft propeller design method is used, where at each radius, for a section, the lift and drag coefficients are calculated by using the data on an airfoil section in an infinite stream.

Some points to be remembered about fan assembly design:

i) fan area / T.S. area $\simeq 2.0$

ii) Tip speed should be less than the speed of sound (Upper limit approx. 550 ft/sec, exceeding this, the compressibility effects will begin to appear.

iii) Nacelle diameter $\simeq 0.5$ fan diameter

iv) To specify the fan for a wind tunnel

a) pressure rise across the fan

b) volume flow rate or mass flow rate

c) diameter of the duct.

Drive arrangements

Fans are invariably driven by electric motors. In selecting an electric motor we must keep in mind the speed variation range for the wind tunnel.

There are two ways of changing the wind tunnel speed.

i) changing the speed of rotation of fan. This requires a variable speed motor. Usually a D.C. shunt-wound type motor.

ii) Use a constant speed fan driven by a constant speed motor. Induction or Synchronous m[illegible]

a) Change the pitch of the fan blades (only minor variat[illegible] in speed are possible)

b) Use throttling or variable inlet area to control the speed.

c) Use a hydraulic transmission to give a variable speed.

Question: a) where to place fan assembly?

b) Why is straightener vane loss greater than skin friction alone.

c) Why are thin propeller blades necessary on an airplane but not in a wind-tunnel.