Module 1 **Lectures 1- 5**

Wind tunnels

Keywords: Model making, geometric similarity, dynamic similarity, low speed wind tunnels, turbulence reduction, power economy in wind tunnels.

Topics

1.0 Introduction

Need of experiments

(i)Theory is incomplete and needs to be supplemented.

(ii) Information of fundamental nature needed in many areas.

Experimental information towards solving aerodynamic problems could be obtained in a number of ways. Flight tests, rocket flights, drop tests water tunnels, ballistic ranges and wind tunnels are some of the ways by which aerodynamic data can be generated. With the help of well performed experiments even information of fundamental nature could be derived.

Wind tunnel

Majority of experimental data needed in aerodynamics is generated using wind tunnels. Wind Tunnel is a device for producing airflow relative to the body under test. Wind tunnels provide uniform flow conditions in their test section.

1.1 Classification of wind tunnels

Wind tunnels may be classified based on any of the following:

(a) **Speed, Mach no**

They are classified as of low speed or high speed wind tunnels .In wind tunnel parlance, high speed wind tunnels are those operating at speeds where compressibility effects are important. They are also classified based on the Mach number of operation as subsonic, transonic, supersonic or hypersonic wind tunnels.

(b) **Mode of operation** (Pressure storage, in-draft or Pressure vacuum type.)

(c) **Kind of test section** (T.S) - Open, Closed or Semi enclosed

1.2 Applications of wind tunnels

1. *Aerodynamic applications*
2. *Non-Aero applications in*
    - Civil Engineering
    - Automobile Engineering
    - Calibration of instruments

1.3 Model making, Non-dimensional parameters

Geometric similarity

One of the most important requirements of models is that there should be geometric similarity between the model and the prototype. By geometric similarity it is meant that ratios of corresponding dimensions in the model and the prototype should be the same.

Dynamic similarity

Equally important as the geometric similarity is the requirement of dynamic similarity. In an actual flight, when the body moves through a medium, forces and moments are generated because of the viscosity of the medium and also due to its inertia, elasticity and gravity. The inertia, viscous, gravity and elastic forces generated on the body in flight can be expressed in terms of fundamental units. The important force ratios can be expressed as non dimensional numbers. For example,

- Reynolds number (Re) = Inertia force/Viscous force
- Mach number = Inertia force/Elastic force
- Froude number = Inertia force/Gravity force

The principle of dynamic similarity is that a scale model under same Reynolds number and Mach number will have forces and moments on it that can be scaled directly. The flow patterns on the full scale body and the model will be exactly similar.

It is not necessary and may not be possible that all the aforesaid non dimensional numbers be simulated simultaneously in any experiment. Depending on the flow regime or the type of experiments, certain non-dimensional parameters are important. For example, in a low speed flow regime, simulation of Reynolds number in the experiments is important to depict the conditions of actual flight. In a high speed flow, simulation of Mach number is significant. It may even be necessary and significant that more than one non dimensional parameter are simulated. The principle of dynamic similarity is applicable in other fields of engineering too. As examples:

Stanton number is simulated in heat transfer experimentation.

Stanton no (St) = Heat transferred in to the fluid / Thermal capacity

$$St = \frac{h}{c_p \rho\ v}$$

where h =convective heat transfer coefficient

ρ = density

c_p = specific heat at constant pressure

v = velocity

Expressing in terms of non-dimensional parameters,

$$St = \frac{Nu}{Re * Pr}$$

$$St = \frac{q}{\rho c_p (T_0 - T_w)}$$

Strouhal number is used in experiments dealing with oscillating flow

$$S = \frac{f_s l}{u}$$

f_s is vortex shedding frequency,

l is the characteristic length and

v the velocity

Knudsen number Kn = $\frac{\lambda}{l}$ is simulated in low density flows.

In the definition above, λ is the mean free path and l the characteristic dimension.

1.4 Low speed wind tunnel

Low speed wind tunnels may be of open circuit or closed circuit.

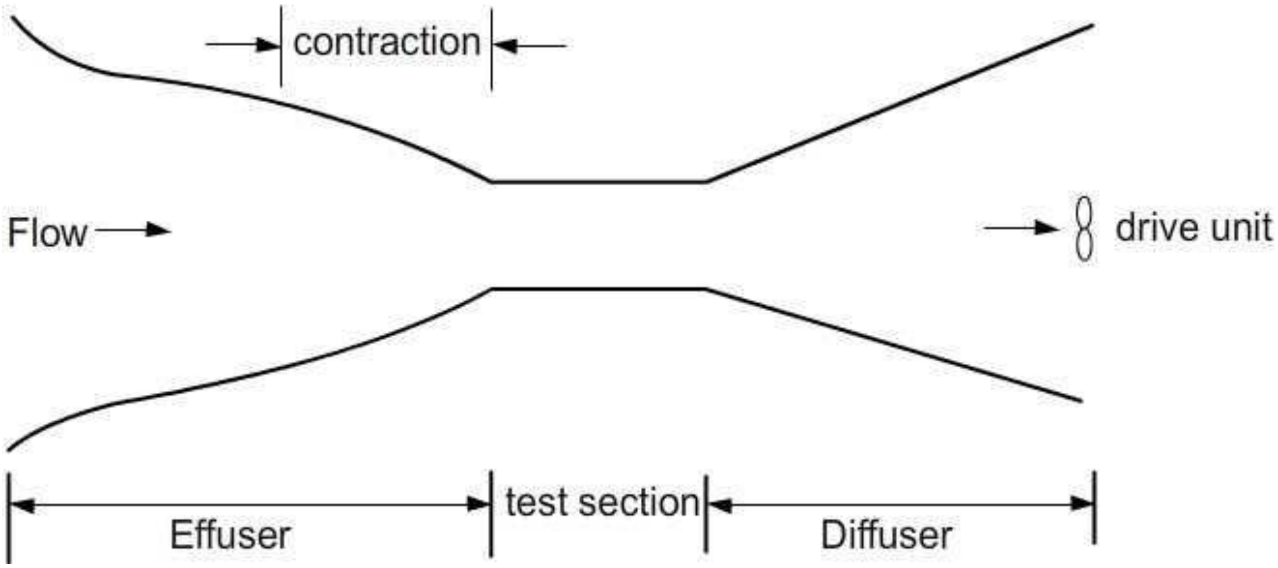

Figure 1.1 Schematic of an open circuit low speed wind tunnel

Figure 1.1 shows an open circuit low speed wind tunnel. After each run, the intake gets air fresh from the atmosphere. The effuser of the wind tunnel is the part of the wind tunnel from the beginning to the entry to the test section. The effuser makes the flow ready for the test section conditions. The test section provides the desired uniform flow conditions along and across the section. It is important that the test section conditions are controllable. Figure 1.2 shows a closed circuit wind tunnel. Losses in vorticity, eddies and turbulence are unavoidable in the tunnel circuit. If velocity is large, skin friction and losses due to obstacles will be correspondingly large.

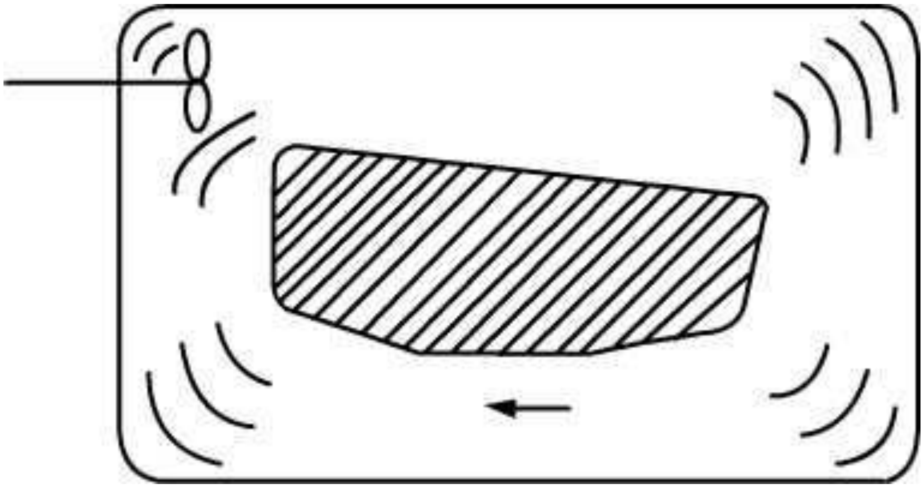

Figure 1.2 Schematic of an open circuit low speed wind tunnel

1.4.1 Irregularities of flow in low speed tunnels

1) Spatial non uniformity → Mean velocity not be uniform over a cross section. This is overcome by transferring excess total head from regions of high velocity to those of low velocity.
2) Swirl → Flow may rotate about an axis resulting in variation of direction of flow. Flow straightness and honey combs are used to reduce swirl.
3) Low frequency pulsation → These are surges of mean velocity. Under their influence, time taken for steady conditions becomes excessive. It is difficult to locate the source of such pulsations.
4) Turbulence → Turbulence generates small eddies of varying size and intensity and results in time variations of velocity. Turbulence may be defined as irregular fluctuations of velocity superimposed on mean flow.

In order to quantify turbulence:

Take components of mean velocity as U, V, W

Those of turbulent velocity u, v, w

RMS values $\sqrt{(\bar{u})^2}, \sqrt{(\bar{v})^2}$ and $\sqrt{(\bar{w})^2}$ are denoted as u', v', w'

Intensity of turbulence = $\frac{u'}{V_0}$ or $\frac{v'}{V_0}$ or $\frac{w'}{V_0}$ where, V_0 is the mean of U, V, W

Scale of turbulence $L = \int_0^\infty R_y \, d_y$

where R is the coefficient of co-relation between the longitudinal component of turbulent velocity at A and that at another point B distant y from it.

$$R_y = \frac{\overline{u_A u_B}}{u'_A u'_B}$$

1.4.2 Reduction of turbulence

Effect of screens on turbulence

Use of wire meshes (also called as gauzes or screens) is very common. Screens of very fine mesh size are used. They are kept as far upstream of the test section as possible. Screens are usually made of metal, nylon or polyester. With the use of screens, larger eddies are broken down to smaller ones and the smaller ones decay rapidly. Multiple screens reduce turbulence intensity.

The scale of eddies depends on the flow Re based on wire diameter of the flow through the screens. The eddies are practically absent when the Re is < 40.One of the important reasons for keeping the screens at the beginning of the tunnel circuit is to ensure that they are at the low velocity regions where the Re is the least. Effect of screen on turbulence depends on K, the pressure drop coefficient.

$$K = \frac{p_1 - p_2}{1/2 \rho v_1^2}$$

where p_1 and p_2 are values of pressure up and downstream of the screen. K depends also on β, Re, θ. Re the Reynolds number and θ is the flow incidence angle measured from normal to the screen β is the open area ratio and is defined as $\beta = \left(1 - \frac{d}{l}\right)^2$ ‘l’ and ‘d’ are marked on Figure 2.

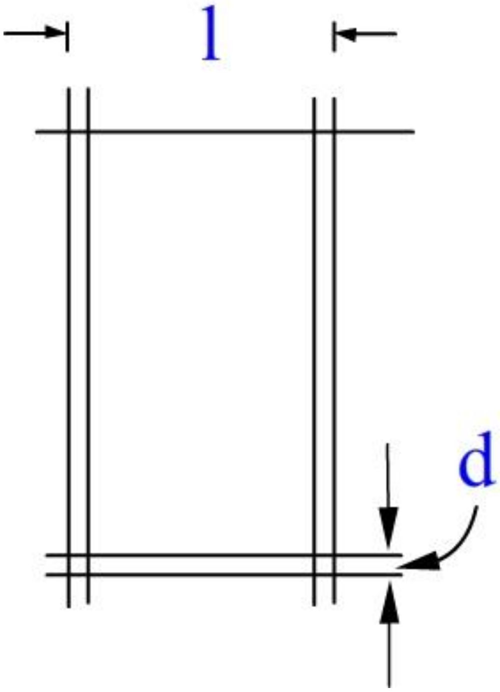

Fig.1.3 Mesh size of screens

According to Mehta and Bradshaw → If K = 2, turbulence is absent. According to Collar and Batchelor, if $U+u_1$ is the longitudinal velocity far upstream of the screen and $U+u_2$ the corresponding value far downstream, hence

$$\frac{u_2}{u_1} = \frac{2-K}{2+K}$$

so that non-uniformity is removed by a screen whose pressure drop coefficient K is equal to 2.0 and reversed if K is greater than 2.0.

1.4.3 Honey combs

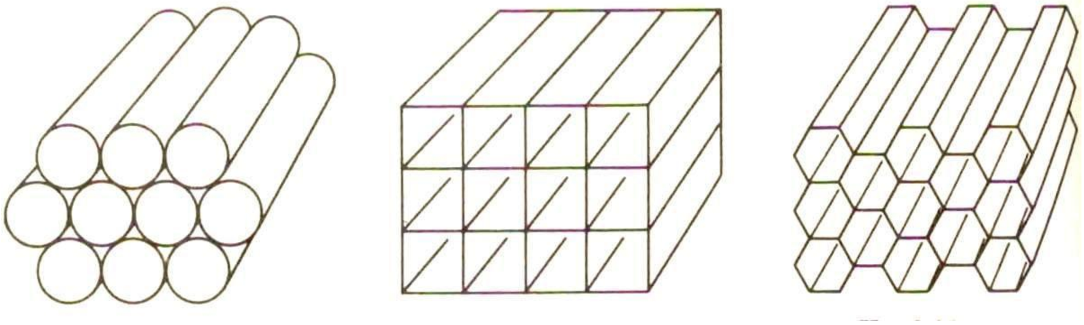

Fig.1.4 Honeycombs with different cell cross sectional shapes

Honey combs are effective in removing swirl and lateral mean fluctuations. Incidental effect is to reduce turbulence. In order to restrain the boundary layer thickness and transition in to turbulent boundary layer the cell length is usually kept within 5 to 10 times the cell dimension [Cell diameter or cell width].

1.4.4 Wind tunnel contractions

Wind tunnel contraction serves a few purposes

(i) Enables velocity to be low at the location of placement of the screens.

(ii) Reduces both mean and fluctuating velocity variations to a smaller fraction of the average velocity.

(iii) Reduces spatial variations of velocity in the wind tunnel cross section.

The most important parameter of the contraction is the contraction ratio ‘n’. The following one dimensional analysis shows how effective is the contraction in reducing the spatial non uniformity.

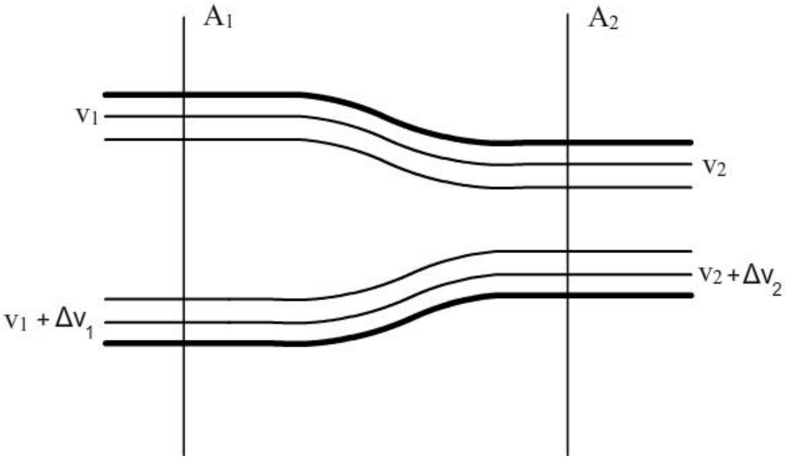

Fig.1.5 Schematic of a wind tunnel contraction

Referring to Fig.1.5 p, v and A represent present pressure, velocity and area respectively.

$a_1 = \frac{\Delta v_1}{v_1}$ is the fractional variation of velocity at the inlet to the contraction.

$a_2 = \frac{\Delta v_2}{v_2}$ is the fractional variation of velocity at the exit of the contraction $n = \frac{A_1}{A_2}$ is the contraction ratio.

$$p_1 + \frac{\rho v_1^2}{2} = p_2 + \frac{\rho v_2^2}{2}$$

$$p_1 + \frac{\rho}{2}(v_1 + \Delta v_1)^2 = p_2 + \frac{\rho}{2}(v_2 + \Delta v_2)^2$$

$$v_1 \Delta v_1 = v_2 \, \Delta v_2$$

$$\Delta v_1 = \Delta v_2 \frac{v_2}{v_1}$$

$$a_1 = \Delta v_2 \frac{v_2}{v_1^2} = \Delta v_2 \frac{v_2}{\left(\frac{v_2}{n}\right)^2} = n^2 a_2$$

1.4.5 The diffuser

The diffuser in the wind tunnel serves the purpose of salvaging the kinetic energy of flow in the test section as pressure energy. A well designed diffuser does this efficiently. In subsonic wind tunnels, the diffusers are diverging passages with a semi divergence angle of about 7.5 to 8.0 degrees. The Bernoulli's equation written in differential form in the context of a diffuser is as follows:

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

This implies that for a decrease of kinetic energy $d\left(\frac{v^2}{2}\right)$ per unit mass, there is a corresponding increase in pressure energy. The pressure gradient in a subsonic diverging passage is adverse. It is difficult to avoid boundary layer thickening and flow separation. Hence, the conversion of kinetic energy into pressure energy is never fully efficient.

The efficiency of the diffuser is best understood in physical terms when the efficiency term is included in the Bernoulli's equation as below:

$$\eta_D\left(\frac{dv^2}{2}\right)+\frac{dp}{\rho}=0$$ where η_D is the diffuser efficiency

Pressure changes in expanding passages may be examined by referring to the Fig.1.6 to elucidate the statement above.

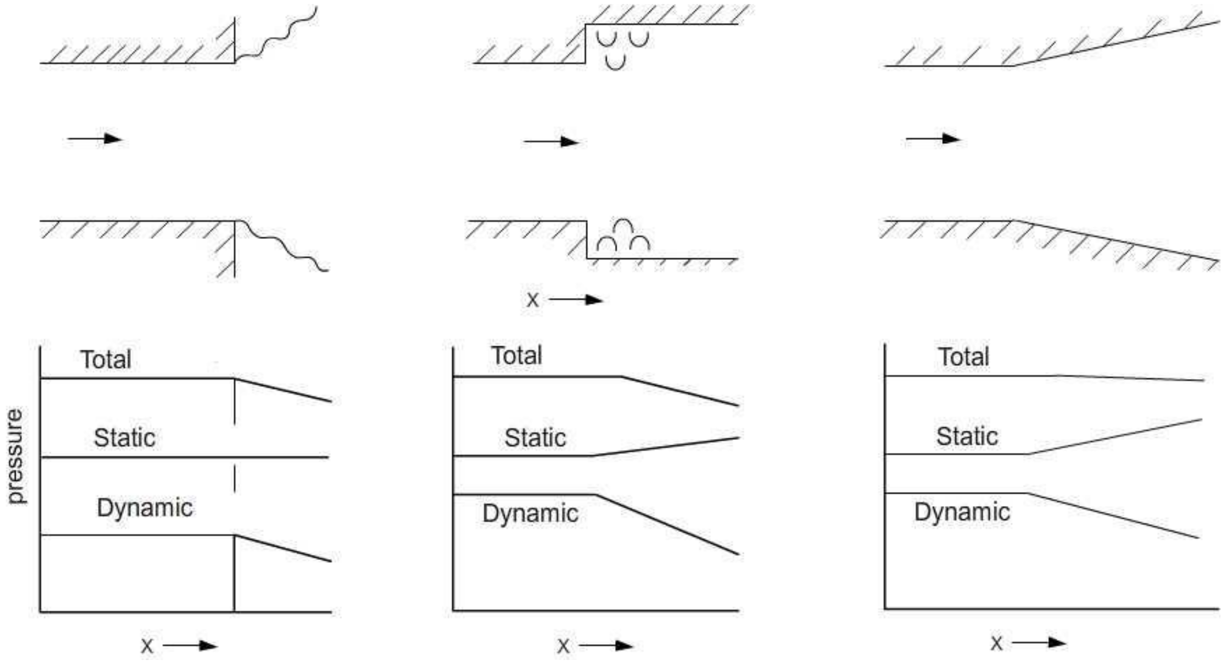

Fig.1.6 Exit pressure profile of jet through different passages

There are two definitions of diffuser efficiency

(a) Polytrophic efficiency (η_D)

$$\eta_D=\frac{p_2-p_1}{\frac{1}{2}\rho v_1^2-\frac{1}{2}\rho v_2^2}$$

Use continuity equation to write the above equation as

$$\eta_D = \frac{p_2 - p_1}{\frac{1}{2}\rho v_1^2\left[1-\left(\frac{A_1}{A_2}\right)^2\right]}$$

where subscripts ‘1’ and ‘2’ refer to conditions at the entry and exit of the diffuser.

As explained before, the equation is indicative that from kinetic energy to pressure energy it is not fully converted. Loss of total head in the diffuser action:

$$\Delta H = \left(\frac{1}{2}\rho v_1^2 - \frac{1}{2}\rho v_2^2\right) - (p_2 - p_1)$$

$$\eta_D = 1 - \frac{\Delta H}{\frac{1}{2}\rho v_1^2\left[1-\left(\frac{A_1}{A_2}\right)^2\right]}$$

(b) Isentropic efficiency

Isentropic Efficiency (η_σ) is defined as the ratio of

$$\eta_\sigma = \frac{\text{Kinetic energy which would have to be transformed to produce the observed pressure recovery}}{\text{Kinetic energy actually transformed}}$$

$\left(\frac{p}{\rho^\gamma}\right)$ = constant for an isentropic process

KE to be transformed to raise pressure from p_1 to p_2 $= \int_{P_1}^{P_2} \frac{dp}{\rho}$

$$\int_{P_1}^{P_2} \frac{dp}{\rho} = \frac{\gamma}{\gamma - 1}\frac{p_1}{\rho_1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

$$\eta_\sigma = \frac{\gamma}{\gamma - 1}\frac{p_1}{\rho_1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

$$\frac{p_2}{p_1} = \left[\frac{(\gamma-1)M_1^2}{2}\eta_\sigma + 1\right]^{\gamma/\gamma-1}$$

$$\frac{p_1}{H} = \frac{p_1}{p_{01}} = \left[\frac{2}{2+(\gamma-1)M_1^2}\right]^{\gamma/\gamma-1}$$

Overall pressure ratio $\frac{p_{01}}{p_2}=\frac{H}{p_2}$. Here p_2 corresponds to the pressure at the exit of the diffuser and H represents the stagnation pressure p_{01} at the entry to the wind tunnel.

$$\frac{H}{p_1}\times\frac{p_1}{p_2}=\left[\frac{2+(\gamma-1)M_1^2}{2+(\gamma-1)M_1^2\eta_\sigma}\right]^{\gamma/\gamma-1}$$

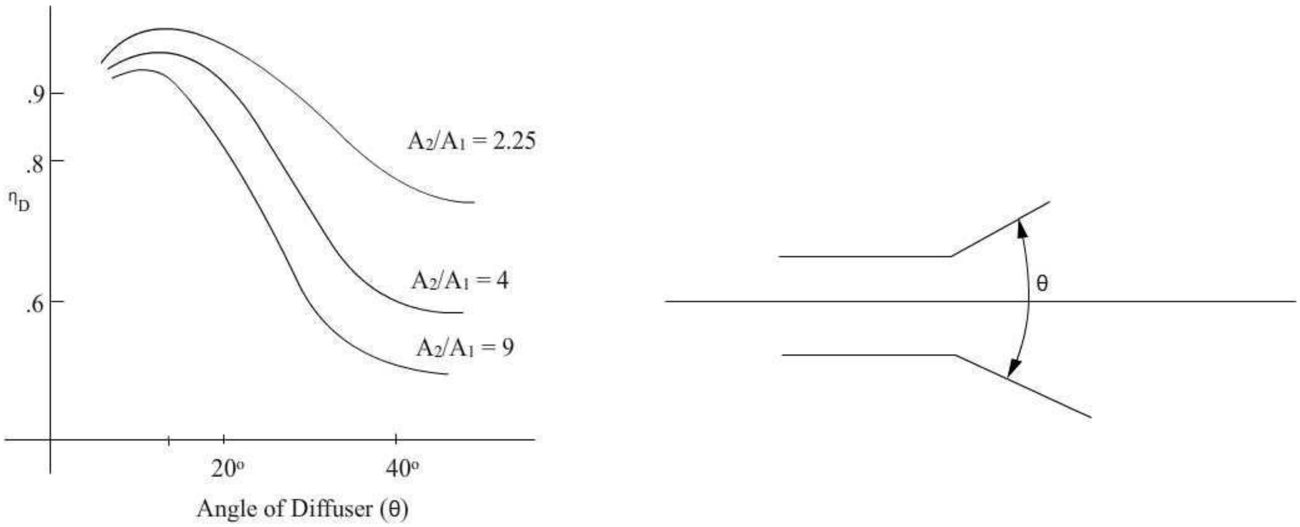

Fig.1.7 Diffuser efficiency as a function of diffuser angle

1.5 Losses in the wind tunnel circuit

Losses are due to:

- Inefficiency of drive unit
- Skin friction, separation etc
- Loss of kinetic energy at the diffuser exit
- Shocks in the case of supersonic wind -tunnels

Losses due to skin friction

Local coefficient of skin friction = $\dfrac{\text{Frictional force}}{\frac{1}{2}\rho v^2 A'}$

where, A' is the surface area of the solid boundary which is subjected to frictional force.

$$\Delta H=\int C_f\frac{1}{2}\rho v^2\frac{L}{A}dS$$

Integral is taken over the length of the duct.

L is the perimeter, ds is an element of length in the direction of flow.

A is the cross sectional area and

C_f depends on nature of the boundary layer, Reynolds number and on the surface nature.

Losses due to resistance in the wind tunnel circuit

Corner vanes, gauzes and screen offer resistance

Resistance Coefficient $C = \dfrac{\text{Resistance force}}{\frac{1}{2}\rho v^2 A} = \dfrac{\Delta H}{\frac{1}{2}\rho v^2}$

$$vA = \text{constant}$$

$$v = \frac{\text{constant}}{A}$$

$\Delta H \,\alpha\, \dfrac{C}{A^2}$, which shows that the power loss is less for large areas.

1.6 Power requirements – Power economy

Power Factor is defined as

$$\lambda = \frac{\text{Power Input}}{\text{Rate of flow of kinetic energy in the test section}} = \frac{P}{\frac{1}{2}\rho v^3 A}$$

where P is the power input. Of the power P, only ηP is communicated to the air stream where η is the efficiency of the drive unit (fan efficiency).

$$\lambda = \frac{\sum \text{losses}}{\eta \frac{1}{2}\rho v^3 A}$$

ηP = losses in the wind tunnel.

Reciprocal of the power factor is an alternative measure of the efficiency of the system.

Power economy

$$P = \lambda \frac{1}{2} \rho v^3 A$$

$$= \lambda \frac{1}{2} \rho v^2 vA$$

$$Re = \frac{\rho vc}{\mu}, M = \frac{v}{a}$$

$$a^2 = \gamma RT = \frac{\gamma p}{\rho}$$

$$\rho = \frac{\gamma p}{a^2}$$

$$a^2 = \gamma \frac{R^*}{\overline{M}} T$$

$$v = \frac{Re\mu}{\rho c}$$

substituting from above

$$P = \lambda \frac{1}{2} \frac{Re^2 \mu^2}{\rho^2 c^2} A Ma \rho$$

$$= \frac{1}{2} \lambda \frac{A}{c^2} Re^2 M \frac{\mu^2 a^3}{\gamma p}$$

→ The ratio $\frac{A}{c^2}$ = the tunnel interference, is constant.

→ The power factor depends largely on the geometry of the tunnel and on the Mach and Reynolds numbers.

1.6.1 Power economy by pressurization

For tunnels of similar geometry, operating at given Re and M.

$p \propto \frac{\mu^2 a^3}{\gamma p}$ Expressing in terms of stagnation properties,

$$\alpha \frac{\mu_0^2 a_0^3}{\gamma p_0}$$

$p \; \alpha \; \frac{1}{p_0}$ Power is inversely proportional to p_0.

Objections to power economy by pressurization

Aerodynamic forces on the model are proportional to $\frac{1}{2}\rho v^2 = \left[\frac{1}{2}\gamma p M^2\right]$

which for given M is proportional to p_0

1.6.2 Power economy by choice of working fluid

For a given pressure → $p \; \alpha \; \frac{\mu_0^2 a_0^3}{\gamma}$

At constant temperature $a_0^3 \; \alpha \left(\frac{\gamma}{\bar{M}}\right)^{3/2}$

$$a^3 = \left(\frac{\gamma R^* T}{\bar{M}}\right)^{3/2}$$

μ_0 falls as the number of atoms in a molecule increases.

$\gamma = \frac{2n+3}{2n+1}$ where n is the number of atoms in the molecule.

γ falls when n increases.

$p \; \alpha \; \frac{\mu_0^2 \gamma^{1/2}}{\bar{M}^{3/2}}$ → Power economy can be achieved by working fluid of higher molecular weight.

Limitations

→ Complete dynamic similarity can be got with only the same γ.

→ Boiling point of higher molecular weight fluids is high. Hence, to keep the working fluid in gaseous state, the temperature should be high.

Table 1.1 Power required with a different working substance

$T_0 = 288$ K

Fluid	Boiling Point K			Power relative to air
Air	90	$a_{0\,SF6} / a_{0Air}$ = 0.395μ	μ_{0SF6} / μ_{0Air} =0.529	0.020
SF_6	222			

The Table 1.1 above shows that the power required when SF_6 is used as the working fluid is only 1/50 of that while using air.

1.6.3 Power economy by reduction in stagnation temperature

For a given working fluid, p_0, λ, M and Re.

$$P \alpha \mu_0^2 a_0^3$$

$$a_0 \alpha T_0^{1/2}$$

$$\mu_0 \alpha \frac{T_0^{3/2}}{T_{0ref}+C}$$ C is a constant.

$$P \alpha \frac{T_0^{9/2}}{\left(T_{0ref}+C\right)^2}$$

Objections

- Reducing stagnation temperature brings down the flow temperature too. Boiling point is one consideration.
- Severe metallurgical problems at low temperatures.

Exercises

Answer the following

1. What are the important non-aerospace applications of wind tunnels?
2. What is understood by dynamic similarity of wind tunnel models?
3. Why are the wind tunnels sections tapered in the direction of flow?
4. Define scale and intensity of turbulence.
5. What is the purpose of using wire meshes in the effuser of a wind tunnel
6. Why are the wire meshes kept at the largest area section of the wind tunnel intake?
7. How effective is wind tunnel contraction in reducing flow non-uniformity?
8. What is the purpose of honey combs in wind tunnels?
9. Wind tunnel contraction serves multiple purposes in wind tunnels. What are they?
10. Derive and express polytropic efficiency of a subsonic wind tunnel diffuser in terms of total head loss.
11. Show the variation of diffuser efficiency with diffuser angle.
12. What are the possible ways of achieving power economy in wind tunnels?
13. How effective is the use of alternate working substance in reducing power required in a wind tunnel?
14. What is the functional relationship between stagnation temperature and the power required for operating a wind tunnel?

Solve the following numerical problems

1. A low subsonic wind tunnel has a diffuser of area ratio 9. At a test section velocity of 30m/s and a temperature of 330K, the diffuser is found to have an efficiency of 90%. If the pressure at the inlet to the diffuser is 1.195 x 105N/m2 calculate the head loss in the diffuser.
2. A subsonic wind tunnel contraction has an area ratio of 3 and a 5% spatial non uniformity of velocities was observed in the exit section of the contraction. In order to improve the non-uniformity to less than 2% what should be the contraction area?