LECTURE NOTES

ON

Experimental Aerodynamics

B. Tech VI Semester (IARE - R16**)**

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UNIT – I FUNDAMENTALS OF EXPERIMENTS IN AERODYNAMICS

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.

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

Applications of wind tunnels

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

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

cp = 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

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

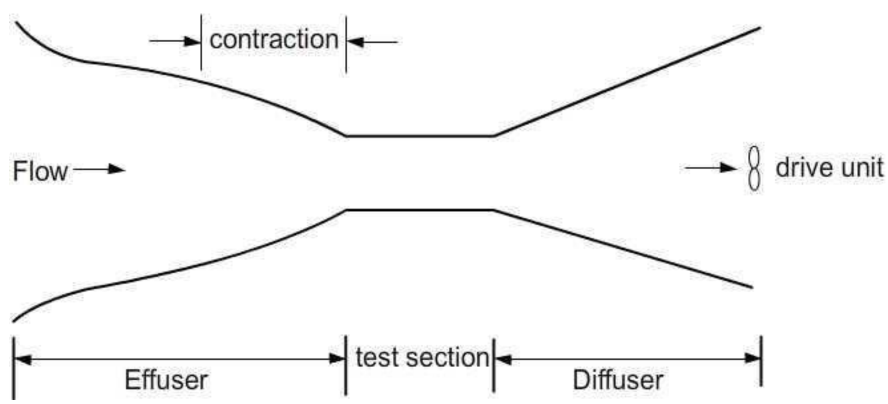
f_s is vortex shedding frequency, l is the characteristic length and v the velocity

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.

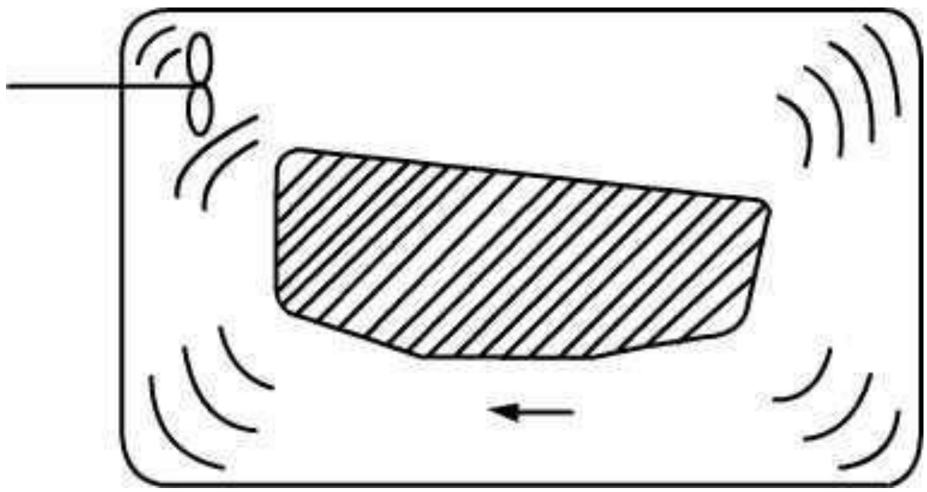
Low speed wind tunnel

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



Schematic of an open circuit low speed wind tunnel

Figure above 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 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.



Schematic of an open circuit low speed wind tunnel

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 $\sqrt{(\overline{u})^2}, \sqrt{(\overline{v})^2}$ and $\sqrt{(\overline{w})^2}$ 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.

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

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.

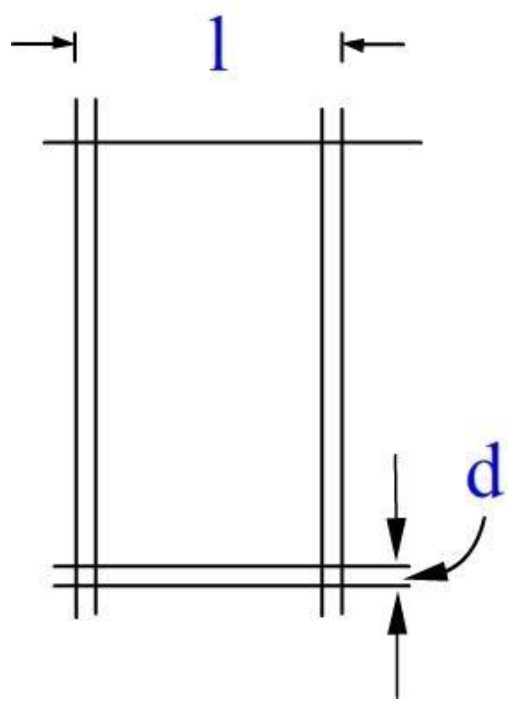
$$K = \frac{p_1 - p_2}{1/2 \rho v_1^2}$$

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

is the open area ratio and is

defined as $\beta = \left(1 - \frac{d}{l}\right)^2$ 'l' and 'd' are marked on Figure



Mesh size of screens

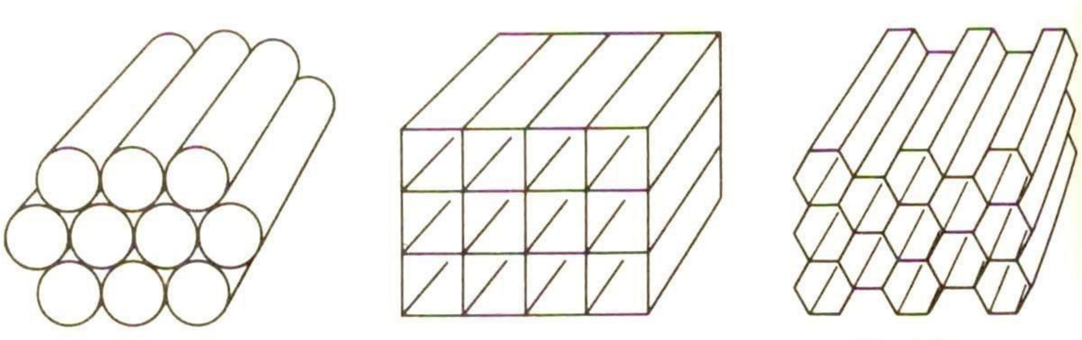
According to Mehta and Bradshaw If K = 2, turbulence is absent. According to Collar and Batchelor, if $U+u_1$ is the longitudinal velocity far upstream of the screen and $U+u_2$ the corresponding value far downstream, hence

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

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.

UNIT-II WIND TUNNEL EXPERIMENTATION CONSIDERATIONS

Honey combs



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].

Wind tunnel contractions

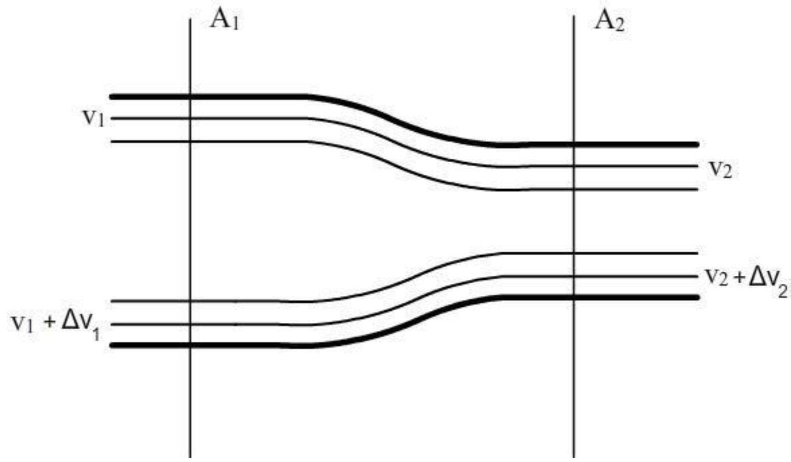
Wind tunnel contraction serves a few purposes

(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.



Schematic of a wind tunnel contraction

Referring to 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 v_2A_2 contraction ratio.

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

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

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

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

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

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

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

as follows: 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.

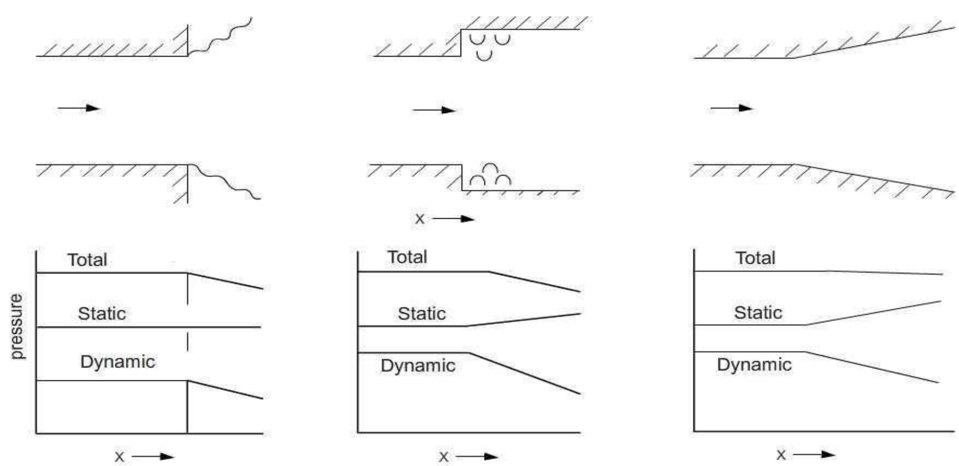
Hence, the conversion of kinetic energy into pressure energy is never fully efficient.

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. below to elucidate the statement above.



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

Raise in pressure from p1 to p2 $= \int_{P_1}^{P_2} \frac{dp}{\rho}$

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

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

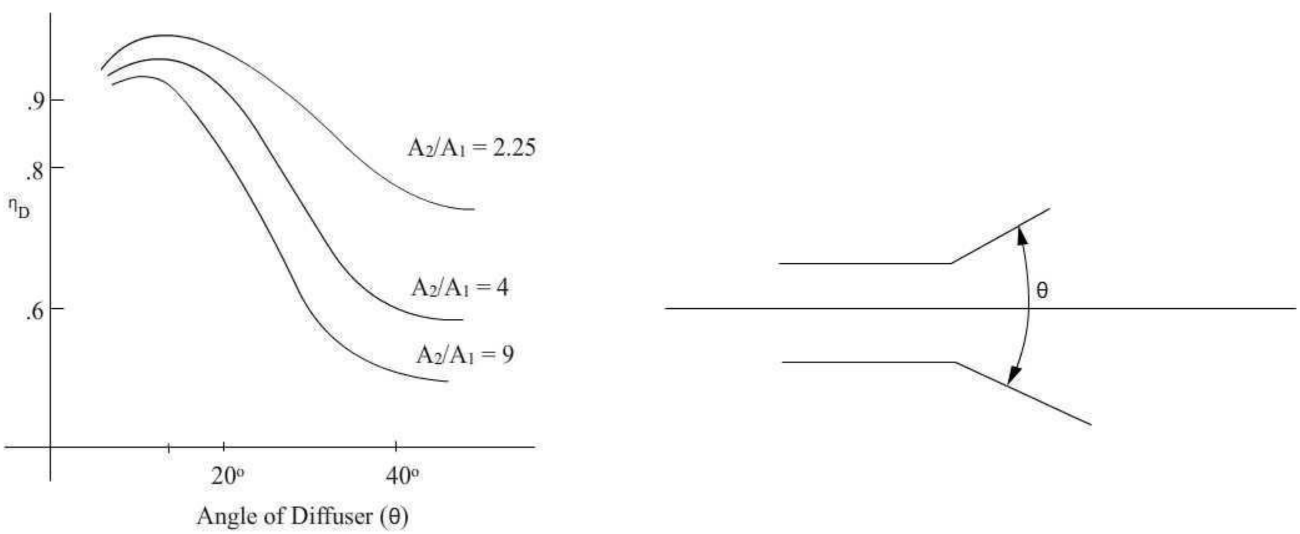
$$\frac{p_2}{p_1} = \left[\frac{(\gamma-1)M_1^2}{2}\eta_\sigma + 1\right]^{\gamma/\gamma-1}$$

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

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.

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



Diffuser efficiency as a function of diffuser angle

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 = $\frac{\text{Frictional force}}{\frac{1}{2}\rho v^2 A'}$ 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

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).

$$\lambda = \frac{\sum \text{losses}}{\eta \frac{1}{2}\rho v^3 A} \qquad \eta P = \text{losses in the wind tunnel.}$$

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

Power economy

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

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

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

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

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

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

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

substituting from above

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

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

- 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.

Power economy by pressurization

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

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

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

Limitations

- Complete dynamic similarity can be got with only the same.
- Boiling point of higher molecular weight fluids is high. Hence, to keep the working fluid in gaseous state, the temperature should be high.

Power required with a different working substance

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

High speed wind tunnels

Definition of high speed

When compressibility effects are pre dominant the flow is generally said to be of high speed. A lower limit is approximately M=0.5. Power requirements vary as cube of velocity in the wind tunnel. This does not hold into the high speed regime exactly. Because of large power requirements, high speed wind tunnels are of the intermittent type.

Types of high speed wind tunnels

1. Continuous (for all speed ranges)
2. Intermittent

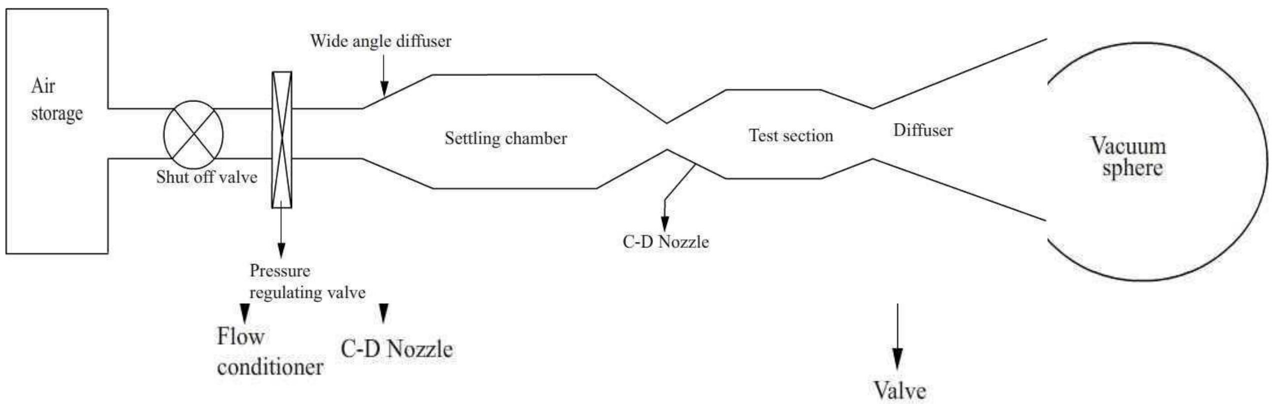
    2.1 Blowdown

$\rightarrow$ M > 0.5 <5.0

    2.2 Indraft

    2.3 Intermittent pressure vacuum tunnel for M>5

Pressure driven blow down supersonic wind tunnel



Indraft type wind tunnel

Comparison between Indraft and Pressure driven wind tunnels

Indraft wind tunnels	Pressure driven wind tunnels
Stagnation temperature at supply condition is constant during a run. So also is total pressure. No fluctuations as those generated by a pressure regulator.	Reynolds number can be varied at a particular Mach no.
No possible contamination such as that due to oil.	Cost is much less than of an indraft tunnel.
Vacuum is safer to handle than pressure.	
Pressure regulators are not needed.	

The wind tunnels described above can be converted as continuous tunnels. The comparison between blow down and continuous wind tunnels are as given in Table

Comparison between intermittent and continuous wind tunnels

Intermittent(blow down) wind tunnels	Continuous wind tunnels
Simple to design and less costly	More in control of conditions and return to a given test condition with more accuracy.
A single drive may run several Tunnels	Check points are easily obtained No panic of rapid testing
Model testing is more convenient	Test conditions can be held constant for a longer time.
Extra power is available to start	
Failure of model will not result in tunnel damage	

Supersonic wind tunnels

Introduction

The nozzle regulates the speed of air entering the test section (T.S) of the wind tunnel so that the desired Mach number is established. Mach number is uniquely determined by the area ratio of the nozzle. A well designed nozzle makes the flow parameters uniform across the cross section. The design of a suitably shaped nozzle contour to obtain the desired uniform flow at the nozzle exit is based on the method of characteristics.

Test section parameters

The test section flow velocity v for a given stagnation temperature T_0 approaches the maximum value v_{max} at relatively low supersonic Mach numbers.

For example,

and a test section Mach number of 5.0, the ratio of v/v_{max} can be calculated to see that it is equal to 0.913. This means at ordinary stagnation temperatures, the velocity in the test section reaches 91% of the maximum possible velocity corresponding to the total energy of the fluid. The stagnation temperature T_0 rather than the Mach number which is important to attain high velocities.

(i) Free stream Reynolds Number (Re)

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

Experimental observation is that μ is independent of pressure in the range of 0.001 to 20 atmospheres.

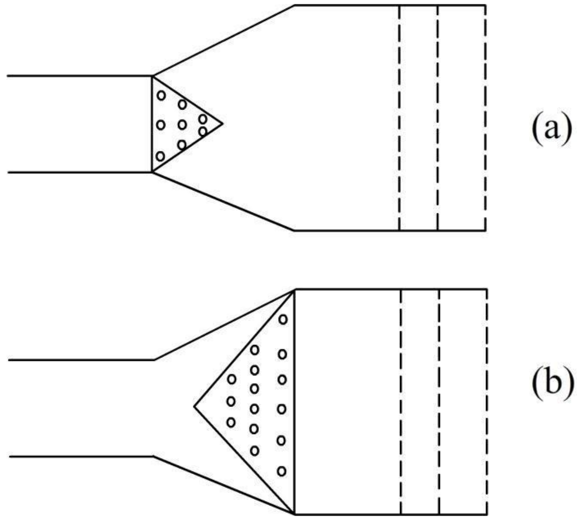
If this relation is assumed then the free stream Re can be expressed as a function of M_1, the T.SMach no and of the stagnation parameters. Reynolds no is functions of stagnation temperature. Both increase with temperature. Hence, appreciable changes in free stream Re/unit length for a given M can be obtained only by varying stagnation density.

Components of supersonic wind tunnels

Air storage tanks

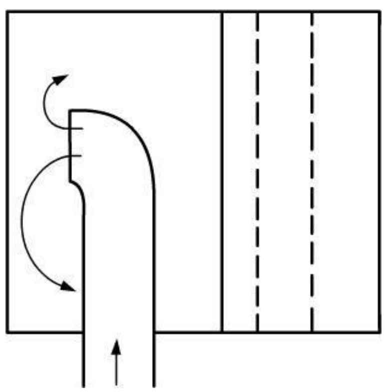
Size of the storage will be dependent on the mass flows required and the frequency of runs. Pressure storage tanks are available on the shelf basis – They are mounted horizontally or vertically. Tanks are painted black to absorb heat. They are provided with safety disk or pressure relief valve. As air is drawn from the storage, polytropic expansion takes place within the tank. This results in drop of reservoir temperature which is very bothersome. Fall of stagnation temperature causes resultant change in the stream temperature for a given Mach.
number. Change in temperature results in the change of viscosity which in turn affects the boundary layer thickness. Changes in Reynolds number and Mach number during a run are thus consequential to the fall in reservoir temperature.
To maintain constancy of stagnation temperature, it is a practice to stack the reservoir volume with empty metallic cans. They serve as heat storing matrix during compression and release heat during the expansion process. Another way to maintain the constant stagnation temperature is by providing heater units in the reservoir.

Settling chamber /wide angle diffusers



Wide angle diffuser

Wide angle diffusers lead the flow to the settling chamber. Arrangements for leading the flow to the settling chamber may be by one of the methods shown in Figure

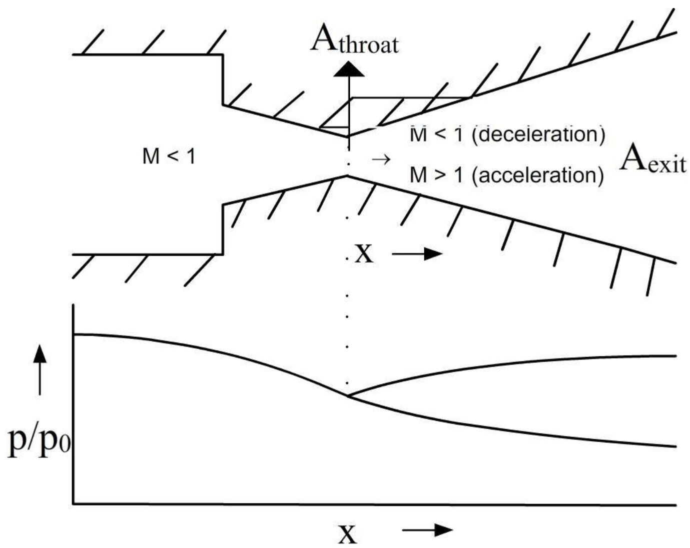


Reverse entry into the settling chamber

Uniformity of flow in the test section is improved if a large area ratio contraction is provided.

Convergent-divergent (c-d) nozzle

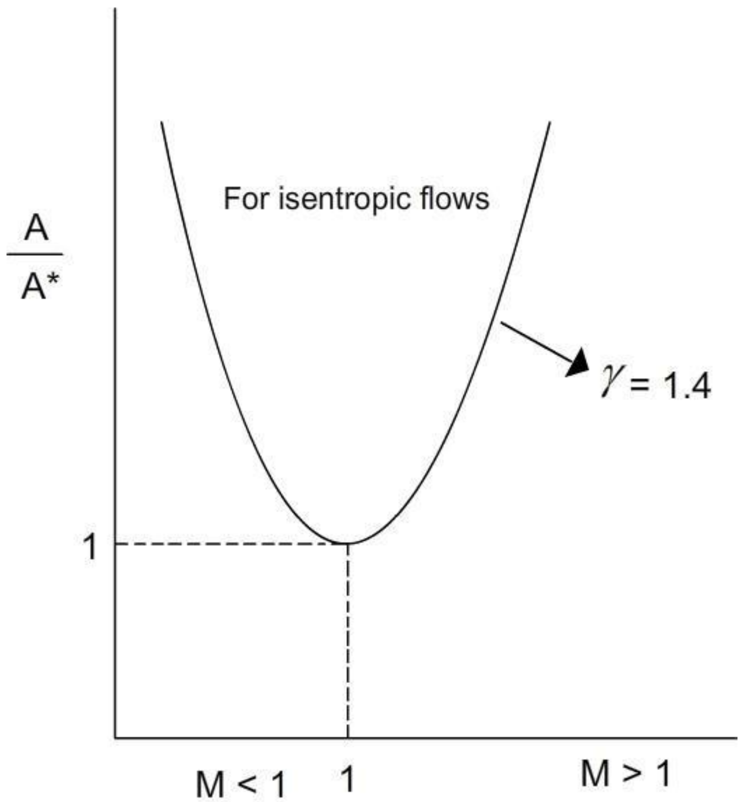
The c-d nozzle forms the heart of the supersonic wind tunnel .For generating supersonic flow in the test section, it is essential that there is a c-d nozzle in the tunnel circuit before the test section. The area ratio of the c-d nozzle (A_{exit}/A_{throat}) uniquely decides the Mach number.



Convergent divergent nozzle and the pressure profile

When the tunnel operation starts, the flow is initiated in the nozzle as subsonic and reaches the sonic Mach number at the throat when sufficient mass flow is allowed. This is called the choked condition of the nozzle. Under this condition, maximum mass flow rate for the given stagnation conditions takes place through the nozzle. The ratio between the upstream stagnation pressure (P_0) and the downstream back pressure (P_b) corresponding to the first time choking is called the first critical pressure ratio of the nozzle. At this pressure ratio, the flow in the divergent part of the nozzle is subsonic. The exit Mach number will be the subsonic value corresponding to the A/A* in the Fig.. In this context A is the exit area and A* the throat area of the choked nozzle. As the value of P_0/P_b is progressively increased, the flow in the divergent part of the nozzle accelerates to be supersonic but shocks are formed in the divergent part until a pressure ratio corresponding to the supersonic Mach number of the nozzle is reached. The pressure ratio corresponding to this Mach number is the third critical pressure ratio of the nozzle. Between the first and third critical pressure ratios shocks of varying strengths take place in the nozzle and outside of it as there is no other isentropic solution between the 1^{st} and

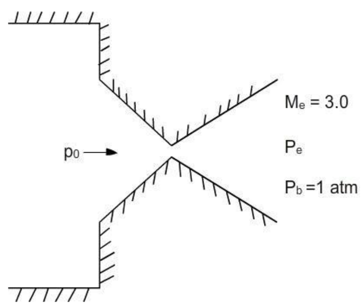
3rd critical pressure ratios. The pressure ratio corresponding to the occurrence of a shock at the exit plane of the nozzle is the second critical pressure ratio of the nozzle.



A/A* vs. Mach numbers

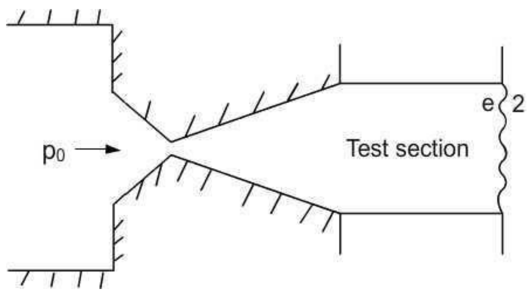
All the shocks generated at the different pressure ratios inside the nozzle will make the post shock Mach number subsonic and the subsonic nozzle exit pressure will be made equal to the ambient pressure in the remaining part of the diffusing divergent channel. Between the second and third critical pressure ratios, oblique shocks of varying strengths depending on the pressure ratio will be formed emanating from the nozzle lip. The physical purpose of these oblique shocks is equalization of pressures between the exit plane and the ambient. If the pressure ratio is increased beyond that corresponding to the third critical pressure ratio, expansion fans will be formed at the lip of the nozzle.

Diffuser- the necessity of providing a diffuser



Nozzle of a free jet facility

Take the case of a free jet facility as in Fig. making use of a c-d nozzle of Mach number 3.0 exiting to the ambient conditions at one atmosphere pressure. In order to avoid shocks and expansion waves at the exit of the nozzle, p_e must be p_b. p_e



for a wave free exit flow from the nozzle.

Free jet nozzle with a test section

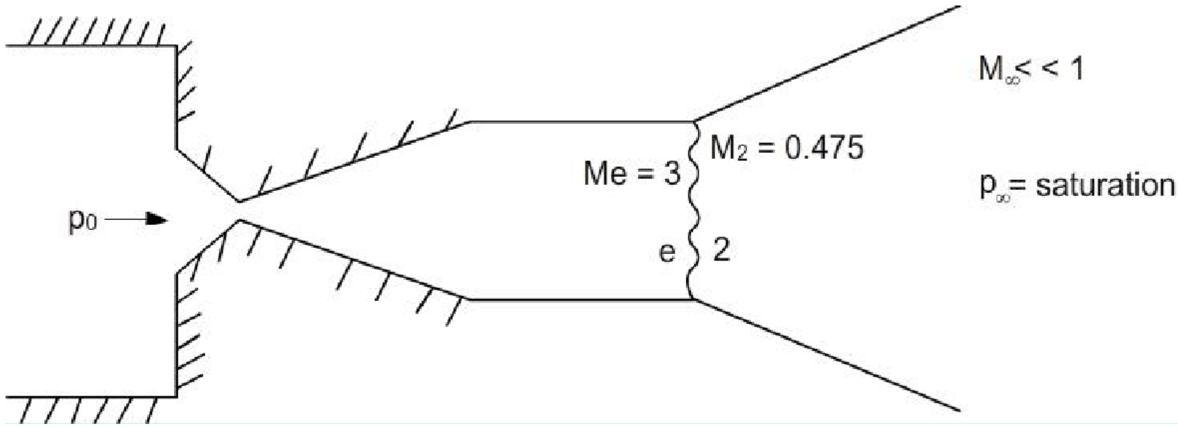
In the Figure b, a constant area section is added to the nozzle exit. The duct similar to the

test section (T.S) of a wind tunnel attached to the nozzle exhausts to atmosphere. p_e

corresponds to static pressure at the exit plane of the nozzle before the shock. Static pressure after the shock (p_2) is equal to ambient pressure.

In the equation above, p_e/p_2 represents the shock pressure ratio at M=3.0.

In the third case, as in Figure a divergent channel is provided after the constant area duct and the shock stands at the end of the constant area duct.

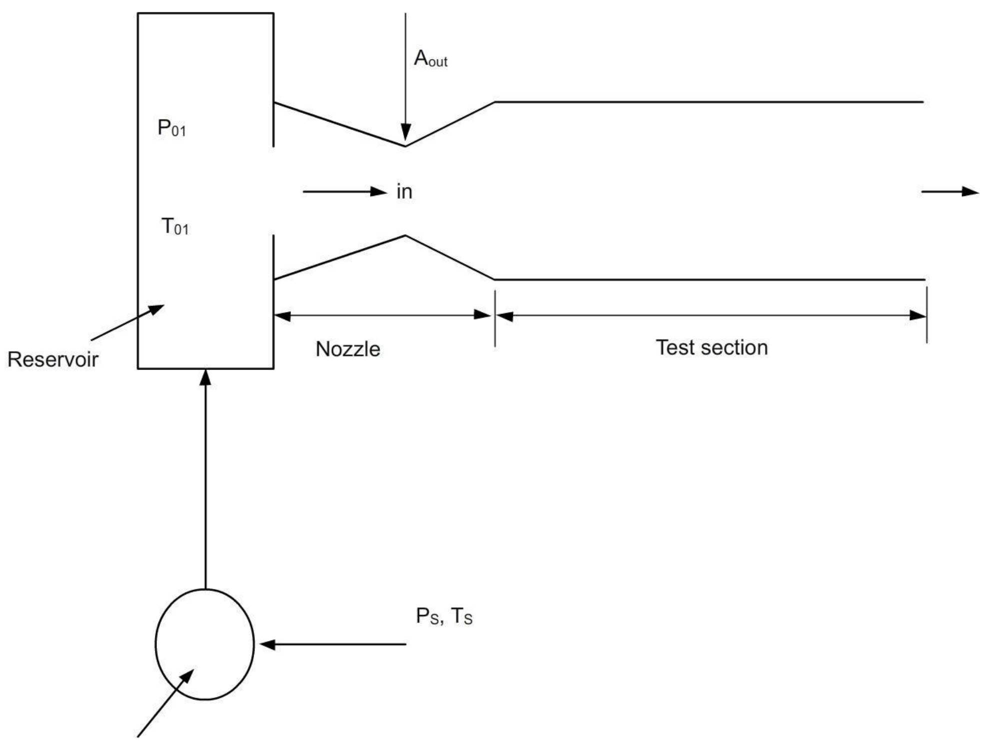


Free jet facility with test section and a diffuser

When M << 1, $p_o = p_\infty$

The three cases described above make it clear that provision of a diffuser of suitable design is required for reducing the pressure ratio required for the operation of the wind tunnel. It is shown in section that the power required to run the wind tunnel increases with the pressure ratio. In supersonic wind tunnels, most commonly used diffuser is of convergent divergent type (also called the second throat diffuser).

Power required for the operation of supersonic wind tunnel



Free jet type wind tunnel with an attached test section

Refer to figure where a free jet type wind tunnel is shown. Let the supersonic tunnel is specified by the Mach number (M) in the test section and test section (A) area .The throat area

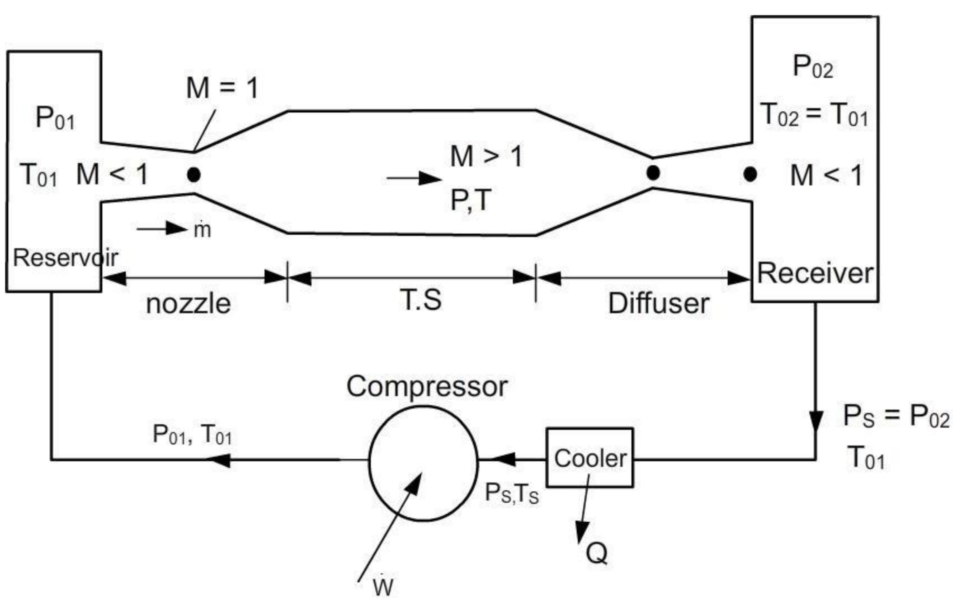
is specified as A_{NT}. The flow parameters in the test section are denoted as p, T, A etc.. Once M is specified, the area ratio A_T/A_{NT} and ratios of pressure and temperature p/p_{01} and T/T_{01} are all known from the isentropic equations. If the compressor is idealized (isentropic) the suction and reservoir conditions are related

The power required to operate the compressor may be found as follows:

If the compressor is isentropic, the work per unit time may be found from the enthalpy difference across the compressor.

The very large power required for the operation of a supersonic wind tunnel is attributed to the large operating pressure ratio. If the wind tunnel is equipped with a suitably designed diffuser and a closed circuit arrangement as shown in the next section, the stagnation pressure of the diffused high velocity air can be made use of by the compressor and the effective pressure ratio can be reduced.

Closed circuit supersonic wind tunnel



Continuous type supersonic wind tunnel

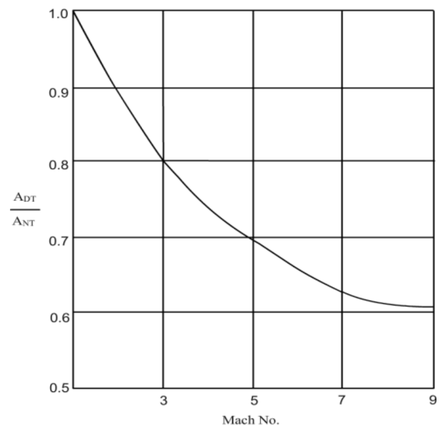
A convergent-divergent (c-d) diffuser is provided as shown in Fig. Only if the flow is isentropic, the stagnation pressure regained in the receiver following the diffuser (p_{02}) is equal to that of the flow entering the nozzle (p_{01}).

In that case, $p_{02} = p_{01}$

Then, $r_p = 1$, so that compressor does no work. In practical cases, because of entropy changes $p_{02} < p_{01}$ and $r_p > 1$. If the entropy change is confined to the region between the two throats, the diffuser throat area A_{DT} must be larger than the nozzle throat area A_{NT}. Diffuser throat area must be large enough to accommodate the stagnation pressure loss of the strongest shock. A cooler is included prior to the compressor because compressor work is proportional to the intake temperature.

The practical operation of the closed circuit wind tunnel may be explained as follows: As the tunnel is started, flow through it begins as subsonic and as the pressure ratio is increased the nozzle is choked. Further increase in the pressure ratio causes shock to be formed in the divergent section. At a pressure ratio corresponding to second critical pressure ratio, shock is formed at the exit plane of the nozzle which is same as the entry section to the test section. The formation of shocks during the starting process gives rise to fall in stagnation pressure. The total pressure after the shock is designated as $p_{02.}$ This necessitates that the diffuser throat is designed larger as decided by the ratio p_{02}/ p_{01}. The ratio of diffuser throat area to the nozzle throat is in the inverse ratio of total pressures given above.

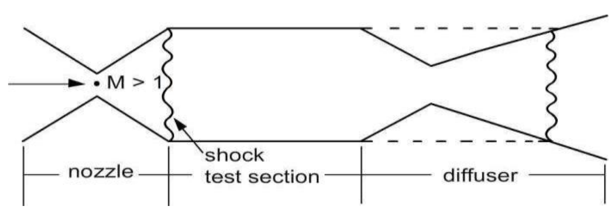
The ratio of areas for different test section Mach numbers calculated based on



normal shock losses is given in Fig.. This makes sure that the starting shock passes through the diffuser throat. The diffuser throat area calculated as above does not take in to account the non- isentropy of frictional flows and only the shock losses are considered.

Ratio of diffuser throat and nozzle throat for different test section Mach numbers

Assuming a frictionless operation, the shock may assume any section in the constant area test section. But, the effect of friction is to make the shock unstable in the constant area duct. The shock that is generated during starting of the tunnel does not stay at the nozzle exit (entry to test section) but is moved downstream by the effect of friction.



Shock movement from nozzle exit to diffuser

The starting pressure ratio minimum required to cater to the shock at the test section Mach number is corresponding to that for locating the shock at the nozzle exit. (worst shock)

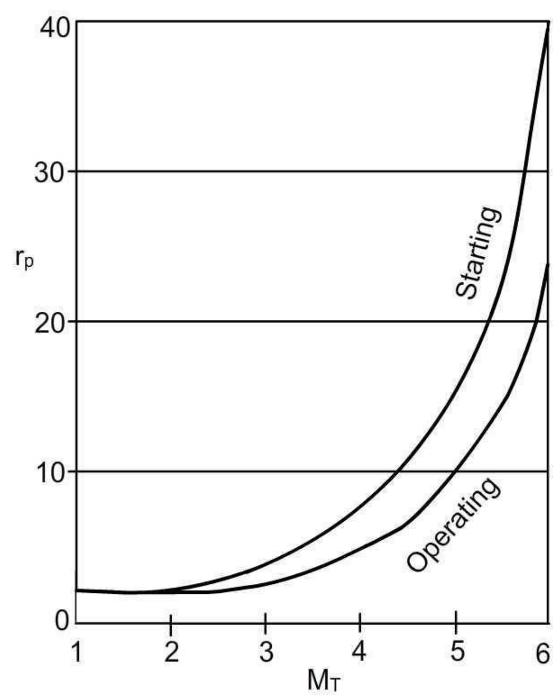
As the starting pressure ratio is maintained, the starting shock which moves down stream can be stable only at an area equal to that of the test section. In the convergent part of the diffuser the Mach number will be less than that in the test section. With the value of starting pressure ratio which produced the shock at the test section Mach number being maintained, shock losses at that Mach number is being catered to. Hence the starting shock stabilizes only in the diverging part of the diffuser at a section where there is equal area and Mach number as the test section.

The starting shock crossing the diffuser throat and remaining in its divergent part is called the '**swallowing of the starting shock'.**

It has to be remembered that as the diffuser throat is larger than the nozzle throat, the Mach number there will be more than one but less than that in the test section. After the brief

duration of starting, the pressure ratio may be decreased and the shock may be brought to the diffuser throat. Therefore the higher pressure ratio is required only during the starting when a shock at the test section Mach number is necessarily to be catered to and thereafter the pressure ratio can be that corresponding to shock at the diffuser throat. The smallest pressure ratio at which the tunnel may be continuously operated (r_{Po}) after its starting is that corresponding to the stagnation pressure loss of the weakest starting shock which can be made to occur at the diffuser throat.

In summary, the pressure ratio for starting the wind tunnel is corresponding to the normal shock losses at the test section Mach number and that for operation is that corresponding to normal shock losses at the diffuser throat. Hence the power required can be considerably reduced by incorporating the well designed diffuser and by judicious control of the two pressure ratios during 'starting 'and 'operating' of the wind tunnel.



Pressure ratios for starting and operating the wind tunnel of different Mach numbers

Actual flow in the supersonic wind tunnel

The boundary layer (B.L) thickness and the total loss of momentum increase with increasing distance from the 1^{st} throat. The growth of boundary layer thickness with distance from first throat is predictable and can be accounted for in the nozzle design. In the steady state operation, viscous effects between the throat and test section are not of much importance.

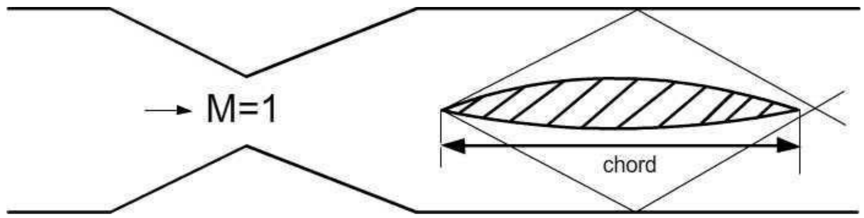
During the transient process in which tunnel is started, viscous effects are much important. So, important are these effects that pressure ratios required to start high Mach number tunnels are atleast 100% greater than the normal shock pressure ratio equal to normal shock losses.

B.L. is stable when the pressure is decreasing in the direction of its growth. When the pressure is increasing in the direction of flow, it has a tendency to separate. As normal shock passes through the nozzle, it imposes a severe unfavorable pressure gradient which can cause separation. If B.L separates, it disturbs the flow over a large portion of nozzle. If B.L. does not separate the high pressure gain in the downstream of shock will tend to flow to low pressure

B.L. and the flow in the duct will be altered over a significant length of the nozzle. In the diffuser viscous effects are predominant during starting and steady state operation of the wind tunnel. Unfavorable pressure gradient exists always. An oblique shock from the convergence creates additional pressure gradients when they strike the opposite wall.

Sizing the wind tunnel model

The theoretical unobstructed cross section area of the test section at the model required for starting is the same as the second throat area.



Typical shock wave pattern from a model

In choosing the dimensions of the model, reflection of shocks should be also considered. The oblique shocks formed as shown in Figure at the leading edge of the model get reflected from the wind tunnel wall. It has to be remembered that shock reflection is not specular which means that the angle of incidence of the shock at the test section wall is not same as that for reflection. The chord length of the model is so chosen that the reflected shocks do not interfere with the model.

Two problems in the operation of supersonic wind tunnels

(i) Condensation

The amount of moisture that can be held by a unit volume of air increases with increasing temperature. When the air isentropically expands to higher Mach numbers in the test section, the temperature falls. It may become super cooled. Moisture will then condense.

Factors affecting condensation

a) Amount of moisture in the stream
b) Static temperature of the stream
c) Static pressure of the stream
d) Time during which the stream is at low temperature

Effects of condensation

Condensation results in changes of local Mach number and other flow properties due to latent heat addition. The extent of changes depends on how much heat is released through condensation and may be evaluated using the two equations given below:

The notations used in the equations are:

dQ = heat added through

condensation H = enthalpy

per unit mass

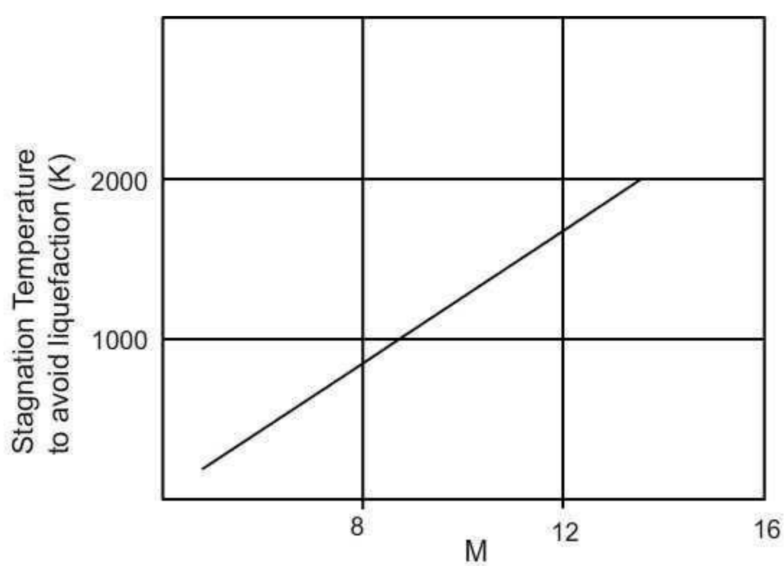
A = duct area

When M > 1, Mach no decreases and pressure increases. When M < 1, Mach no increases and pressure decreases.

Drying the working fluid is the best way to avoid condensation. Increasing the temperature by providing stagnation heaters is another solution.

(ii) Liquefaction

In a manner parallel to condensation, the components of air liquefy when proper temperature and pressure conditions are met. Liquefaction troubles might start around M=4 if high pressure air is expanded from room temperature.



Stagnation temperature to avoid liquefaction at different Mach numbers

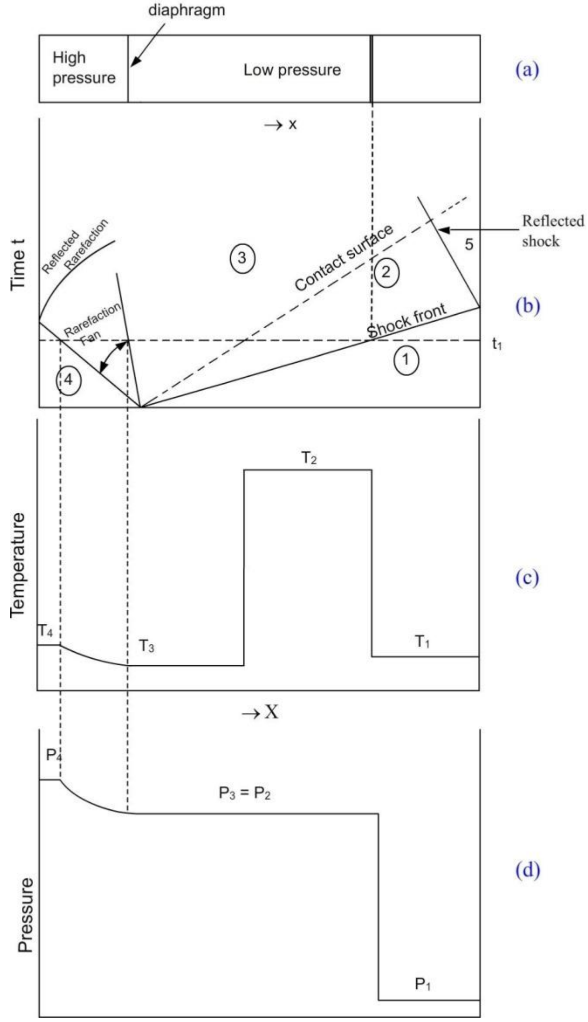
Fig. shows the stagnation temperature required to avoid liquefaction at different Mach numbers. It can be seen that corresponding to a Mach number above 12 the temperature required will be about 2000K.

Introduction on shock tube

The shock tube is a device in which a plane propagating shock is produced in a long tube by the abrupt rupturing of the diaphragm separating one section of the tube at higher pressure than that in the other section. This device, developed after a series of studies and experiments in mid 1800s started with the realization that waves from explosions travel at a velocity faster than the sound waves. In 1948 Sir George Stokes discussed the instability of finite amplitude sound waves. Paul Vieille (1899) measured the speed of the pressure pulse generated in a glass tube in which a thin diaphragm across a pressure ratio of 27atm was burst. This pioneering work on bursting diaphragm shock tube led others to follow similar experiments with different aims. Payman, Shepherd and other colleagues of Mines Research Board did a series of investigations on the ignition of explosive gas mixtures by shock waves. The first research paper making use of shock tube was published by the Royal Society and authored by Payman and Shepherd (1946). During the post 2nd world war period, led by many Universities around the globe the shock tube was developed as a tool for aeronautical research.

The shock tube

The shock tube is a long tube of uniform cross section and with uniform internal dimensions. The diaphragm separates the high pressure driver section from the low pressure driven or test section. The material of the diaphragm and its thickness are dictated by the pressure ratio between the sections. On abrupt rupturing of the diaphragm, pressure waves emanating from the diaphragm station coalesce to form



the shock front which propagates in to the low pressure section. As the shock front moves in to the low pressure section, a contact surface which is an imaginary line of separation between the driven and driver gases follows the shock front. The wave diagram of the shock tube after the diaphragm rupture is given in Figure

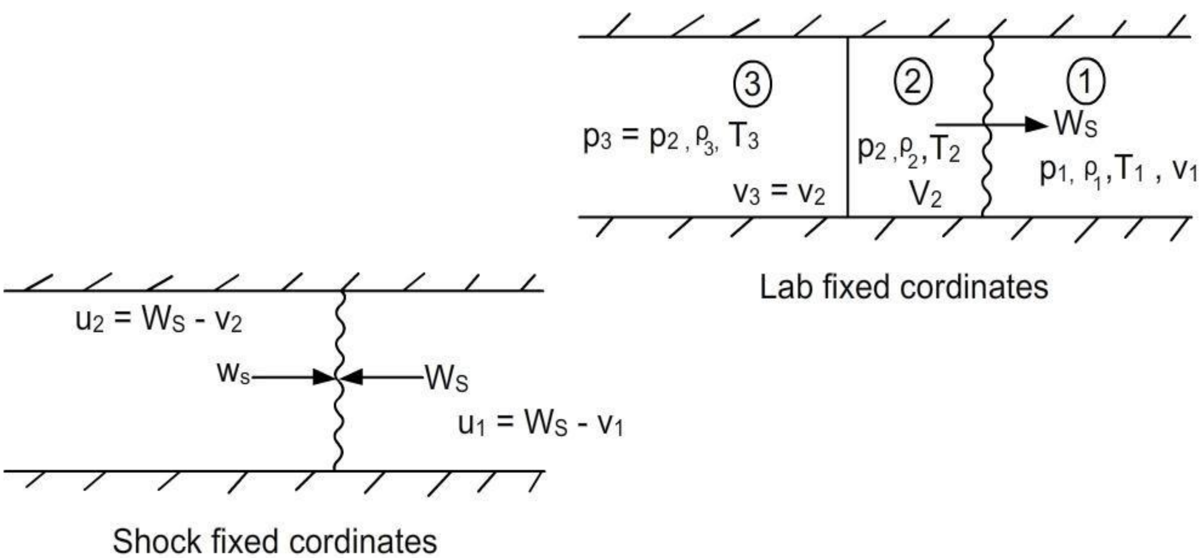
Simultaneously an expansion fan travels in to the driver section. The wave diagram in Fig shows these wave systems. The regions in the wave diagram are designated as 1, 2, 3 and 4. Region 1 represents the initial conditions in the driven section. The conditions of gas in this region are denoted by subscript 1.The Region 2 corresponds to the shocked gas conditions. The region between the contact surface and the expansion fan is referred to as 3. Region 4 represents the conditions of the initial high pressure driver gas.

The shock tube is a versatile experimental facility for the study of gaseous phenomena at elevated temperature and pressure. Along with the wave diagram, which is in the (x-t) plane, the diagrams showing the temperature and pressure history in the shock tube along its length are given in Fig. and at time. The temperature and pressure history corresponds to a particular time t_1 on the wave diagram. As shown in the figures, the experimental gas is brought almost instantly to a known and high temperature in region 2 and held at steady temperature and pressure for a few hundred micro sec. Usually there is some mixing and inter diffusion of gases at the contact surface so that the temperature fall is less sudden, than in the ideal case.

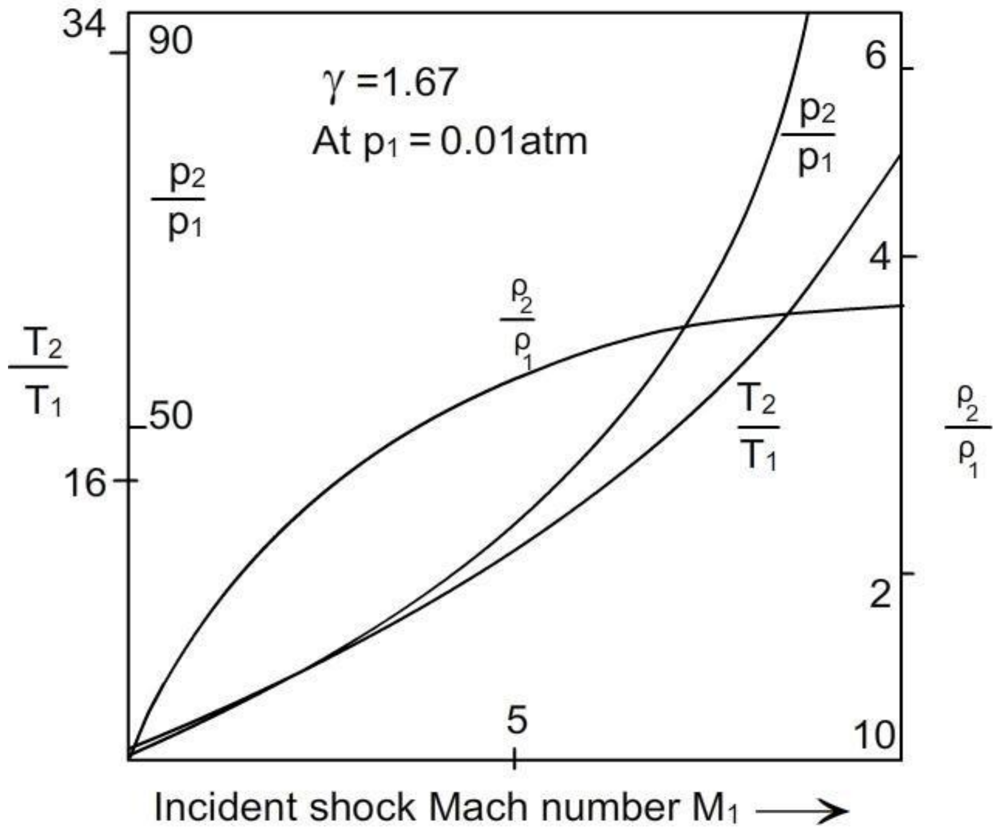
Shock tube equations

The equations applicable in the case of shock tube which are the moving normal shock equations may be derived considering the shock fixed coordinate system. In the figures, Ws represents the wave speed which is the speed at which the shock front propagates in the shock tube and v_1 and v_2 are the gas particle velocities ahead and behind the moving shock respectively. To convert the Laboratory fixed coordinates to shock fixed, wave speed Ws is applied in the opposite direction of the propagating shock.

u_1 and u_2 are the relative velocities in the shock fixed candidates



Laboratory fixed coordinates (b) Shock fixed coordinates



Theoretical ratios of shocked gas properties

Comparison between shock heating and isentropic heating

For a given pressure change (or density change) in a gas, the temperature produced by a strong shock wave is greatly in excess of those in the isentropic case. Shock wave is an irreversible adiabatic compression

Conservation of energy derived for flow where a resistance to motion occurs. In the case of shock wave, the abrupt pressure rise across the front presents a resistance to flow and as such implies an irreversible conversion of kinetic energy (K.E) into heat.

Across the shock front there is an increase of entropy, for an adiabatic process. From this, for a perfect gas

piston across which differential pressure is kept small.

Comparison between isentropic and shock heating

$\frac{p_2}{p_1}$	Shock Wave $(T_2\,K)$	Isentropic Compression $(T_2\,K)$	M_1
2	420	357	1.32
10	895	566	2.95
25	1753	735	4.45
50	3177	897	6.55

Illustration of calculation of particle velocity (v_2) and Mach number behind the moving shock

What is shown above is that increase of shock velocity (Ws) and consequently the shock Mach number will not correspondingly raise the Mach number after the shock (M_2) based on v_2. Understandably, the reason is the increase in the post shock temperature (T_2) and the value of speed of sound (c_2) after the shock to high values.

Reflected shocks

When the primary shock wave reaches the end of the shock tube it gets reflected back in to the medium which is already heated by the incident shock. Higher temperature and pressure are obtained behind the reflected shock. Additionally the gas behind the reflected wave is at rest relative to the shock tube.

Summarizing:

a) Much higher temperatures are obtained that too at high pressures. Dissociation is prevented because of increased pressures.

b) Study on a fixed group of molecules can be conducted. Behind the incident shock, the gas particles are moving with a velocity v_2 and it is impossible to follow a fixed volume of gas.

Reflected shock parameters

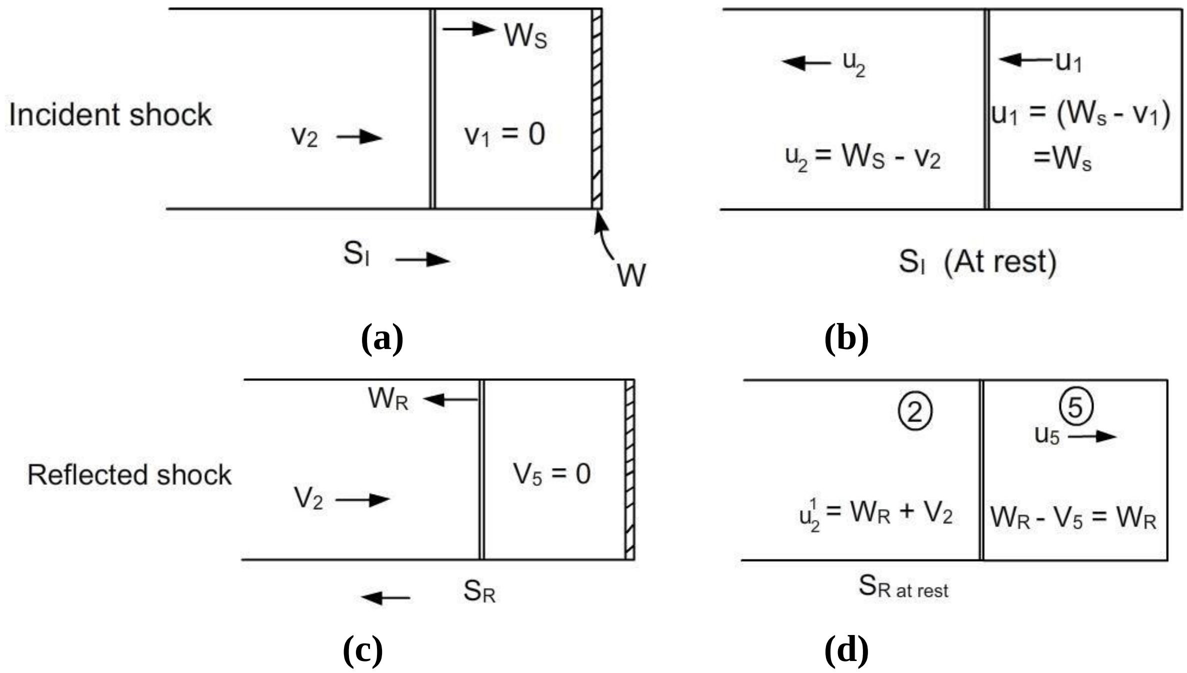


Fig. Incident and reflected shocks: (a&c) Laboratory fixed coordinates, (b&d) Shock fixed coordinates

Table Reflected shock parameters in terms of incident parameters

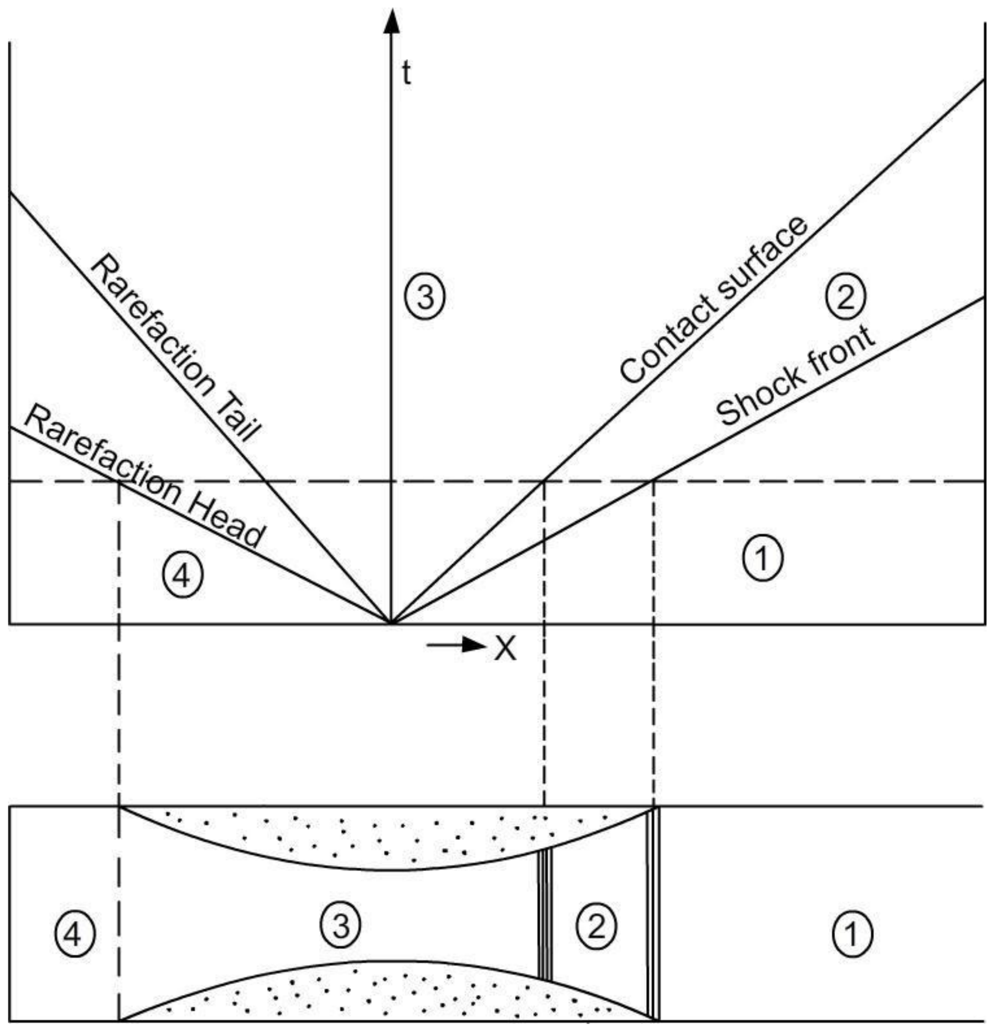
γ	**M_1**	$\frac{p_2}{p_1}$	$\frac{p_5}{p_2}$	$\frac{T_2}{T_1}$	$\frac{T_5}{T_2}$	$\frac{W_R}{W_S}$
1.4	2.95	10	4.95	2.62	1.76	0.423
	6.56	50	7.12	9.31	2.28	0.351
1.66	2.87	10	4.22	3.42	1.94	0.589
	6.34	50	5.54	13.4	2.34	0.517

Viscous effects and the shock tube boundary layer

Due to the viscous nature of the flow in the shock tube, boundary layer is formed. Its thickness will be zero at the shock front and increases back through the shock heated region and the contact surface in to the expanding driver gas and becomes zero again at the head of the rarefaction fan. Schematic of the boundary layer formed is shown in Figure . Important effects of formation of the boundary layer are the following.

1. Kinetic energy is dissipated as heat in the retarding layer of the boundary layer and this is conveyed to walls as by heat transfer.
2. Deceleration of the shock front.
3. Acceleration of contact surface.

One of the important effects of the formation of boundary layer is its reducing effects of the useful observation time in shock tube experiments.

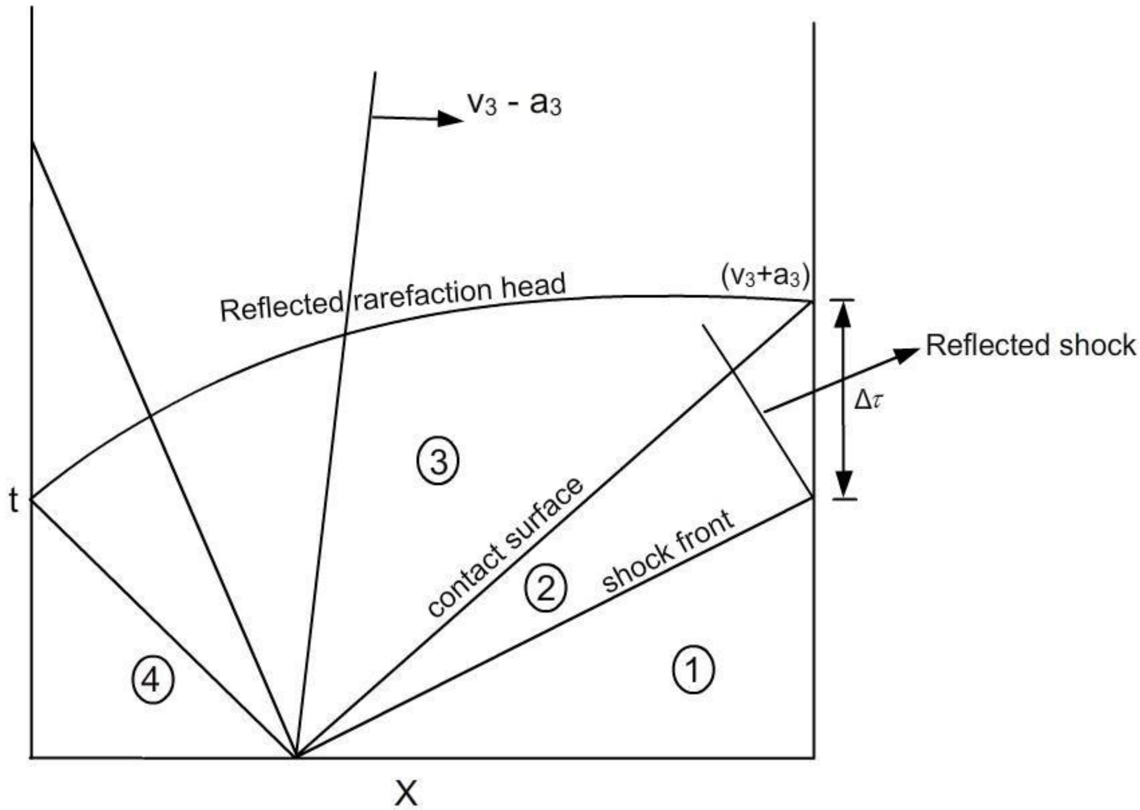


Schematic of the growth of boundary layer in a shock tube

Observation time in shock tube

Observation time is decided by

a) length of observation station from diaphragm
b) length of driver section [due to the influence reflected rarefaction fan]
c) length of end plate from diaphragm [influence of the reflected shock]
d) growth of the boundary layer



(x,t) diagram of the shock tube indicating the different waves

Interaction of reflected shock and contact surface

The reflected shock, after going through the shocked gas in the region 2 encounters the contact surface and the reaction will be dependent on the speed.

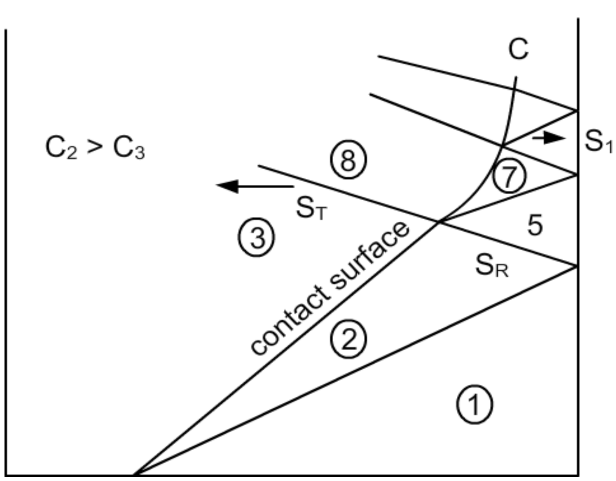


Fig. (a)

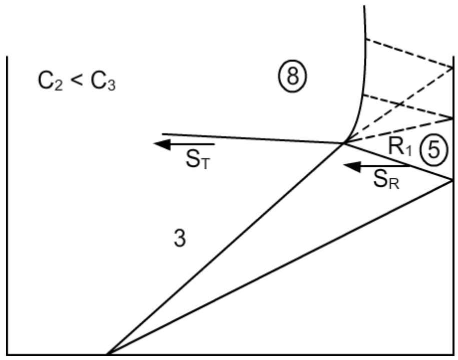


Fig. (b)

Time available for measurements in the reflected shock region can be improved.

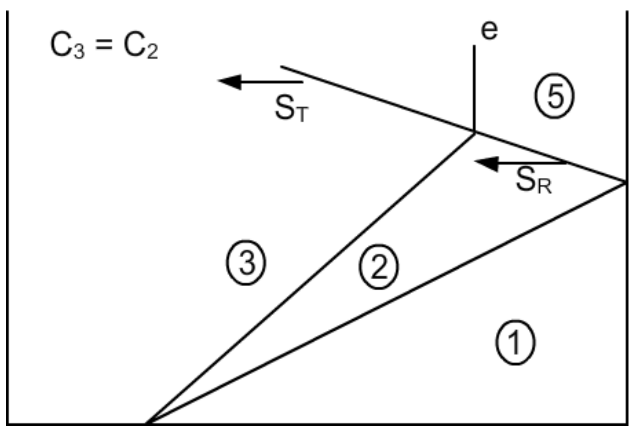


Fig.(c)

Fig. Interaction of reflected shock with the contact surface (a) $c_2 > c_3$ (b) $c_2 < c_3$ (c) $c_2 = c_3$

Speed of sound in regions 2 and 3. The schematic of the wave systems generated based on the values of c_2 and c_3 is shown in Figures (a) and (b). As shown in Fig.a when $c_2 > c_3$, the reflected shock after passing through the contact surface enters a region of higher Mach number. The resultant properties in the region 3 would be greater than those in regions 2.This is physically not feasible and in order to make the pressures on either side of the contact surface an additional shock system is generated in region 5. The opposite effect is there corresponding to the situation in Fig b where $c_2 < c_3$.The resultant wave system in the reflected shock region is an expansion wave. In both the cases, flow in the reflected shock region is disturbed by the additional waves generated. In order to have larger observation times behind the reflected shock c_2 is designed to be same as c_3.This is called ‘tailoring’ of the shock tube contact surface. The wave system when $c_2 = c_3$ is shown in Fig.c.Tailoring enhances the observation time behind the reflected shock.

Shock tube diaphragm and bursting techniques

Diaphragms vary from 0.025mm cellophane sheet to 6mm thick steel plate. For the same material the diaphragm rupturing pressure increases directly as the pressure and inversely as the exposed area.

1) pressure driving
2) Mechanical piston drive
3) Combustion driving
4) Heating of driver gas

Measurement of shock speed

Conventionally, the time distance method is used for the measurement of shock speed. Sensors of pressure or temperature are mounted flush with the interior of the low pressure section of the shock tube at known distance between them. Time taken by the propagating shock to transverse the known distance is used to calculate the shock speed. Though this is a simple method to implement, the speed obtained is an average value between the two stations. Other methods such as that making use of Doppler principle could give higher spatial resolution.

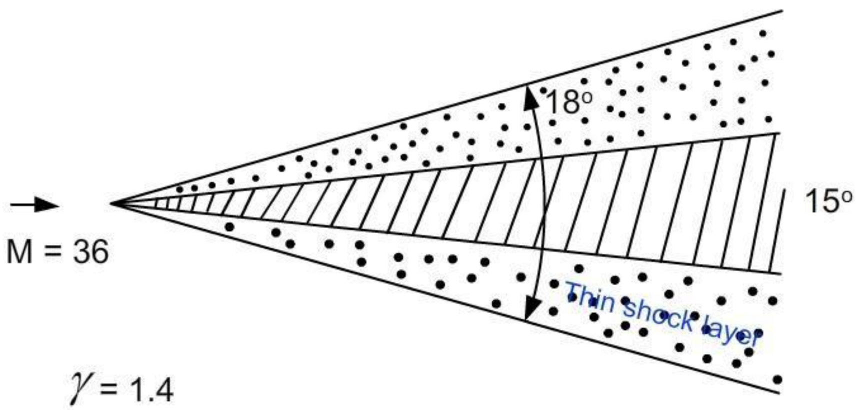
HYPERSONIC FACILITIES

Hypersonic flow - Special characteristics

Hypersonic regime is conventionally considered above Mach number of 5.0. Though there is nothing abrupt about this limiting Mach number, certain physical phenomena become progressively more important at such high Mach numbers. Some of the features of high Mach number flows are the following:

a) Thin shock layers

The oblique shock that is formed on the body in hypersonic body is closer to the body than at lower Mach numbers.

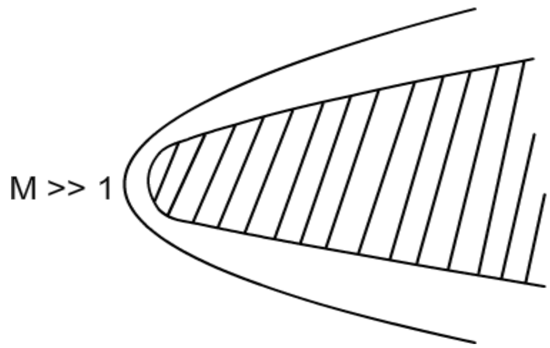


Thin shock layer over a hypersonic body

In the Fig a 15^0 wedge is shown encountering a flow at a Mach number of 36. At higher density the mass flow behind the shock can squeeze through smaller areas. Shock waves lie close to the body. One of the most important effects of this is that the shock layer and boundary layer merge.

b) Entropy layer

In front of a blunt body in high Mach number flows, a detached shock as shown in Fig.is formed. The shape of the shock and the detachment distance depend on factors like the flow Mach number and the shape of the body.

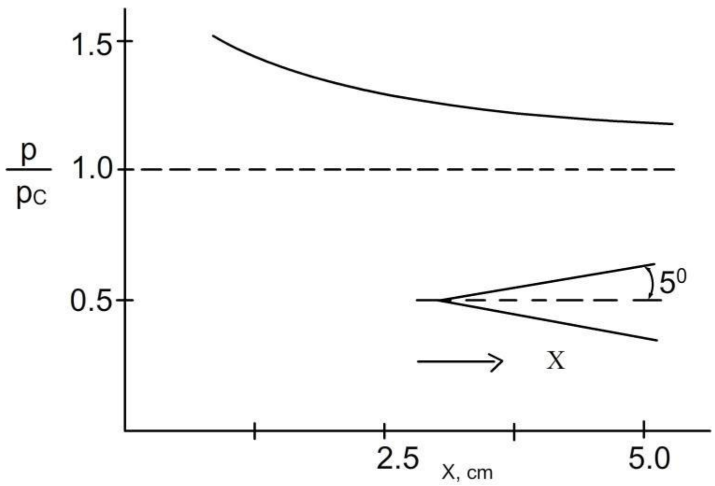


The entropy layer

The bow shock thus formed is a combination of all possible shocks from normal shock in the stagnation region to Mach wave far away from the central region. The stagnation streamline will undergo a large increase in entropy compared to a streamline that undergoes a weaker shock. This gives rise to strong entropy gradients among the streamlines. This entropy layer flows downstream and wets the body for large distances from the nose. The boundary layer is inside the entropy layer. According to Crocco‟s theorem, the entropy layer is a region of vortices too.

c) Viscous interaction

Hypersonic flow contains large kinetic energy. When slowed down by viscous effects, the kinetic energy is transformed into internal energy. Coefficient of viscosity increases with temperature and this by itself makes the boundary layer thicker. Density decrease also causes increase in boundary layer thickness. Viscous interactions have important effects on surface pressure distributions and hence on lift, drag etc. Skin friction and heat transfer are increased by viscous interaction.



p_c = pressure on surface of the cone without viscous interaction

Pressure distribution on a sharp cone in viscous flow

shows the pressure distribution on a 5^0 right circular cone in a flow of Mach number 11.0. The figure shows the pressure distribution from the experiments [Ref: „Hypersonic viscous flow over cone at Mach11 in Air ", J.D. Anderson, Wright Patterson Airforce Base, Ohio July 1962] .The dotted line represents that calculated with inviscid assumptions. The pressure distribution is given as a function of distance „x" in inches from the nose.

d) High temperature flow

Friction causes heating of the body even beyond the melting point of hypersonic bodies. The high value of kinetic energy is dissipated by the influence of friction within the boundary layer. This dissipation gives rise to high temperatures. Real gas effects become important at the higher temperatures. Depending on the temperature range vibrational energy of the molecules will be excited or dissociation or ionization of the gas will take place. If the hypersonic body is protected by an ablative heat shield, the products of ablation will also be present in the boundary layer. It is not only the boundary layer that is affected by the hypersonic flow. For example, the forward region of the body is elevated to enormously high temperatures due to shocks. Shock waves generate a region of high temperature and pressure setting up complex reactions. In short, around the body there will be high temperature, chemically reacting flow.

High temperature chemically reacting flows can have influence on lift drag and moments on a hypersonic vehicle. Most predominant effect of high temperature flows is the high heat transfer rates to the body caused by the aerodynamic heating .The aerodynamic heating causes heat transfer (called as convective heating) from the hot boundary layer to the cooler surface of the body. Additionally, the high temperature of the shock layer at high Mach numbers and the thermal radiation cause radiative heat flux to the body. At high Mach numbers the radiative heat flux constitutes a significant percentage of the total heating.

Among the commonly used gases dissociation of O_2 begins at 2000K and gets completed at 4000K. N_2 dissociation begins at 4000K and is totally dissociated at 4000K. Above 9000K ionization happens in the case of N_2.

$$N \rightarrow N^{+} + e^{-}$$

$$O \rightarrow O^{+} + e^{+}$$

Gas becomes partially ionised at higher temperatures. Ionisation produces positive ions and free electrons which absorb radio frequency radiation. This happens at certain velocities and at certain altitudes. Under such conditions radio waves can not be sent to or from the hypersonic vehicle and this is referred to as “communication black out”.

e) Low density flows

Hypersonic flights take place at high altitudes through outer regions of atmosphere. Low density flows are characterized by the Knudsen number(Kn) .They are classified based on the value of Knudsen number(Kn) which is defined as:

Kn = Mean free path/ characteristic dimension = $Kn = \lambda / L$

- Continuum $Kn < 0.01$
- Transition $0.1 < Kn < 10$

- Free Molecular   Kn > 10

The region between continuum and free molecular regimes, neither Navier- Stokes nor Kinetic theory solutions are possible.

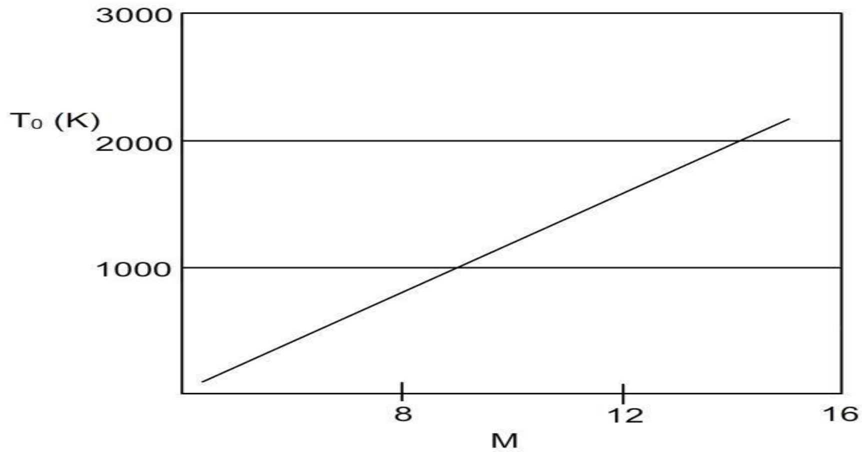
Hypersonic facilities

Because of the special features of the hypersonic flows, the facilities required for hypersonic testing are of specialized nature. Some of the commonly used facilities are:

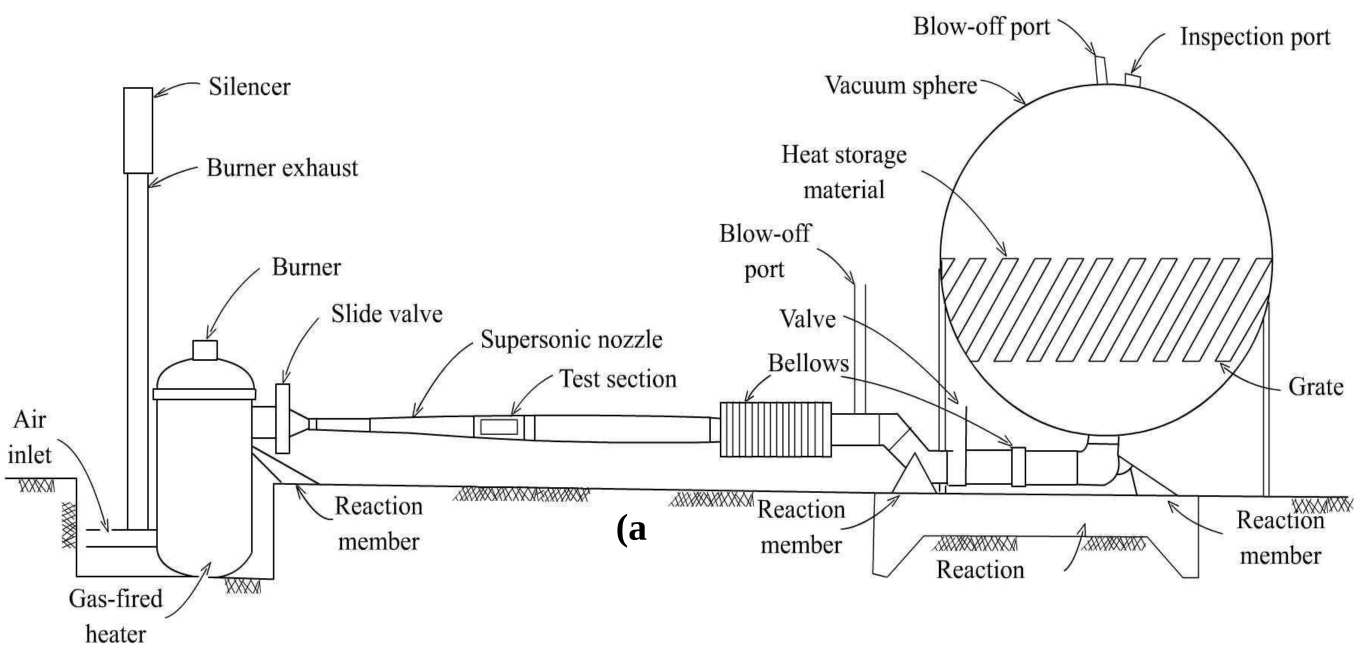
1) Hypersonic wind tunnels with air heater
2) Hypersonic shock tunnels
3) Free piston tunnel / Gun Tunnels
4) Plasma arc tunnels
5) Ballistic ranges

Wind tunnels with air heater

In principle, they are similar to supersonic wind tunnels. The point of difference is that as the Mach number of the supersonic wind tunnel is higher, the static temperature (T) in the test section falls for a given stagnation temperature(T_0).If the static temperature falls below 90K, air, which is the working fluid, liquefies. The minimum stagnation temperature to avoid liquefaction of air at different Mach numbers is given in the Figure . Another way to increase the Mach number with ordinary stagnation temperature is to use alternate working fluid such as Helium which has lower boiling point than air though it has limitations of loosing dynamic similarity. Conventional wind tunnels for higher Mach numbers usually make use of storage heaters.



Stagnation temperature to pressure liquefaction



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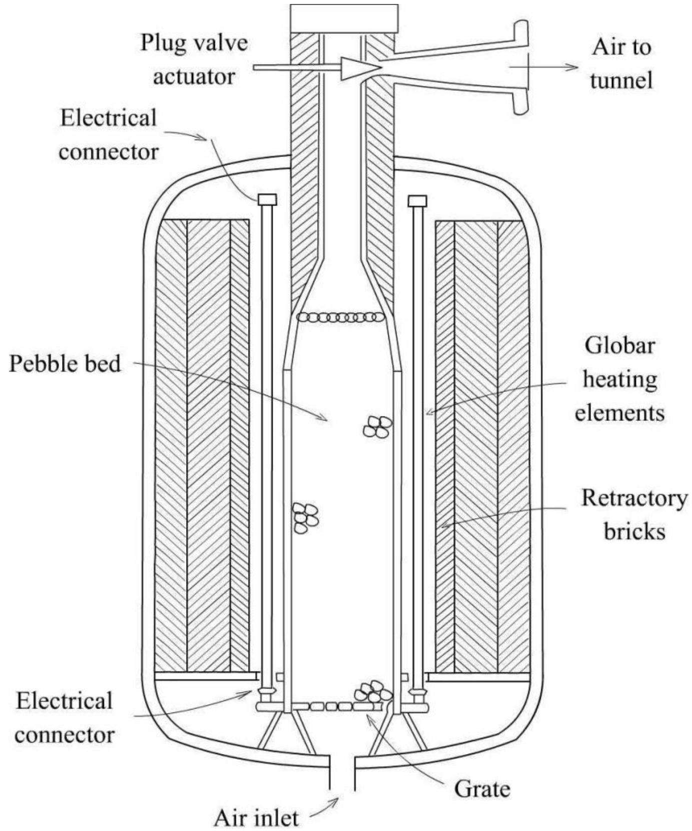


(b)

a) Schematic of the conventional hypersonic wind tunnel

b) Schematic of the pebble bed air heater

One such heater unit is shown in Figure b. The schematic of an hypersonic wind tunnel employing a storage heater is given in Fig. . The bed of pebbles of refractory material is heated using products of combustion of hydrocarbon fuels or by electric heating. Once the bed reaches its maximum temperature, compressed air is led through the heated matrix to the wind tunnel. There are limitations of maximum temperature of the bed arising primarily from the maximum permissible temperature of the refractory pebble and of the casing material .The maximum temperature reached by the working fluid through such heaters is about 2200K. Much higher temperatures (6000 to 10,000K) required for higher temperature experimentation can be reached only by plasma heating. The most vulnerable part of the conventional hypersonic wind tunnel with air heater is the throat section due to the high thermal stresses. The throat is usually made of a replaceable segment.

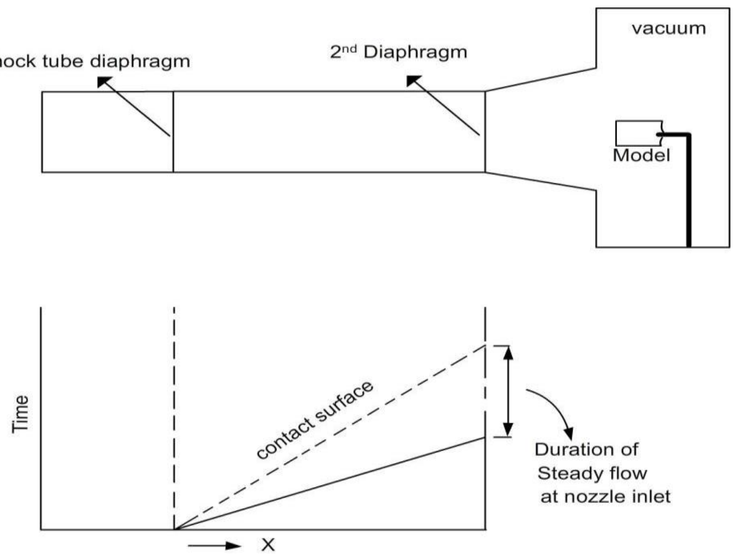
Hypersonic shock tunnels

As described in Chapter 3, the shock tube itself is a good experimental facility for short duration, high enthalpy, high velocity experimentation in various areas of science and technology though it is not a high Mach number facility. The shock tunnels are shock tube based facilities which make use of the high enthalpy high velocity flow in the shock tube. Shock tunnels are of two modes (i) straight through mode (ii) reflected mode.

a) Straight through mode of hypersonic shock tunnel

Fig. gives the schematic of the straight through mode of the shock tunnel. Important features of the straight through mode of hypersonic tunnel are the following. The nozzle attached at the far end of the driven section of the shock tube is diverging. A thin second diaphragm separates the shock tube section from the nozzle section. The second diaphragm offers no resistance to the shock and its purpose is to act as a separation between the shock tube and the tunnel section**.** This enables the two sections to be maintained at different levels of pressure. The incident shock generated in the shock tube should be of sufficient strength that

the Mach number of flow behind the shock (M_2) should be supersonic. The stagnation conditions of the flow in the nozzle are those corresponding to M_2. The diverging nozzle accelerates the flow to reach much higher hypersonic Mach numbers. The nozzle exhausts in to an evacuated dump chamber which is of large volume to prevent any possible reflections of the waves returning to the model. The straight through shock tunnels are designed so as to get Mach number in the range up to ~ 6.0 in order that the nozzle dimensions are of reasonable dimensions.

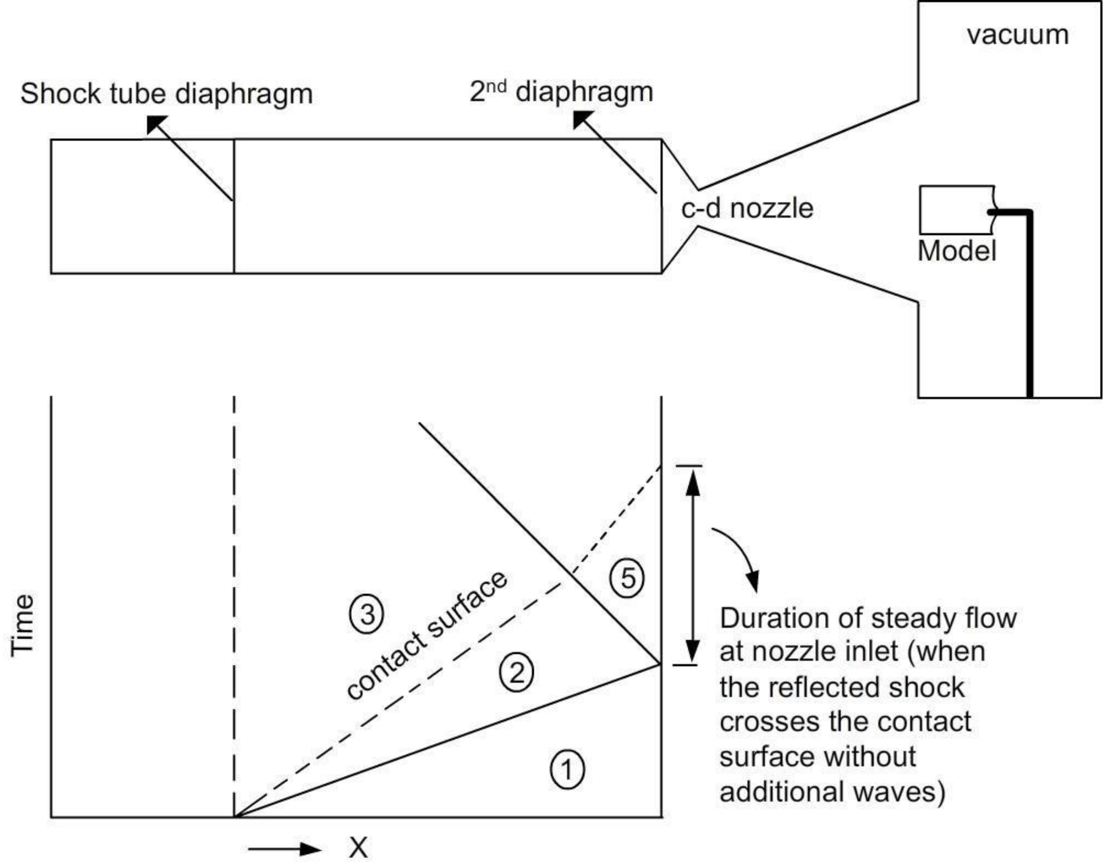


Hypersonic shock tunnel of the straight through mode

b) Reflected mode of shock tunnel

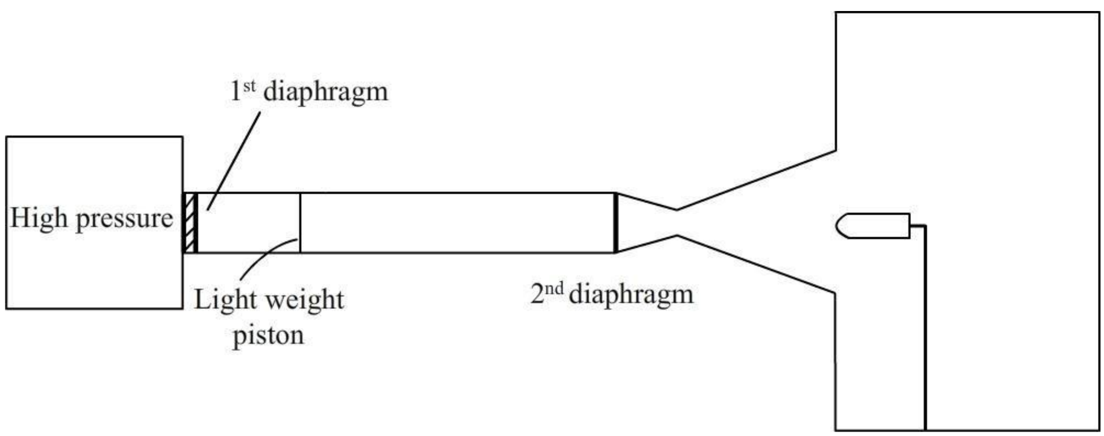
Figure shows the reflected mode of the hypersonic tunnel as in the case of the straight through mode a thin second diaphragm is kept at the end of the shock tube. The major difference from the straight through mode of the shock tunnels is in the use of the c-d nozzle.

The incident shock goes through the second diaphragm without any resistance and gets reflected on the short convergent part of the c-d nozzle. On reflection, the reflected shock parameters T_5, p_5 etc are the stagnation conditions of the flow through the c-d nozzle of large area ratio which expands the flow to higher Mach numbers. Much higher run times of the shock tunnel can be obtained by tailoring the contact surface. In case of reflected mode of the shock tunnel also, the evacuated dump chamber prevents possible reflected waves.



Hypersonic shock tunnel of the reflected mode

Adiabatic shock tunnel or Gun tunnel



Adiabatic shock tunnel

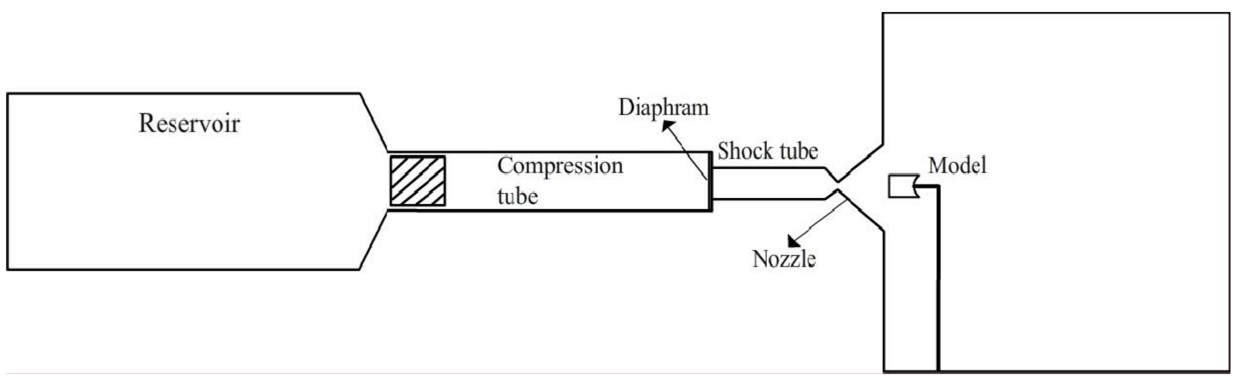
Important features

1) High temperatures are obtained by adiabatic compression.
2) It consists of a long tube down which a freely fitting light weight piston travels at supersonic speed. The piston mass is typically 4 to 15grams for say

40mm diameter. The piston is so light that they can be easily accelerated to high velocities/supersonic speeds.

3) The shock formed ahead of the piston is repeatedly reflected from the diaphragm at the far end of the tube.
4) Gas enclosed between piston and second diaphragm attains high temperature and pressure. The piston comes to rest with equal pressure on both sides.
5) At the time of rupture of the gun tunnel diaphragm, stagnation temperature up to say 3000K is attained.
6) Because of piston limitations, the ratios of driver to driven pressures are considerably less than in a shock tube.

Free piston tunnel or Stalker tube

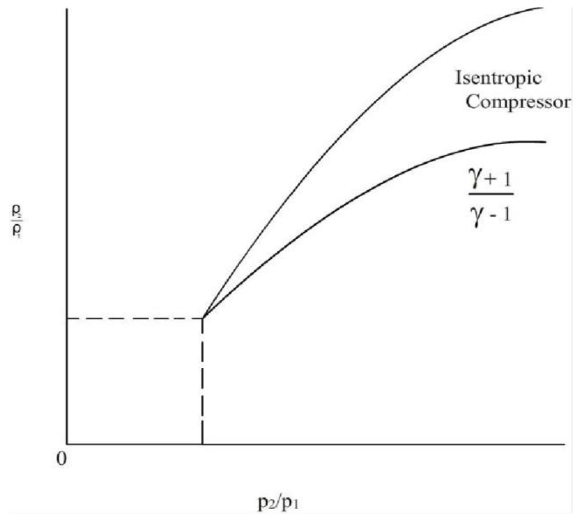


Free Piston Tunnel or Stalker Tube

References

7) Development and use of free piston wind tunnels J.L Stollery and R.J. Stalker 14th International Symposium on Shock Waves (Sydney).
8) Recent Developments with free piston drivers **R.J**. Stalker 17th International Symposium on Shock Waves (Leighh) 1989.
9) A Study of the Free Piston Shock Tunnel R.J. Stalker AIAA Jl. Vol.5 No.12 p.2160 1967.

The Rankine-Hugoniot equations give the relation between the density and pressure ratios across a shock wave as below. The plot in Fig. gives the relation along with that in an isentropic compression graphically.



Relation between the density and pressure ratios

In the case of piston motion in a cylinder, at one end of the spectrum, the piston mass is zero corresponding to a conventional shock tube. The compression is done by a highly non- isentropic plane propagating shock. The facility utilizing this becomes usual reflected type shock tunnel. On the other end, it can be heavy piston executing isentropic compression. The

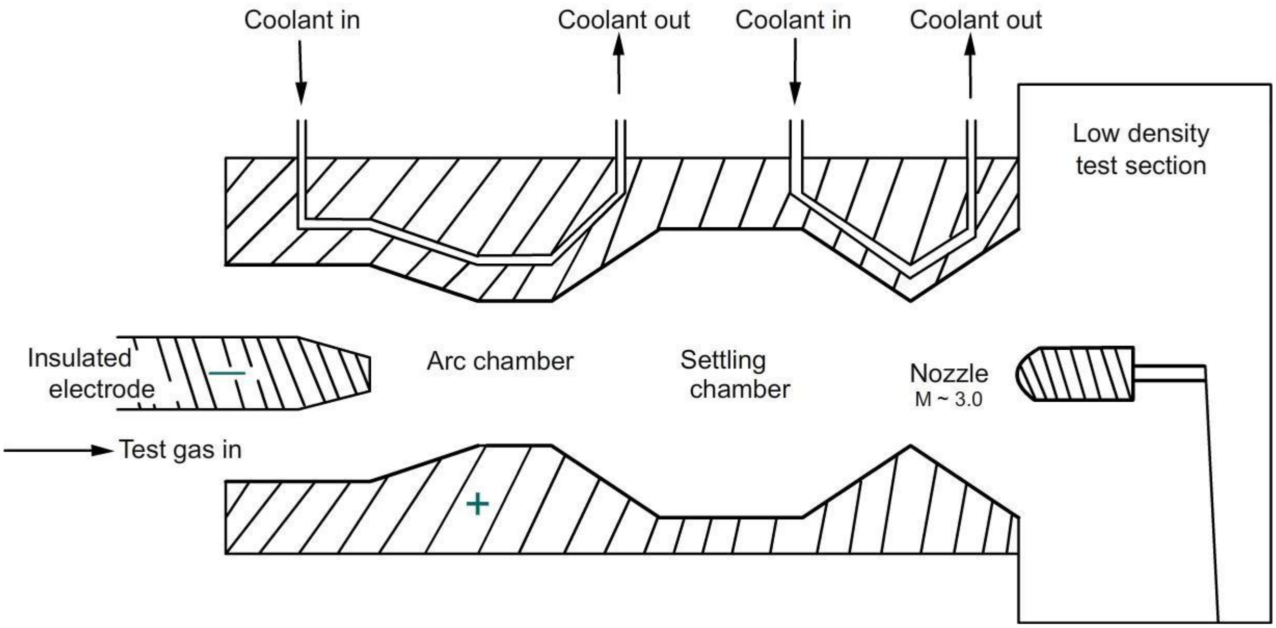
density increase due to the shock is limited to an asymptote
isentropic compression is infinite. The free piston tunnels attempt to provide the driver conditions in a shock tube driven facility much higher than which can be reached in conventional shock tubes by combustion/detonation and so on. In a conventional shock tube the shock Mach number is dependent among other factors, on the properties of the driver and driven gases.

The driver gas conditions are denoted by subscript „4‟. Raising speed of sound in the driver gas is an effective way of producing higher Mach number shocks without the use of very large pressure ratios across the diaphragm. For a M_1 ~18 and for keeping diaphragm pressure ratio less than 30,000 [with the objective of not storing driver gas at pressure above 2000bars], the ratio of c_4/c_1 should be atleast 10. This means that a driver gas with a speed of sound of 4km/s is required to if the test gas (air) is at room temperature. If Helium is assumed the driver gas, for getting a speed of sound of 4km/s the T_4 has to be ~ 4600K. This is what is achieved in a Free Piston Tunnel. Using a piston which is pushed in to the compression tube, the temperature of 4600K can be reached if the volumetric compression ratio is ~60.

Stalker tube is a free piston driven shock tube facility using compressed air at 200atm to drive a heavy piston into helium initially at 2 atmos. When the piston comes to rest at the end of the compression tube the helium pressure and temperature reach 2000atm and 4500K. At this condition the shock tube diaphragm is burst and the shock tube flow is initiated. On rupture of the shock tube diaphragm, it functions as a shock tunnel.

Plasma arc tunnels

Plasma arc tunnel consists of 1) Arc chamber 2) Nozzle 3) Evacuated test section. Arc is stuck between insulated electrodes in the arc chamber and the body of the arc chamber. They use high current arc [10^6A] to heat the test gas to a high temperature. Operational for few minutes, temperature up to 12000K is easily obtained. The temperature of the test gas is raised to an ionisation level and test gas becomes a mixture of free electrons, positive ions and neutral atoms.

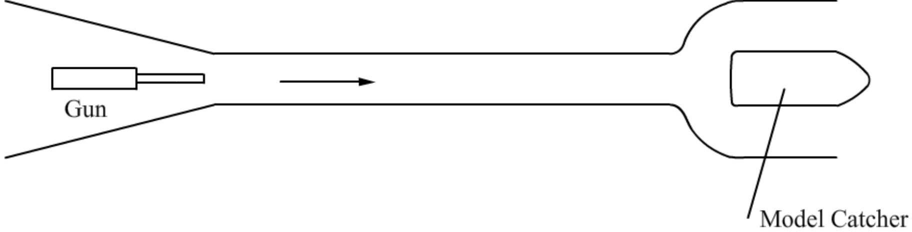


. Schematic of a Plasma arc tunnel

Stagnation pressure is usually less and the temperature is high. Because of the problems associated with the oxidation at high temperature an inert gas such as Argon is used as test gas. Plasma arc tunnels are not high Mach number facilities and the plasma is expanded to moderate supersonic Mach number of ~3.0 only. Possible application of plasma arc tunnel is in material testing at high temperatures.

Ballistic ranges

Ballistic ranges are Free flight facilities. They consist of long tubes into which model are launched from a special gun. Full scale Mach number and temperature can be obtained projecting the model at actual flight velocity. Reynolds number can be obtained by adjusting the pressure in the tunnel. Actual free flight velocities can be obtained.



Schematic of a ballistic range

Special guns are in use in which light gas propellants are burned or heated by adiabatic compression or electric heating. Muzzle velocity upto 4.5km/sec is reported to have been reached in such cases. Reynolds number could be varied by changing the pressure in the tube.

The position and trajectory of the model are determined in space and time by observing the model at a number of points along its flight path. A series of antennas along flight path are mounted to receive signals from transmitters inside the model. The transmitter should withstand high accelerations.

All components of the transmitter are cast in epoxy which forms body of the model. Stability characteristics at different flight velocity can be studied .Direct photography of the model is also possible.

The advantages of ballistic ranges are that high Mach no and Reynolds no can be obtained. Absence of interference from model supports is another advantage. Directness of the measurements of flight velocity and gas parameters is considered advantageous too although it is more labor consuming involving more complicated instruments.

Low density wind tunnels

Hypersonic flights take place at high altitudes where density is considerably lower compared to sea level (S.L) conditions. For example, at an altitude of 48km density is $1x10^{-3}$ of that in sea level. At an altitude of 85 km, density is $6.5x10^{-6}$ of S.L.value. At these high altitudes the mean free path and the Knudsen number are very large. The Navier - Stokes equations are not usable for explaining the flow in these conditions. Facility required to simulate these conditions is different from the conventional wind tunnels.

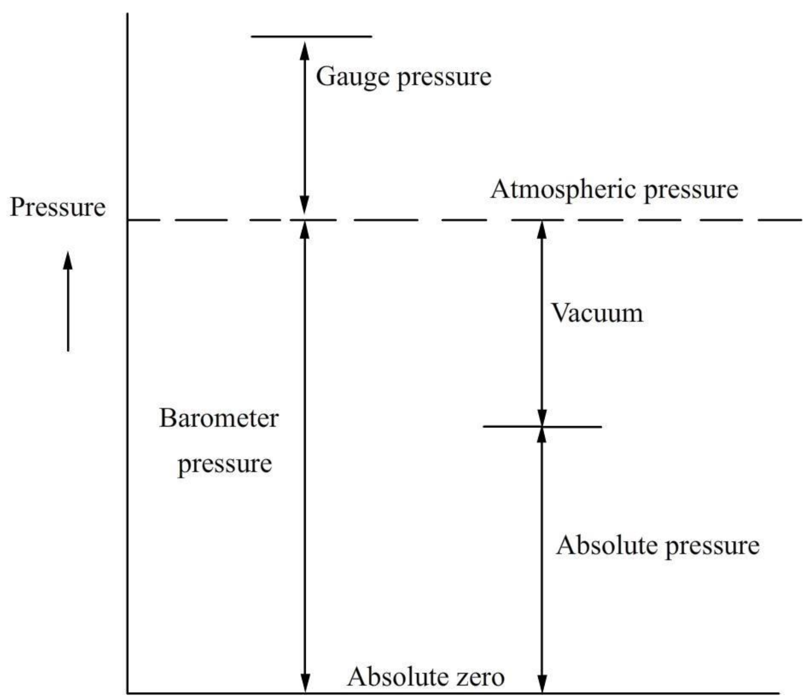
Low density wind tunnels are essentially vacuum facilities with specialized measurement devices suited to low pressure conditions. The level of vacuum reached in the facility is in a way simulates the altitude that is simulated in the facility. Measurement of pressure, temperature, and forces is possible using specialized devices/methods.

Conventional visualization methods are not applicable to visualize the flow under low density conditions as the optical methods require certain level of molecular density. Usually electric discharge method is used for visualizing low density flows. It works on the principle that electric discharge in gases at low pressure is accompanied by emission of flight. .Intensity of this radiation depends on density of gas.

UNIT-IV PRESSURE, VELOCITY & TEMPERATURE MEASUREMENT

Introduction

Pressure measurement is important in many fluid mechanics related applications. From appropriate pressure measurements velocity, aerodynamic forces and moments can be determined. Pressure is measured by the force acting on unit area. Measuring devices usually indicate differential pressure i.e. in relation with atmospheric pressure. This is called gauge pressure. The measured pressure may be positive or negative with reference to the atmospheric pressure .A negative gauge pressure is referred to as vacuum.



Explanation of the pressure terminology

Units of pressure

1Pascal($1N/m^2$) = 10dyne/cm^2

1mmHg = 133.32pascals

=

13.595mm Water Standard atmosphere = $1.013 * 10^5 N/m^2$

1 millibar = 1000 dyn/cm^2

1 micron = 10^{-6}mHg

1 torr = 1 mmHg

= 1000micron

Absolute pressure

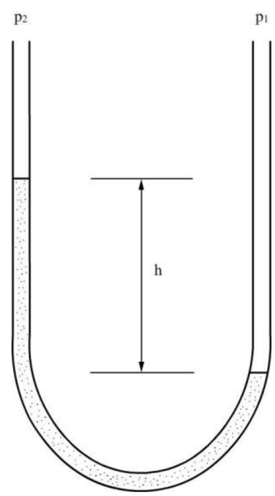
Absolute pressure is determined as algebraic sum of the readings of a barometer and of a manometer showing the gauge pressure. Manometers which measure absolute pressure are also available. They measure the pressure with reference to absolute zero pressure.

Pressure measuring devices

Main characteristics of manometers are pressure range, accuracy, sensitivity and speed of response. Pressure range of manometers varies from almost perfect vacuum to several hundreds of atmosphere. The conventional instruments used for pressure measurement are divided into the following groups.

1) Liquid column manometers
2) Pressure gauges with elastic sensing elements
3) Pressure transducers
4) Manometers for low absolute pressures
5) Manometers for very high absolute pressures

5.2.1 Liquid column manometers



Liquid column manometer

For amplifying the deflection in a liquid column manometer, liquids with lower density could be used or one of the limbs of the manometer may be inclined. Commonly used manometric liquids are mercury, water or alcohol. Some of the important and desirable properties of the manometric liquids are:

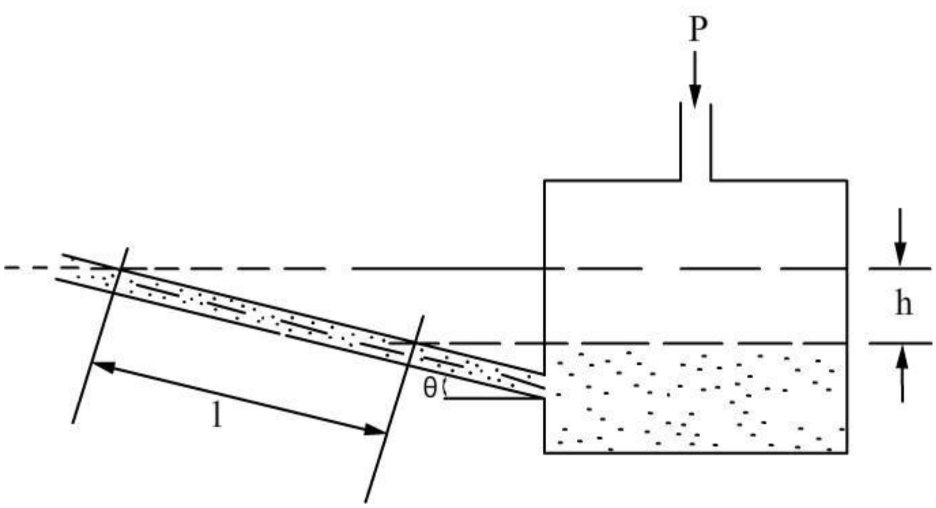
- High chemical stability
- Low viscosity
- Low capillary constant
- Low coefficient of thermal expansion
- Low volatility
- Low vapour pressure

High thermal stability and low volatility are important for maintaining a constant. Specific gravity. High viscosity causes transmission lags .Thermal expansion causes changes in zero reading. While measuring low pressures, vapour pressure of the manometric fluid is an important consideration. Properties of some of the commonly used fluids are given in the Table .

Typical properties of manometric fluids

Fluid	Specific gravity	B.P.(°C) at 760mm Hg	Surface Tension dyn/cm	Viscosity C_P	Coeft.of Volumetric Expansion $*10^5$
Methyl Alcohol	0.792	64.7	22.6	0.59	
Ethyl Alcohol	0.789	78.4	22.0	1.9	110
Mercury	13.55	356.59	465	1.55	18
Toluene	0.866	110.8	28.4		
CCl_4	1.594	76.8	26.8	0.97	

Inclined manometer



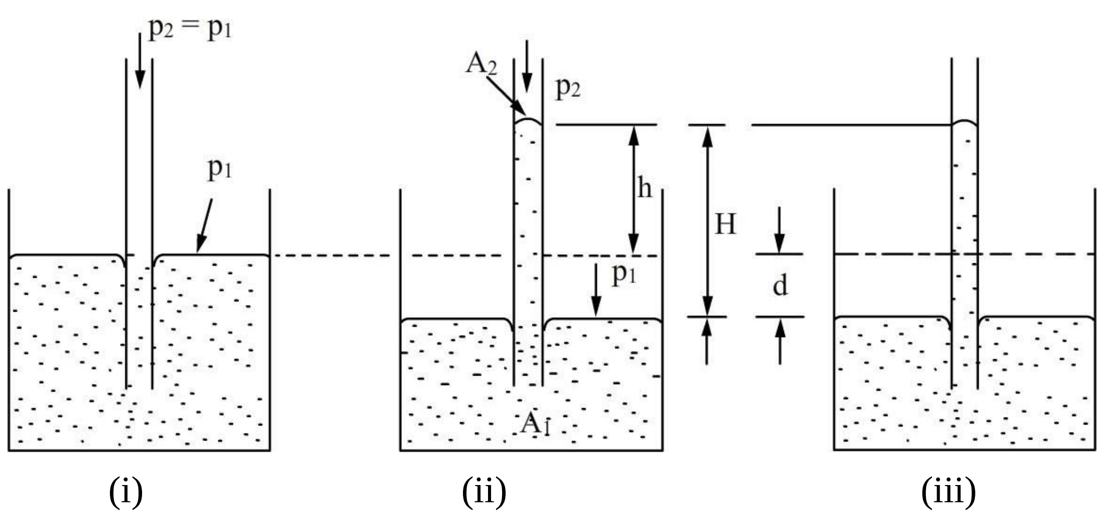
Inclined manometer

The Figure shows the amplification of the reading of applied pressure „h" as

$$\frac{h}{l} = \sin\theta$$

Mercury barometer

Barometer is the device used to measure the atmospheric pressure. Mercury barometer consists essentially of a glass tube sealed at one end and mounted vertically in a bowl or cistern of mercury so that the open end of the tube is submerged below the surface of mercury in the cistern. In the Fig. (i) the zero level of mercury in the cistern is shown under the influence of atmospheric pressure p_1. When p_2=p_1 = atmospheric pressure, the zero level in the cistern can be marked. If the tube is open and if different pressures act in the cistern and in the tube, then there will be difference in the levels of mercury. If p_1 is greater than p_2 as shown in Fig. (ii), then mercury will be forced down in the cistern and corresponding rise will be there in the tube.



Principle of mercury barometer

The balance of pressures will be given by $p_1 = p_2 + H\rho$

(where H is the difference between levels of mercury in the cistern and in the tube and ρ the density of mercury). From the Figure (ii), H=h+d

The quantity of mercury that has left the cistern is same as that has risen in the tube.

$A_1 d = A_2 h$ where A_1 and A_2 are areas of the cistern and the tube respectively.

Micromanometer

For accurate measurement of extremely small pressure differences micromanometers are used

.In the Figure the instrument is initially adjusted such that $p_1 = p_2$.

Typical Micromanometer

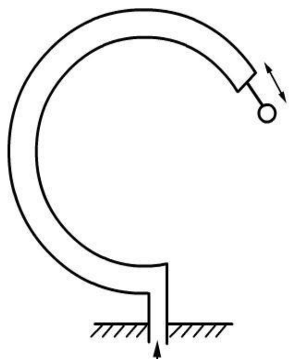
The meniscus in the inclined tube is located at a reference level fixed by the hairline viewed through the magnifier. The reading of the micrometer is noted. Application of the unknown pressure difference causes the meniscus to move off the hairline but it can be restored to the initial position by raising or lowering the well (mercury sump) The difference in the initial and final micrometer readings gives the height of the mercury column and hence the pressure. Pressures as low as 0.025mm water column can be measured.

Mechanical manometers

Mechanical manometers provide faster response than liquid column manometers. In liquid column measurements, lag is due to the displacements of the liquid. In elastic sensing element type of manometers the time lag is due to the time required for equalisation of pressure to be measured with that in the sensing chamber. The deformation of elastic sensing elements is measured with the aid of kinematic, optical or electrical systems. There are three types of elastic sensing elements which are (i) Bourdon Tubes (ii) Diaphragms (flat or corrugated) (iii) Bellows

Bourdon tube

Bourdon tube is the oldest pressure sensing element .It is a length of metal tube of elliptical cross section and shaped into letter „C‟.



Bourdon tube pressure gauge

One end is left free and the other end is fixed and is open for the pressure source to be applied. A tube of elliptical cross section has a smaller volume than a circular one of the same length and perimeter. When connected to the pressure source it is made to accommodate more of the fluid. Resultant of all reactions will produce maximum displacement at the free end. Within close limits, the change in angle subtended at the centre by a tube is proportional to the change of internal pressure and within the limits of proportionality of the material; the displacement of the free end is proportional to the applied pressure.

The ratio between major and minor axes decides the sensitivity of the Bourdon tube. The larger is the higher is the sensitivity. Materials of the Bourdon tube is Phosphor bronze, Beryllium bronze or Beryllium Copper.

Elastic diaphragms

The pressure sensors making use of elastic diaphragms consist of a diaphragm fixed in a tubular member. The pressure to be measured is applied on one side.

To have a linear pressure deflection relation, the second and later terms

should be small. p = applied pressure

t = thickness a = radius

y_c =

central

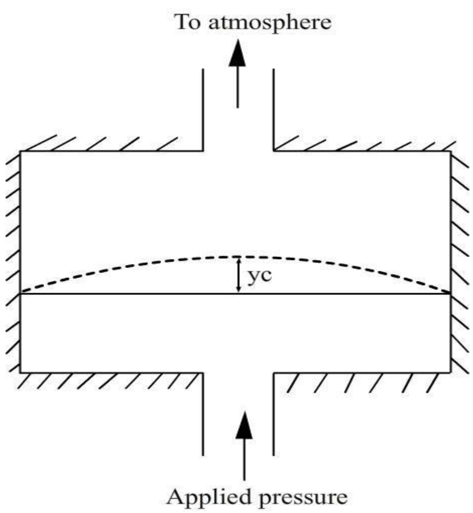
deflection

E =

Youngs

modulus

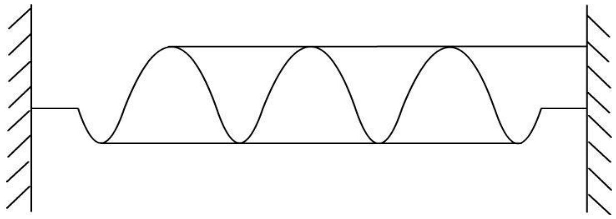
μ = Poisson‟s ratio $\rightarrow \frac{\text{lateral strain}}{\text{Axial strain}}$



Diaphragm pressure gauge

a) Corrugated diaphragms

Corrugated diaphragms permit considerably larger deflections than flat diaphragms. Their number and depth control the response and sensitivity. The greater the number and depth, the more linear is its deflection and greater is the sensitivity.



Corrugated diaphragm

(b) Capsules, Bellows

For even larger deflections than the diaphragms corrugated diaphragms are made in to boxes or bellows. Bellows are most commonly used to measure small steady pressures.

Pressure Transducers

Diaphragm type pressure transducers

They convert the pressure to be measured into electrical signals. For example, pressure transducers whose operating principle is based on measuring changes in inductive, capacitive or ohmic resistances caused by the deformation of an elastic element.

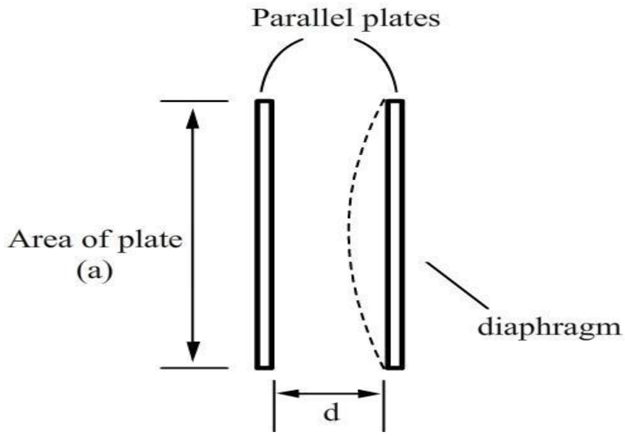
Capacitance C = $\in_a$ a/ d 5.10

where $\in_a \rightarrow$ absolute permittivity

$$\frac{\in_a}{\in_0} = \frac{1}{4\pi\times9\times10^9} E/m$$

a = area of plates

d = distance between the plates



Elastic diaphragm used in a parallel plate capacitor

With the application of pressure, the diaphragm deforms with the central deflection as shown. This changes the capacitance in an electrical circuit which can be calibrated against pressure to be measured.

Piezo-Electric pressure transducers

The word piezo-electric is derived from the Greek word “piezein” meaning squeeze or press. Certain materials possess the ability to generate electrical potential when subjected to mechanical strain. Conversely, they change dimensions when supplied with voltage. The potential developed by application of stress is not held under static conditions. Dynamic pressures in the range of frequencies from kHz to 100MHz can be measured using piezo- electric transducers. The use of piezo-electric effect is limited to dynamic measurements. Some materials exhibiting piezo electric properties are quartz, tourmaline, barium titanate, and Lead zirconate. Quartz is the preferred material, as it possesses good mechanical properties. Also, it is a good insulator least influenced by moisture.

Pressure Sensitive Paints (PSP)

They are composed of luminescent molecules dispersed in Oxygen permeable polymer binder. When PSP is exposed to blue or an ultraviolet light the luminescent molecules are excited to a higher energy level.

From this excited state they can discharge in three ways:

(i) by discharging light

(ii) by transferring energy to the polymer binder(heating)

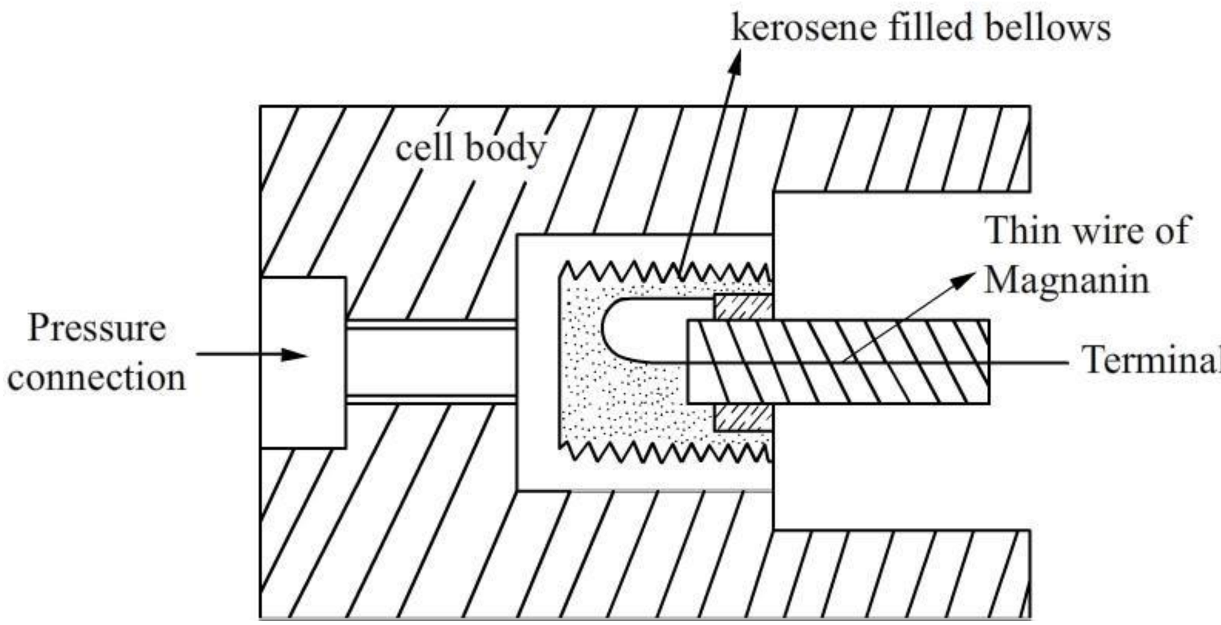
(iii) colliding with Oxygen molecules.

Since the luminescent molecules react with Oxygen they collide and release light at the same time. The amount of light emitted is inversely proportional to the amount of Oxygen molecules on the surface.

Measurement of high pressures

Electrical resistance gauges – principle of operation

Bourdon Tube or strain gauge can be used for high pressures. Very high pressures (say above 1000bars) may be measured by means of electrical resistance gauges which are known as **Bridgeman gauge.** By way of principle of operation, they make use of resistance change brought about by direct application of pressure to the conductor itself. Referring to the Figure, the sensing element is the thin wire of Magnanin (84 Cu + 12 Mn + 4 Ni) or an alloy of Gold and Chromium (2.1%) which is loosely wound. When pressure is applied, bulk compression effects produce a change in resistance which may be calibrated against pressure. The general relation between electrical and mechanical may be derived as follows:



Measurement of vacuum

Pressures below atmosphere is vacuum. Very low pressures may be defined as below 1mmHg. Ultra low pressures is less than a milli micron (<10^{-3}micron)

Measurement of vacuum may be by two methods

Direct measurement

Resulting in a displacement caused by the action of force [Spiral Bourdon tubes, flat or corrugated diaphragm, capsules and various other manometers]

Indirect measurement or inferential methods

Pressure is determined through the measurement of certain pressure controlled properties such as volume, thermal conductivity etc.

Inferential methods

a) McLeod gauge

The working of McLeod Gauge is based on Boyles‟ fundamental equation.

where p and V refer to pressure and volume respectively and subscripts 1 and 2 refer to initial and final conditions. Conventional McLeod gauge is made of glass. Refer to Fig.. It consists of the capillary „C‟, bulb „B‟ and the mercury sump which is connected to the lower end of the glass tube such that it can be moved up and down.

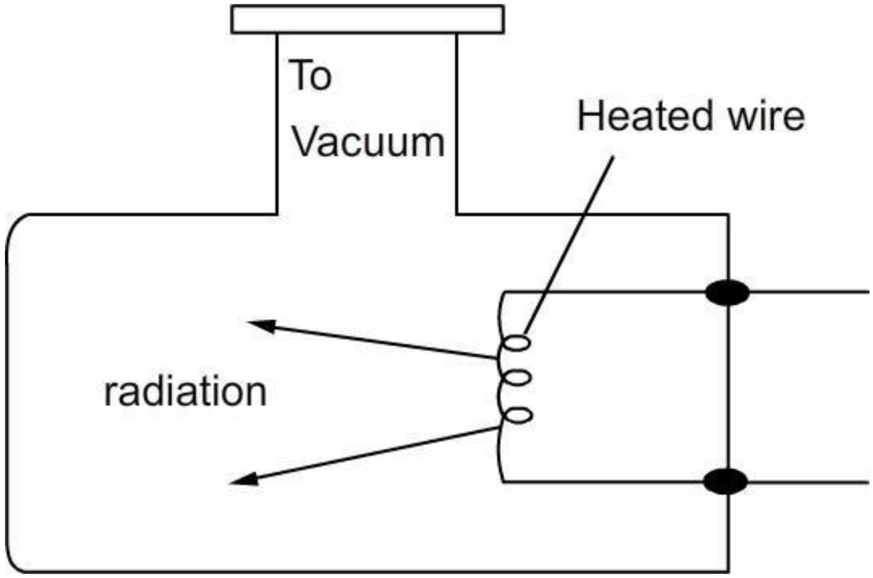
The pressure to be measured (the unknown pressure) is connected to the upper end of the glass part. When the mercury level in the gauge is below the cut off „F‟, the unknown pressure fills the gauge including the bulb B and capillary C. When the mercury sump is moved up, the level in the gauge rises and when it reaches the cut off „F‟ a known volume of gas at pressure to be measured is trapped in bulb B and capillary C.

Mercury is then forced up into the bulb and capillary. Assume the sump is raised to such a level that the gas at the pressure to be measured which filled the volume above the cut off is now compressed to the volume represented by the column h.

Suppose the original volume after then mercury reaches F is V_0. This is at a pressure being measured p_1Thermal conductivity gauges

The working principle of thermal conductivity gauges is that at low pressures heat lost by a heated object by conduction through molecules will depend on pressure. This is valid only for certain pressure range.

When the mean free path is comparable with the dimensions of the gauge head the heat loss from a heated wire in the gauge head will be by (i) conduction through leads (ii) radiation to surroundings (iii) conduction through molecules.



Gauge head of the thermal conductivity gauge

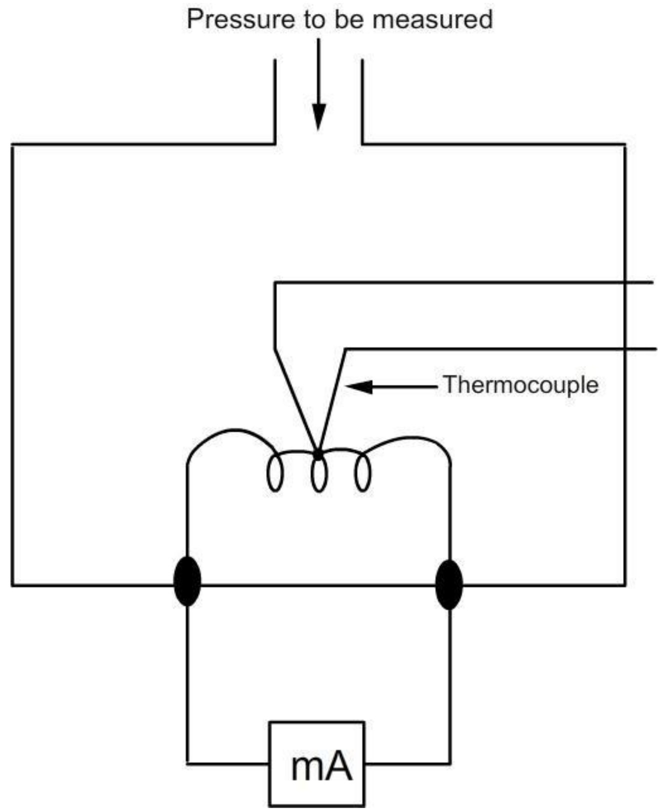
The range of thermal conductivity gauges is from mm of Hg to 10^{-3}mmHg. At higher pressures, heat loss from the heated wire is insensitive to the pressure change. At lower pressure heat loss by (i) and (ii) become more significant. There are two kinds of the thermocouple gauges.

b) Pirani gauge

Measures change in resistance of the heated wire when it looses heat to the gas molecules in the gauge head. In this case the gauge is called pirani gauge.

c) Thermocouple gauge

Instead of measuring electrical resistance, a thermocouple is kept in contact with the heated wire and the temperature of the wire is directly measured as a measure of pressure.

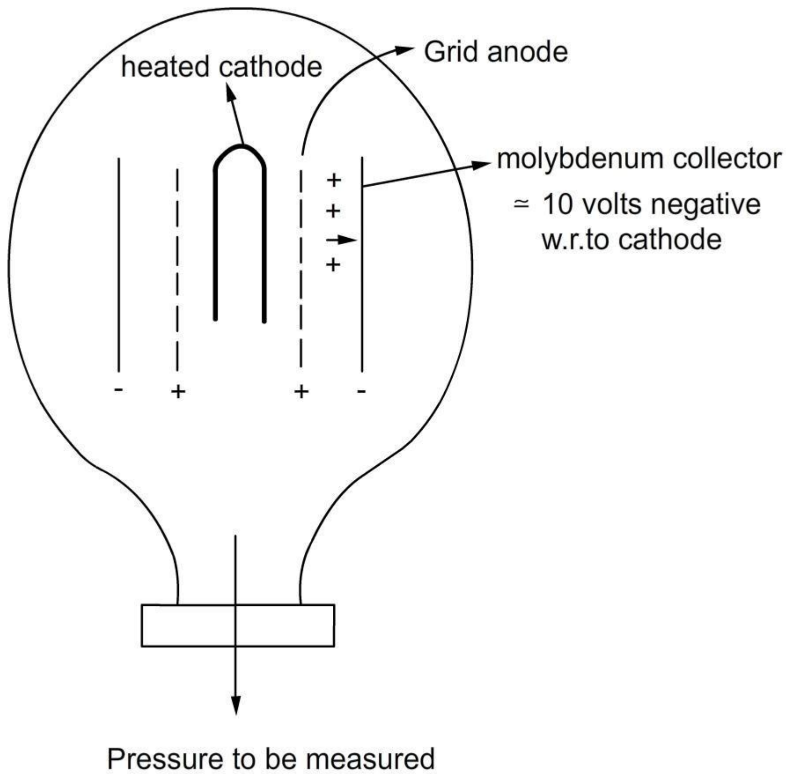


Thermocouple gauge head

d) Hot cathode ionisation gauges

At higher levels of vacuum, the measurement of pressure is by using Ionisation gauges. They operate on the principle of ionising the gas by means of electrons emitted by a heated filament. The kinetic energy acquired by an electron in passing through a potential difference of V volts corresponds to a value equal to V*e where e is the charge of the electron. When this energy exceeds a certain critical value corresponding to the ionization potential Vi, there is a possibility that collisions between molecules and electrons will result in the formation of +ve ions. The relatively high velocity electrons on hitting a gas molecule drives an electron out of it leaving it positively charged. For gases such as N_2, O_2 etc, Vi is ~ 15volts. The measurement of the ions produced is a measure of the pressure. The electrons are speeded up by an electric field and +ve ions produced are collected. The number of

+ve ions formed will depend on the number of molecules and therefore on the pressure.



Ionisation gauge

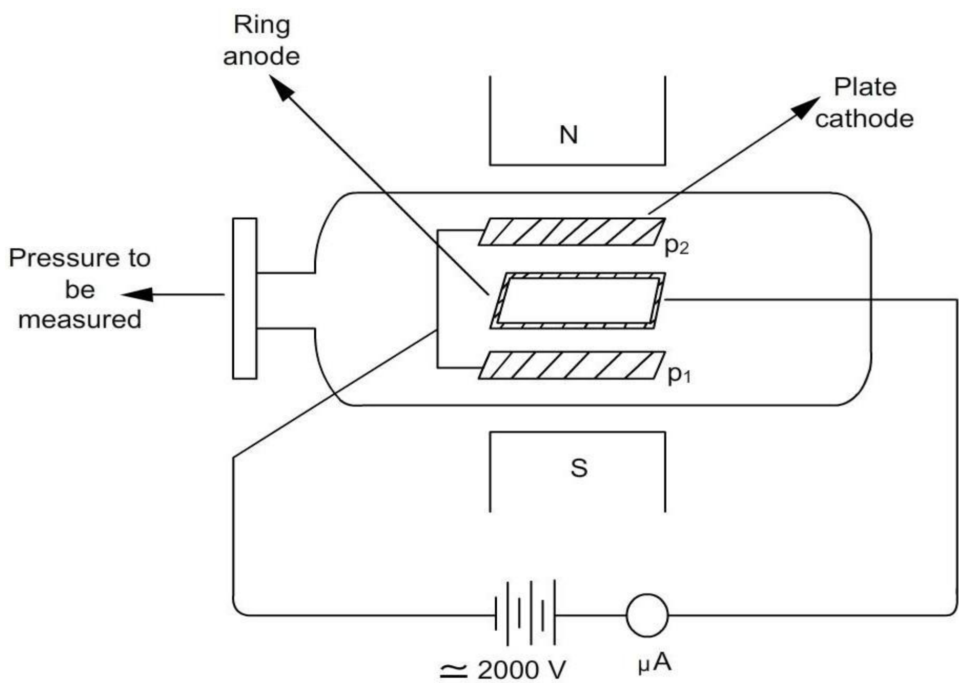
The gauge consists of a cathode, grid anode and a negative plate. The negative plate is at ~10V negative with respect to the cathode. The electrons emitted by the hot cathode (filament) are speeded up by the electric field and the positive ions produced are collected by the negative plate.

g) Cold cathode ionisation gauge (Penning gauge)

This gauge also works on the ionization principle. Positive ions are produced by the electrons and current due to these ions gives a measure of the pressure. Electrons are ejected from a cold cathode of Zirconium, Thorium by electric discharge. The gauge consists of two plate cathodes and a ring anode . A potential difference of

~2KV is applied across the electrodes.

The travel of electrons is made over a much longer distance. The secondary electrons are made to travel in helical paths before reaching the anode. This is accomplished by a magnetic field.



Cold cathode ionization gauge

Magnetic poles are kept such that the flux with lines of force is applied perpendicular to the two cathodes.

Measurement of pressure in flows

In flows, distinction has to be made between static and stagnation pressures.

Static pressure

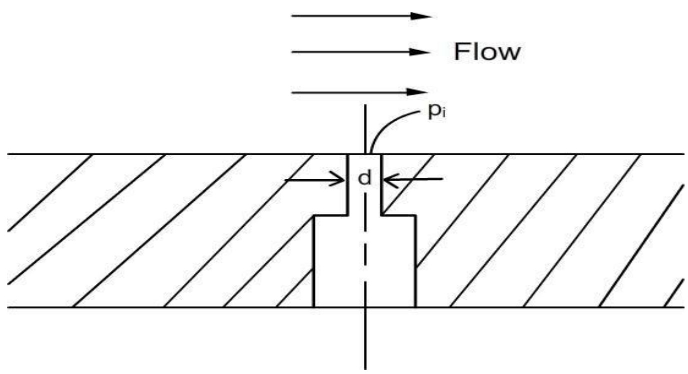
Pressure acting on the surface of a body imagined to be moving with the fluid with the same velocity as the medium is the static pressure.

Stagnation pressure

It is the pressure of a fluid imagined to be brought to rest isentropically.

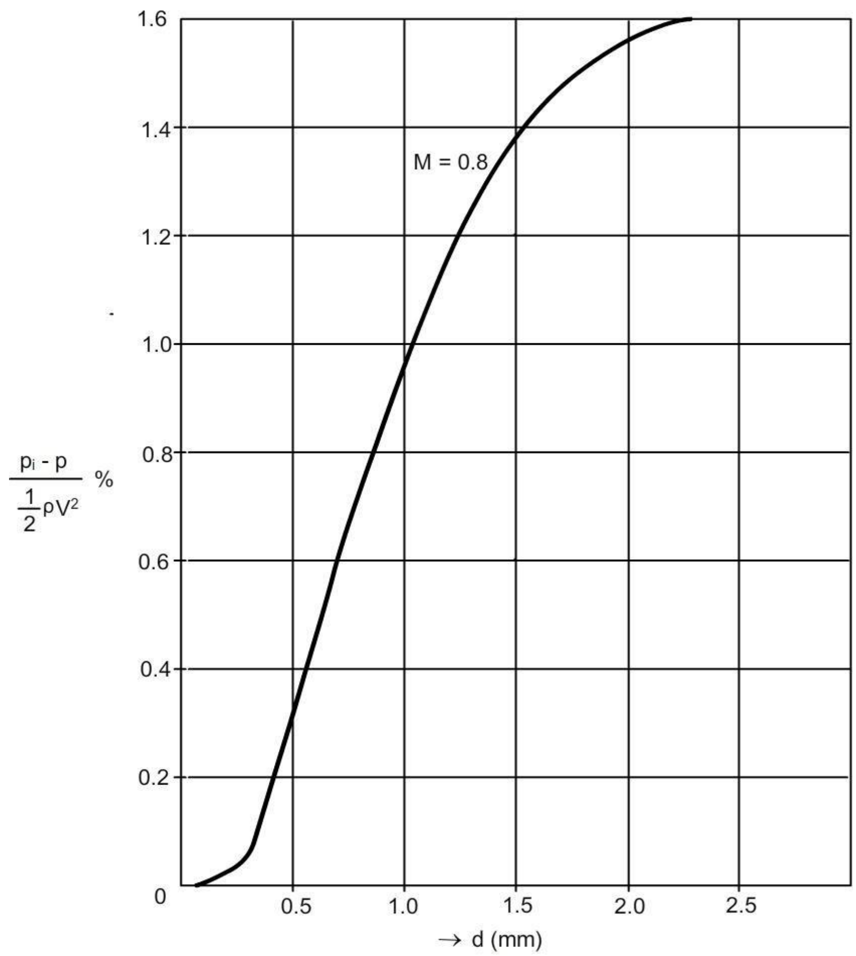
Measurement of static pressure

Common technique is to connect a probe to an orifice drilled perpendicular to the wall of the model where the streamlines are undistorted and parallel.



Static pressure orifice (tap) on a flat wall

Static hole diameter is about 1/5 of the boundary layer thickness. Practically the diameter is about 0.25mm on small models and 2.5mm on larger installations. The correctness of the static pressure measured is dependent on„d‟ the orifice diameter [Fig.]. The influence of the orifice diameter on the error in static pressure measurements is given graphically in Fig.below.

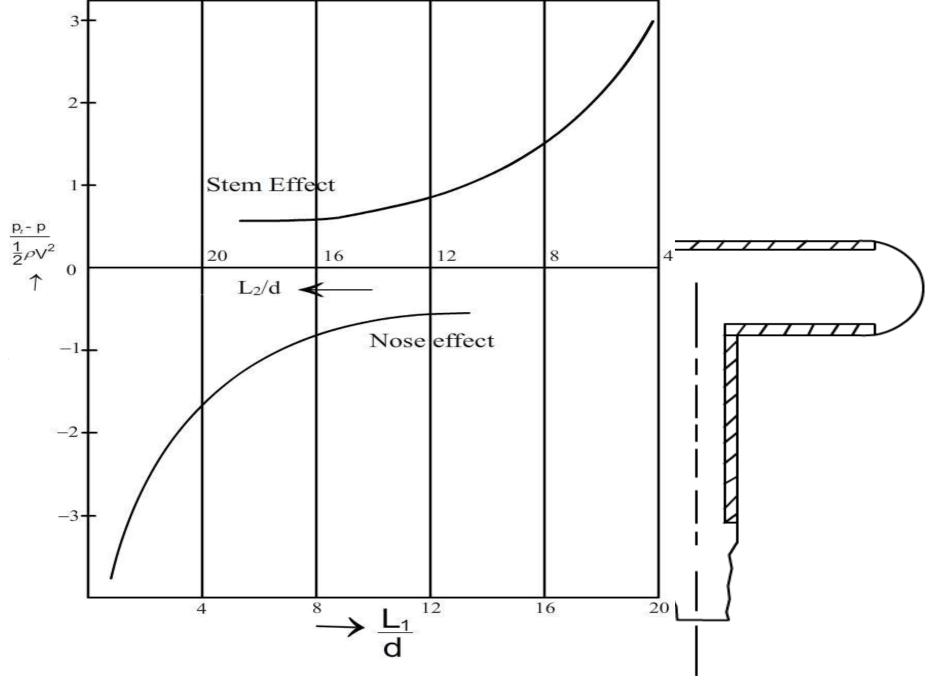


Influence of error on orifice diameter

The static pressure orifices (taps) on the walls of the flow channel provide the wall static pressure. The wall static pressure can not be assumed to prevail inside the flow. In order to get the pressure inside the flow, probes of suitable design have to be made use of.

Static pressure probes for subsonic flow

The commonly used static pressure probe in subsonic flows is the Prandtl probe. The Prandtl probe is an intrusive device. The pressure sensing orifices on the periphery of the probe are carefully located such that the influence of the nose and stem of the probe nullify each other.



The Prandtl probe

The nose and stem effects in a Prandtl tube

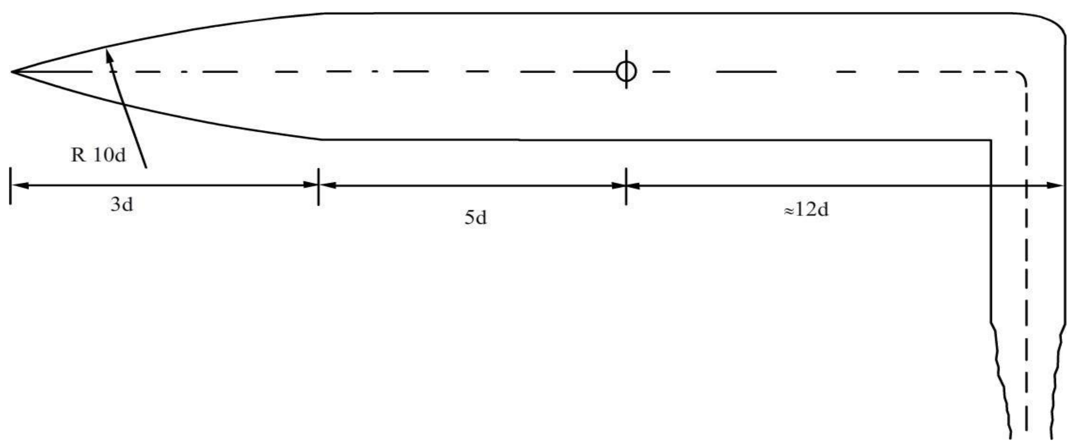
Because of the intrusive nature of the probe, the flow will be accelerated by the nose. The effect will be to reduce the static pressure which is called the nose effect. In contrast, the effect of stem will be to locally stagnate the flow and thereby to increase the static pressure. This

effect is the stem effect. As shown in the Fig., the position of the orifices are so chosen that the two effects neutralize each other. Additionally the probe must be slender (say ~ 1.0 to 1.5mm dia) and kept parallel to the flow.

Static pressure probes for supersonic flow

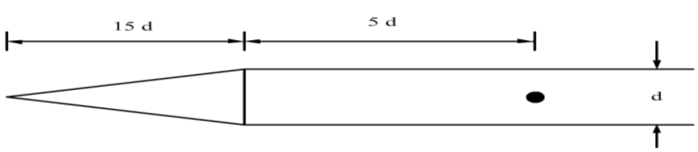
When Mach number is more than 1.0, shock appears. When the cone angle of the probe is less than the shock detachment angle for the given Mach number [shown in Fig.] and if the orifices are located well downstream of the shock wave, the measured static pressure will tend towards the value for the undisturbed flow. Conical or ogival shaped tubes are used.

Probes are made small and with static taps on the cone surface. The effect of yaw is reduced by arranging several orifices so that the pressure inside the tube is an average value. Usually the tube has 4 to 8 orifices whose diameter is about 1/10 th of the outside diameter of the tube.

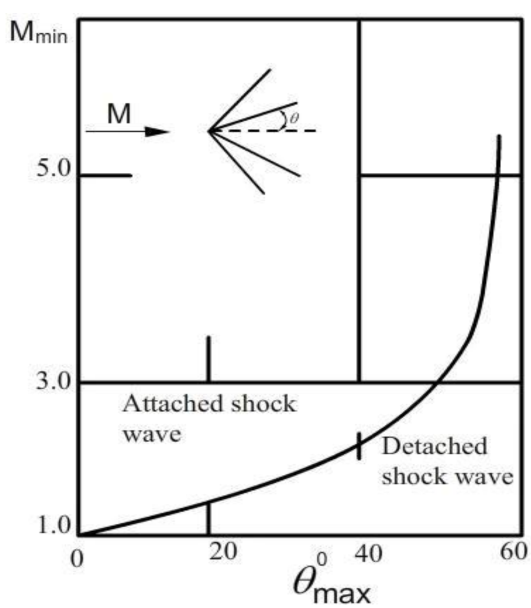


Ogival shaped static pressure probe for supersonic flow

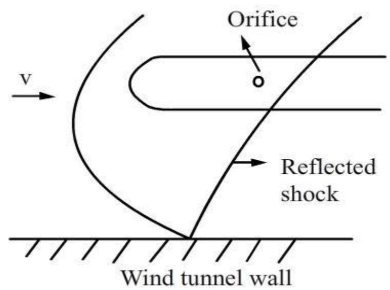
Good results are obtained with ogival tubes. The tube shown in Fig. has a systematic error within 1%. Angle of the cone should be less than the angle at which the shock wave becomes detached from the cone. The error in the measurement of static pressure decreases as the distance of the orifice from the tip of the probe increases.



Conical static pressure probe for supersonic flow



Maximum deflection angle for different Mach numbers



Reflection of the shock from the wall

It is important to have long pointed tubes. Otherwise there is the possibility that the reflected shock may affect the static pressure readings. Roughness at the edges of the orifices too may cause large errors in measurement.

Measurement of stagnation or total pressure

Insubsonic flows

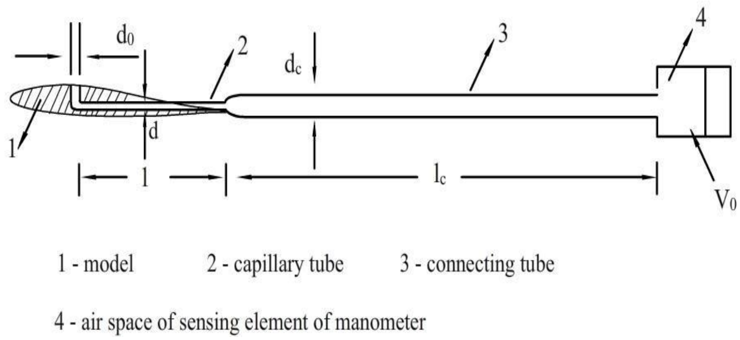
The gas particles come to rest so quickly at the stagnation point of a body, that heat transfer and friction losses are negligible. Therefore, in subsonic flows only isentropic changes occur. Hence the stagnation pressure measured in a subsonic flow is not significantly different from that in the settling chamber. Total pressure is measured with a Pitot tube which a cylindrical tube is having an orifice pointing towards the flow. Axis of tube must coincide with the flow direction. It is a practice to use tubes which generally have blunt ends. Such tubes are insensitive to yaw upto ±10 to 12^0

The relation between the stagnation pressure measured and the static pressure may be expressed as follows:

Insupersonic velocities

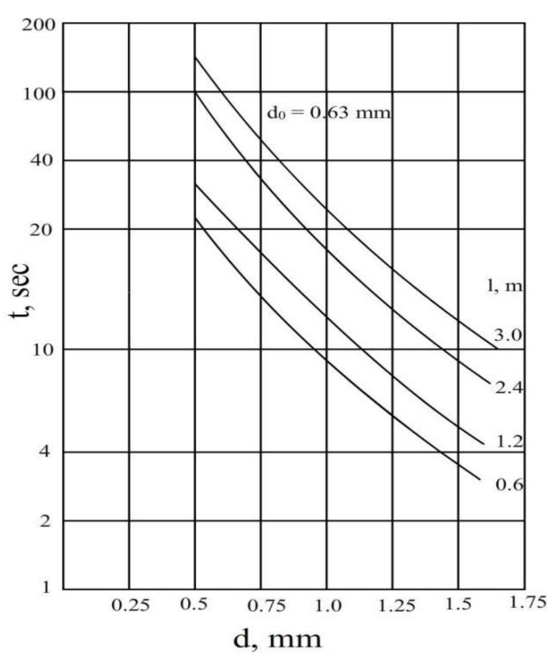
Shockwave appears upstream of the tube nose. Therefore tube measures only pressure behind the shock wave. Normal shock equations give the relation between the total pressures upstream and downstream of the shock. As the bow shock formed in front of the Pitot tube has the normal part only in the central region, the tube diameter for measurements in supersonic flow is usually kept very small.

Lag in manometric systems

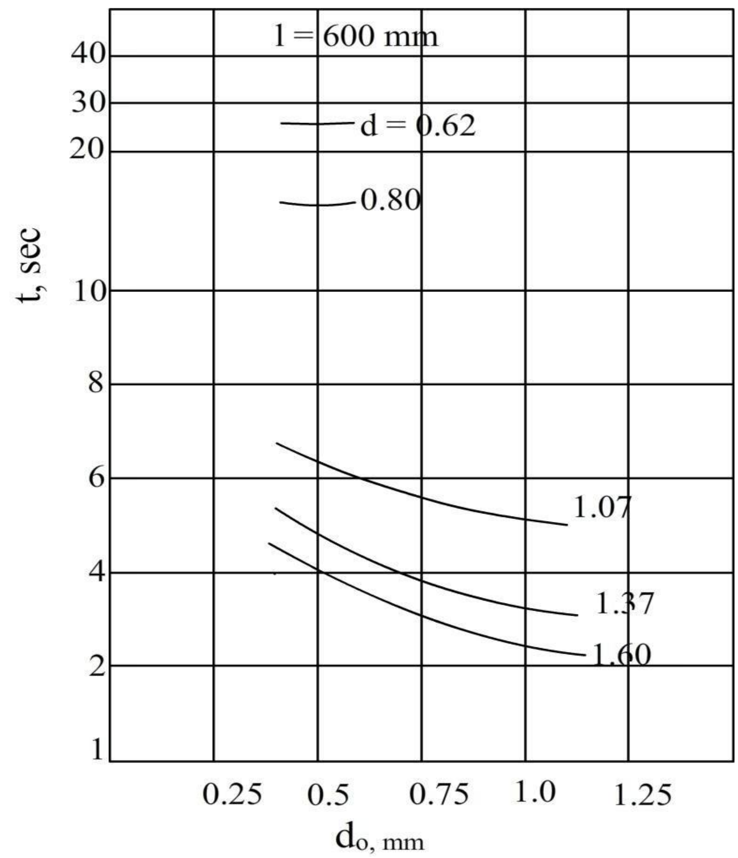


Wind tunnel model with the manometric system

When the pressure changes near the orifice which is connected to a manometer, equilibrium in the manometer is established not immediately but after a certain time. If the pressure is read of earlier there will be gross errors.



Transmission lag as a function of capillary diameter



Transmission lag as a function of orifice diameter

Smaller transmission lags are necessary not only for high reliability but also for reducing the duration of experiments. Equilibrium will be established in the manometric system later after the pressure on the model is stabilized. The run times should be longer than the transmission lag.

Transmission lag is caused by:

a) Resistance of the tubes
b) The change in air density
c) and inertia of the moving masses

The main factors influencing the transmission lag are the orifice diameter d_o, the diameter d of the capillary and d_c of the connecting tube and their respective lengths l and l_c .

The orifice diameter is of small influence when $d/d_o < 2.5$. When $d/d_o > 2.5$ the transmission lag increases sharply. The orifice diameter should not be less than half the diameter of the capillary tube. The influence of the diameter of the capillary tube is very strong. A reduction of this diameter has its main effect an increase in the resistance to the flow of gas. An increase in the length of the capillary tube has a significant effect on the lag. Capillary tubes should have larger diameter and shorter length.

Measurement of Temperature

Introduction

Temperature is generally considered as indicative of quantity of heat. It is equivalent to potential in electricity and level in hydrostatics. On the basis of kinetic theory, the temperature, may be defined as

Temperature is measured by the observation of certain of the properties of matter which are influenced by the degree of heat. The most used are changes in

(1) Physical state

(2) Chemical state

(3) Dimensions

(4) Electrical properties

(5) Radiation properties

The instruments to measure temperature have been classified according to the nature of change produced in the testing body by change in temperature. Based on the above consideration there are four categories of thermometers .They are:

(1) Expansion Thermometers

(2) Change of State Thermometers

(3) Electrical Thermometers

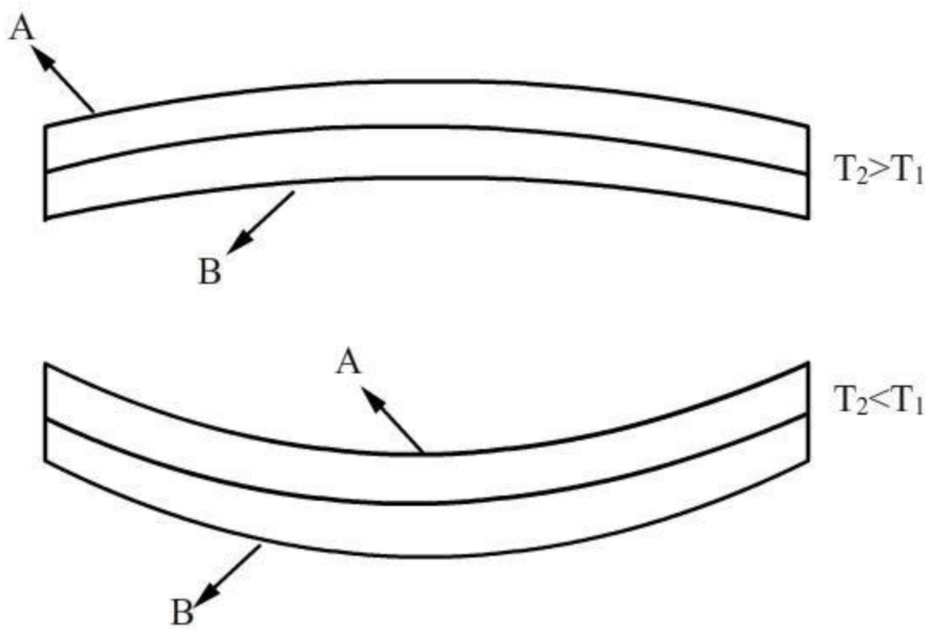
(4) Radiation and Optical pyrometers

Expansion Thermometers or Liquid in Glass Thermometers (LIG)

A liquid-in-glass thermometer is widely used due to its accuracy for the temperature range - 200 to 600°C. Compared to other thermometers, it is simple for usage. It has been used in medicine, metrology and industry. In the LIG thermometer the thermally sensitive element is a liquid contained in a graduated glass envelope. The liquid used in practical thermometers are mercury or alcohol. The principle used to measure temperature is that of the apparent thermal expansion of the liquid.

Boiling point of Mercury is 357^{o}C. Liquid in bulb Thermometers making use of Mercury has a range of -39^{0} to 350^{o}C which are freezing and melting points of Mercury. If alcohol is used the lower temperature can be upto -62^{0}C

Bimetallic thermometers

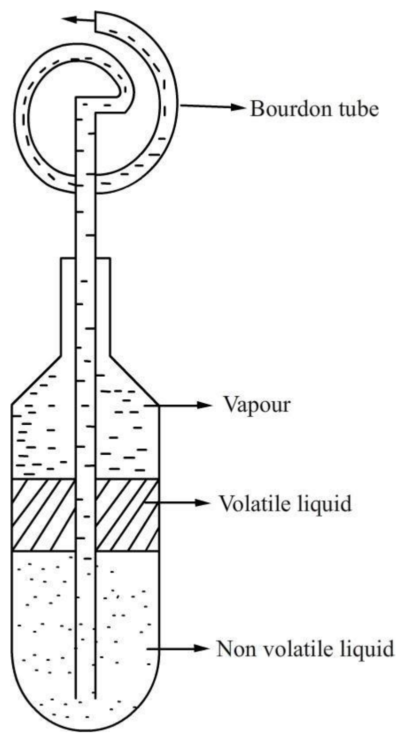


Bimetallic elements subjected to differential temperature

Bimetallic elements are used for temperature measurement and more widely for sensing and control purposes Invar rod (coefficient of expansion =2.7x 10^{-6} cm/^{o}C) and Brass (coefficient of expansion = 34.2x10^{-6}cm/^{o}C because of their large difference in the values of coefficient of expansion are used as a very useful combination.

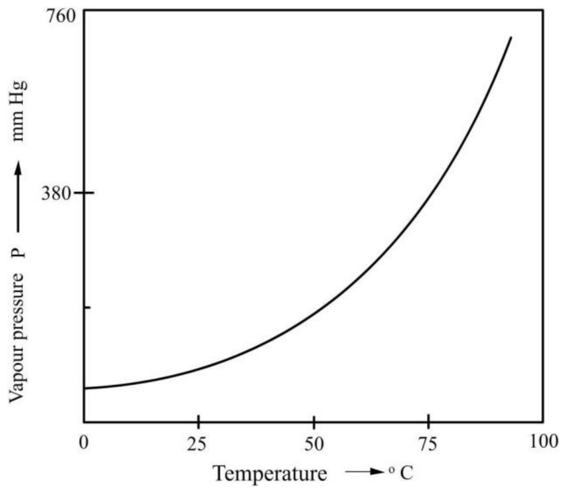
Change of state thermometers: Vapor pressure thermometer

Consider a container having a certain quantity of liquid. The molecules of liquid are in a state of random motion moving in all directions. When vertical component of kinetic energy is greater than the force of attraction at liquid surface, it escapes from the surface. On the other hand, the molecules which constitute vapour are also moving at random. The process of evaporation and condensation go on simultaneously. [When the rates of evaporation and condensation are equal, the vapour becomes saturated].



Vapor pressure thermometer

Saturated vapor pressure depends only on the temperature and properties of the liquid and is independent of the size of the container. The vapor pressure thermometer consists of a (i) bulb containing a fill liquid (ii) a capillary tube (iii) Bourdon Tube.



Saturated vapor pressure of water

The relationship between vapor pressure and temperature is non-linear. As an example, the relation between the saturated vapor pressure of water is shown in Fig.. The range of usage of the vapor pressure thermometer is dependent on the saturated vapor pressure of the liquid. Some of the commonly used fill liquids and the range of temperature in degree C (given in brackets) are Methyl chloride (0-50), Sulphur dioxide (30-120),Water (120-220), Butane (20-
80) and Toluene (150-250). The bulb of the thermometer is exposed to the temperature field to be measured.

Electrical resistance thermometry

In this category there are two types (i) those using conductor sensors (ii) those using semiconductors (thermistors)

Conductor sensors

Resistance of pure metallic conductors increases with temperature in a reproducible manner. Some of the metals and the range of temperature measurement using them are the following Platinum - 190^{o}C to 630.5^{o}C
Copper -
50^{o}C
to 250^{o}C Nickel

-
200^oC to 350^oC
Platinum is the preferred metal because of the following reasons:

(a) Platinum is stable

(b) Can be drawn to fine wires

(c) Available in high purity

The resistance temperature relationship is not linear in the complete temperature range. The resistance at any particular temperature may be written as

$$R = R_0 [1+\alpha_1 T+ \alpha_2 T^2+\ldots\ldots\ldots\ldots\ldots\alpha_n T^n]$$

where R_0 is the resistance at temperature T=0. The number of terms necessary depends on the material, the accuracy required and the temperature range covered. Platinum, nickel and copper require respectively two, three and three of the α constants for accurate representation. Platinum, for instance, is linear within +/- 0.2% from 255K to 366K, +/- 0.4% in the range 90K to 183K and also in the range 200K to 422K.

If assumed linear,

$$R_t = R_o (1+\alpha t)$$

α → (Temperature coefficient of resistance) (t is any temperature)

α is obtained by measuring resistances R_{100} and R_0 at steam and ice.

Semiconductor sensors (Thermistors)

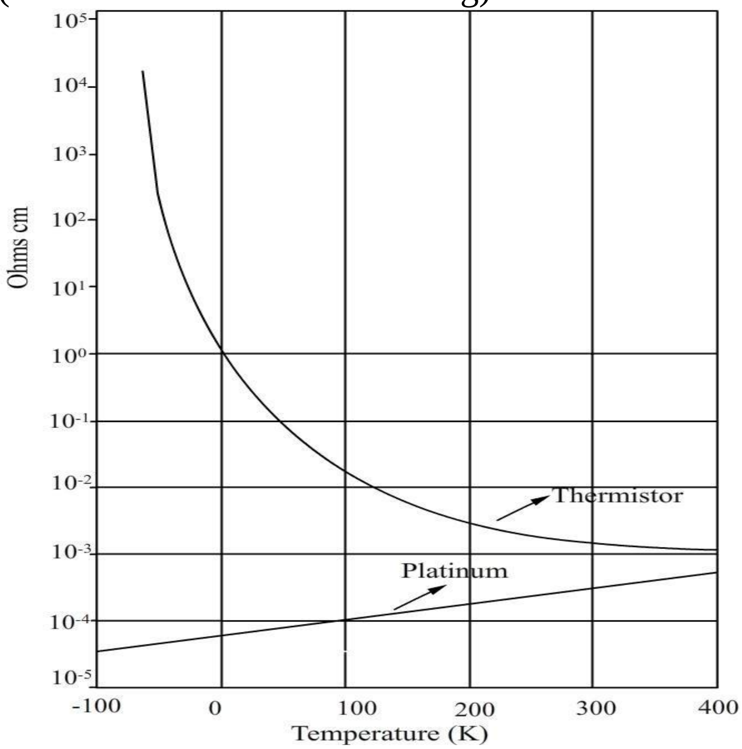
Thermistors are temperature sensitive variable resistor made of semi-conductor material. Thermistors are made of metal oxides and their mixtures viz. Oxides of Copper, Nickel, Manganese, Iron, Tin, etc.

They are available in

(i) beads as small as 0.4mm in diameter

(ii) discs ranging from 5 to 25mm diameter

(iii) rods (a few mm diameter 50mm long)

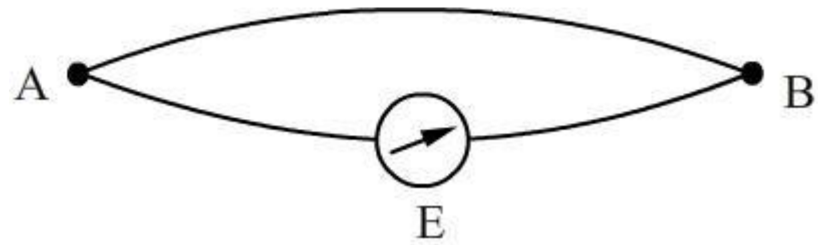


Temperature resistance relation of resistance thermometers

Multiple thermistor sensors can cover a temperature range of -200^{0}C to +1000^{0}C. Because of the high sensitivity at the lower temperature range thermistors are more commonly used in the lower temperature range.

Thermoelectric thermometry

An e.m.f is generated, when junctions of two dissimilar metals are kept at different temperatures. The combination of the two metals is called thermocouple.



The Seebeck set up

The magnitude of e.m.f depends on the difference in temperature between the two junctions. This is called the Seebeck effect. For a combination of metals A and B as in Fig., the Seebeck voltage dE_S for very small temperature difference is

$$dE_S = \alpha_{A,B}\, dT$$

$\alpha_{A,B} \rightarrow$ Seebeck coefficient

Laws of thermocouples

Law of homogeneous circuit

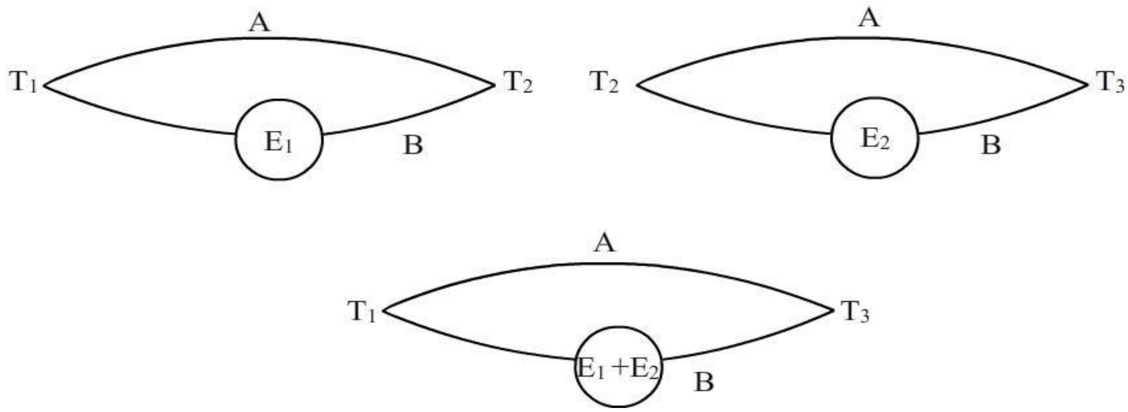
A thermo electric current cannot be sustained in a circuit of a single homogeneous material however varying in c.s. by the application of heat alone. The implication is that two different materials are needed to form a thermocouple.

Law of intermediate materials

Insertion of an intermediate metal into a thermocouple circuit will not effect the net emf provided the two junctions introduced by the intermediate metal are at identical temperature. This means that there can be a measuring instrument, soldered or brazed between the two metals in order to monitor the emf generated.

Law of intermediate temperature

If a thermocouple develops an e.m.f e1 when the junctions are at T_1 and T_2 and an e.m.f e_2 when the junctions are at T_2 and T_3, it will develop an e.m.f $e_1 + e_2$ when the junctions are at T_1 and T_3.



Law of intermediate temperature

20 – 100 20mv

100 – 200 18mv

20 – 200 38mv

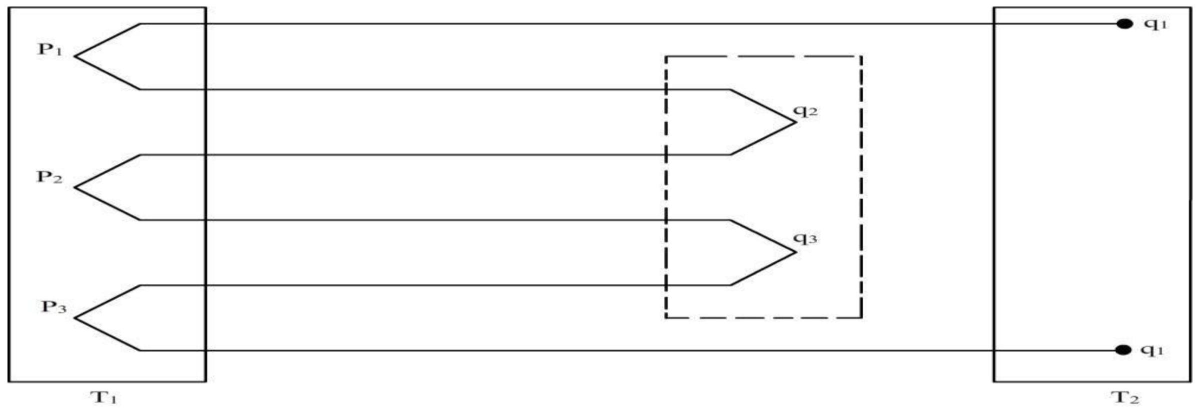
Thermocouple materials

Any two conducting materials could be used as thermocouples. But, certain metals are found to be better than others.

Material	Temperature range
Copper - Constantan	-200 to + 350^{o}C
Chromel - Alumel	-200 to 1300^{o}C
Iron - Constantan	-150 to 1000^o C
Pt – (Pt - 10) Rh Pt – (Pt - 13) Rh	0^{o}C to 1450^o C

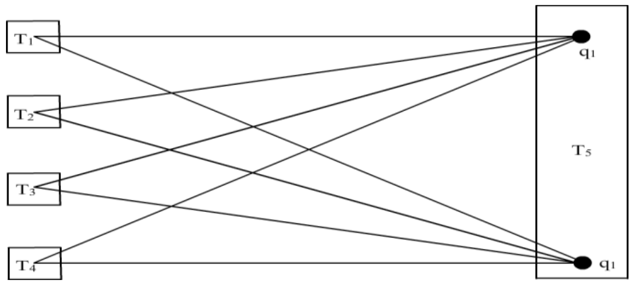
Thermopiles and Thermocouples connected in parallel

Thermocouples may be computed electrically series or parallel. When connected in series, the combination is thermopile.



Thermocouples connected in series – thermopile

Here P_1, P_2 and P_3 are the measurement points and Q_1 to Q_4 are the reference points. The total output from n thermocouples will be equal to the sum of individual emfs. So the purpose is to get a more sensitive measurement.



Thermocouples connected in parallel

Thermocouples when connected in parallel connection provides better averaging. The parallel combination gives the same voltage if all the measuring and reference junctions are at the same temperature, If all the measuring junctions are at different temperatures and the thermocouples have the same properties, the voltage measured is the average of the individual voltages.

Pyrometry

The word is derived from pyros + metron. The methods under this are primarily thermal radiation measurement. There are two distinct instruments. Under this category:

(i) Total Radiation Pyrometer

(ii) Optical pyrometer

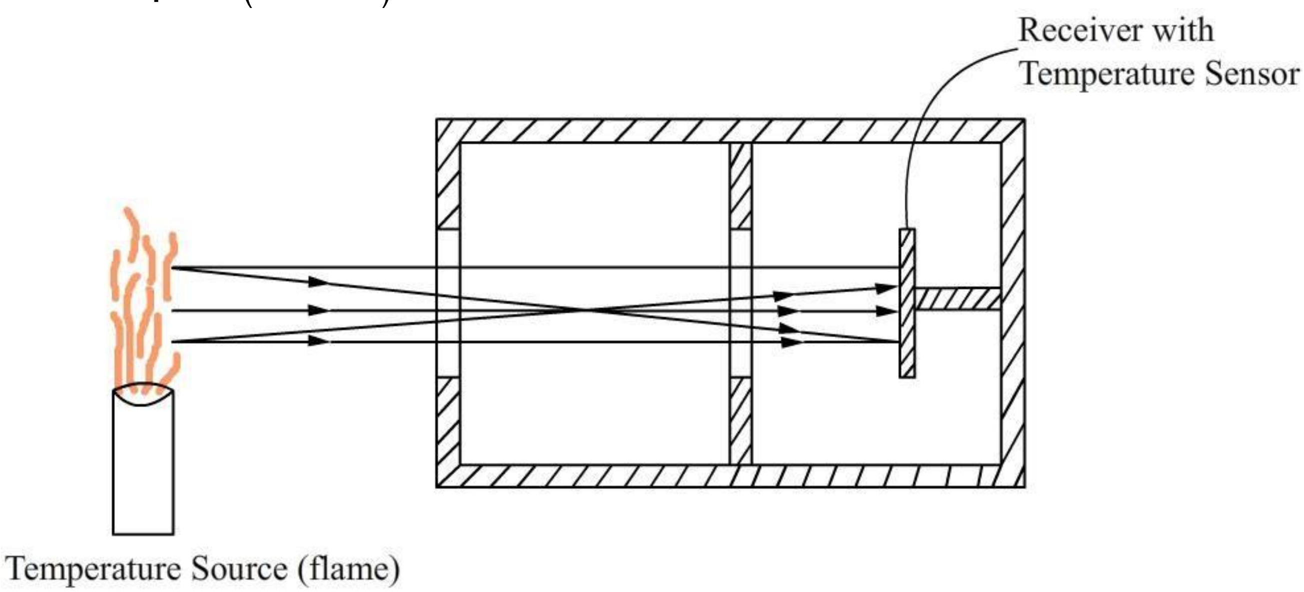
Total radiation pyrometer

Total radiation pyrometer accepts a controlled sample of total radiation and through determination of the heating effect of the sample obtains a measure of temperature. All bodies above absolute zero temperature radiate energy, not only do they radiate or emit energy, but they also receive and absorb from other sources. It is known that all substances emit and absorb radiant energy at a rate depending on the absolute temperature and physical properties of the substance.

Stefan-Boltzman law

According to Stefan – Boltzman law the net rate of exchange of energy between two ideal radiators A and B is,

$$q = \sigma\left(T_B^4 - T_A^4\right)$$



Total radiation pyrometer

In total radiation pyrometers, the radiation from the measured body is focused on some sort of radiation detector which produces an electric signal. Detectors may be classified as thermal detectors or photon detectors. Thermal detectors are blackened elements designed to absorb a maximum of the incoming radiation at all wavelengths. The absorbed radiation causes the temperature of the detector to rise until equilibrium is reached with heat losses to the surroundings. The thermal detectors measure this temperature using a resistance thermometer, thermistor or thermocouple.

In photon detectors, the incoming radiation frees electrons in the detector structure and produces a measurable electrical effect. These events occur on an atomic or molecular time scale and hence are faster than the thermal detectors. However, photon detectors have a sensitivity that varies with wave length, thus incoming radiation of all wavelengths are not equally treated.

Optical pyrometer

Optical pyrometer employs an optical means for estimating the change in average wavelength of visual radiation with temperature. The instrument works on the principle of

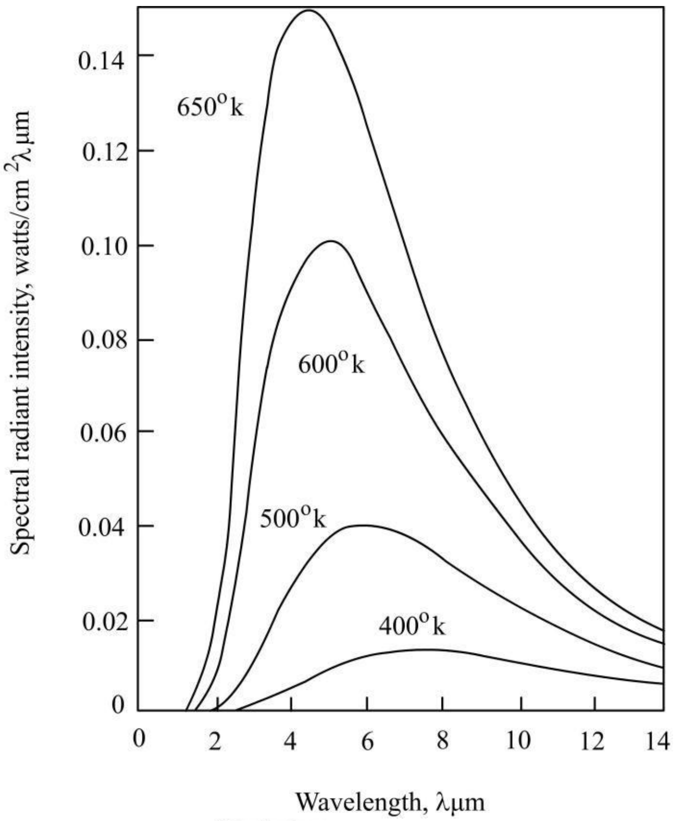
Wien's displacement law states that the wavelength distribution of thermal radiation from a black body at any temperature has essentially the same shape as the distribution at any other temperature, except that each wavelength is displaced. There is a shift in the wavelength of maximum emission toward shorter waves. (From Red to blue).when the temperature increases. The intensity relation is expressed as

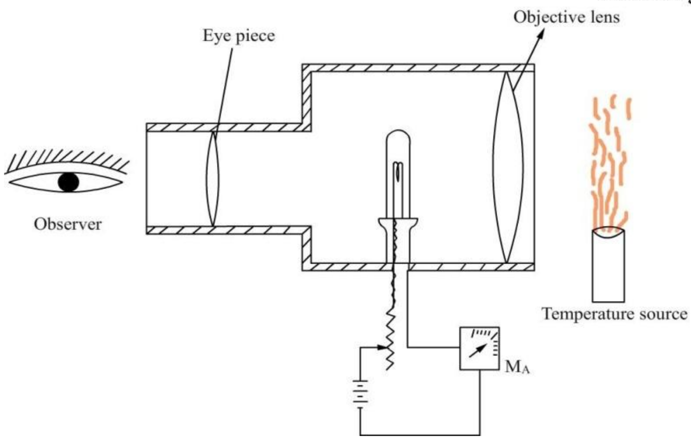
$$E_\lambda = C_1\lambda^{-5} / \left[e^{(c_2 / \lambda T)} - 1\right]$$

E_λ = energy emitted at Wavelength λ

C_1 and C_2 = constants

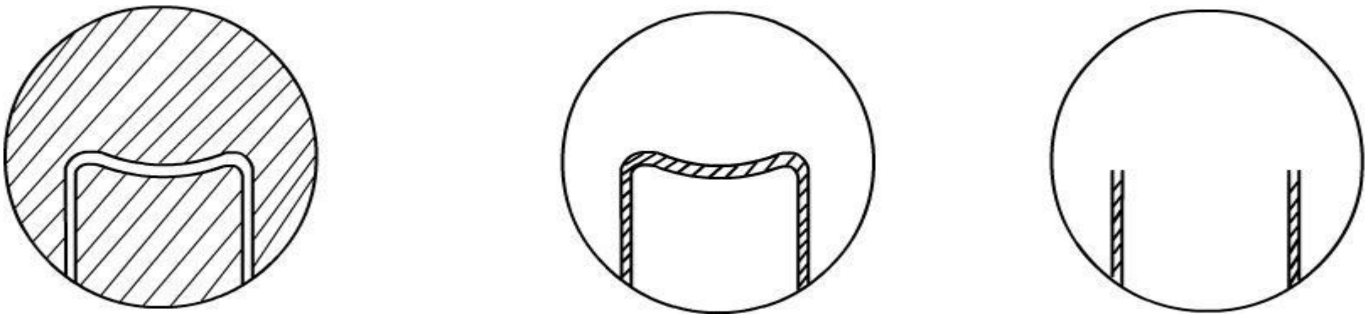
T = absolute temperature of blackbody





Schematic of an optical pyrometer

In the operation of the pyrometer, method of matching is used. Reference temperature is obtained by an electrically heated filament lamp which is controllable. A measure of temperature is obtained by optically comparing the visual radiation from filament with that from the unknown source.



Filament too bright   Filament too cold   Filament and source at equal temperature

The heated filament and the temperature source at different temperatures

Measurement of temperature in Flow

Measurement of the temperature of flowing gas is important in many practical cases. The state of the stationary perfect gas can be defined by two independent physical parameters one of which may be the temperature. When velocity of flow is such that compressibility effects are important, it is necessary to differentiate between static and stagnation temperatures.

Stagnation temperature is that reached by the fluid when it is brought to rest adiabatically.

A thermometer moving with the fluid and emitting no thermal radiation would measure static temperature. An intrusive sensor cannot measure static temperature. Static temperature is measured by non-intrusive methods or estimated indirectly. (by measuring static pressure and then density by optical means) or by measuring the speed of sound. The difference between stagnation temperature T_0 and free temperature T if a moving perfect gas can be determined from

$$T_0 - T = \frac{V^2}{2C_p}$$

Since, shocks do not change the enthalpy; this equation is true for both subsonic and supersonic flows.

Adiabatic wall temperature or Recovery temperature

A thermally insulated surface will be heated by a gas flowing past it to a temperature called recovery temperature (T_a). The recovery temperature depends on

i. Local mach number (or on static temperature) at the outside limit of boundary layer.
ii. On the dissipation of kinetic energy by friction in the boundary layer.
iii. On the rate of heat exchange.

$$T_a - T = K \frac{V^2}{2C_P}$$

Difference between recovery temperature and static temperature is a fraction of the adiabatic temperature rise.

$$K = \frac{T_a - T}{T_o - T}$$

K is called the coefficient of thermal recovery or the recovery coefficient. K represents the proportion of kinetic energy of the medium recovered as heat. K depends on the shape of the

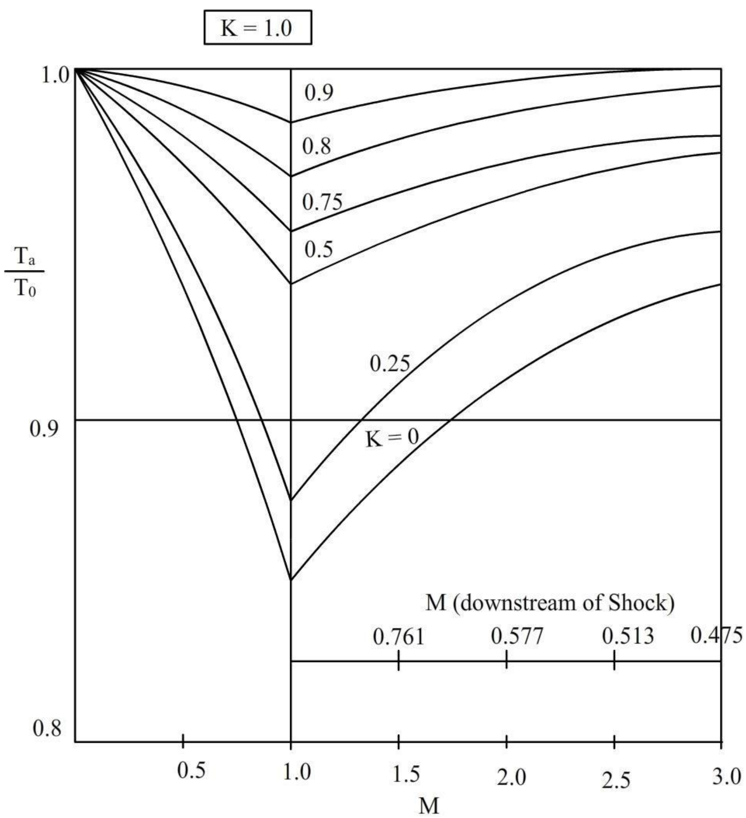
body and on Mach number, Reynolds number, Prandtl number and on the ratio of specific heats γ.

For a given gas Pr and γ are constant over a wide range of temperatures (For air Pr = 0.72 and

γ = 1.4) and so recovery coefficient is a function of M and Re only, where, k is the coefficient

of thermal conductivity $P_r = \frac{\mu C_p}{k}$.

The coefficient of thermal recovery depends on the shape of the surface. For poorly streamlined bodies r varies between 0.6 and 0.7 and for well streamlined bodies it is between
0.8 and 0.9. The relationship between recovery temperature and stagnation temperature depends on the Mach number and can be derived from following two equations:



Free stream Mach no (upstream of shock)

Ratio of T_a/T_0 as a function of Mach number

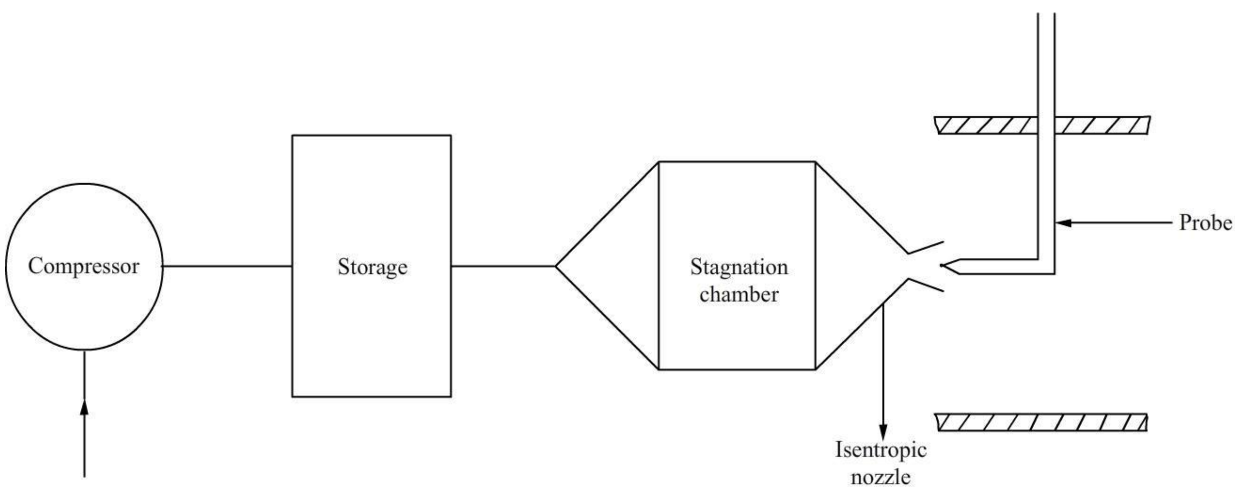
When M exceeds unity a shock appears whose strength increases with increasing incident Mach number. In the absence of heat transfer a thermometer on the wall of a tube inserted into a gas stream would indicate a recovery temperature T_a dependent only on the flow characteristics in the boundary layer around the tube.

When, K = 1, $T_a = T_0$.

In an actual thermometer of a temperature probe, heat exchange with surrounding medium cannot be prevented. Hence, it will indicate a temperature T_n differentiating from the recovery temperature T_a. Recovery coefficient of the instrument

Velocity effects on temperature measurements

Real temperature probes do not attain the theoretical stagnation temperature. Even if conduction and radiation errors are corrected for there remains deviation of actual situation from ideal. Correction for these effects generally is accomplished by experimental calibration to determine recovery factor K of the probe.



Set up for calibration of recovery coefficient

Stagnation chamber velocity = 1/100 nozzle flow velocity.

Measurement of P_o T_o can be found under zero-velocity conditions.

$T_{stag, nozzle} = T_{stat, tank}$

$P_{stag, nozzle} = P_{stat, tank}$

$P_{stat, nozzle} = P_{atmosphere}$

No pitot tube is used.

Sensors / Probes for measuring stagnation temperature

Sensor depends on the intended range of flow velocities and temperatures. For a good sensor

(1) the value of K should be as close to unity (2) the value should be constant. The deviation from unity of the value K depends on

(1) Convectional heat exchange between sensing element and medium
(2) Heat loss by conduction from the sensor through the device holding it.
(3) Radiant heat exchange between sensor and surroundings.

Since, the above factors depend on temperature and velocity. Probes are divided into a few categories.

(1) Sensors for low and high velocities at low temperature.
(2) Sensors for high velocities and temperature upto 300 and 400^{o}C
(3) Sensors for low and high velocities (upto 1000 to 1200)

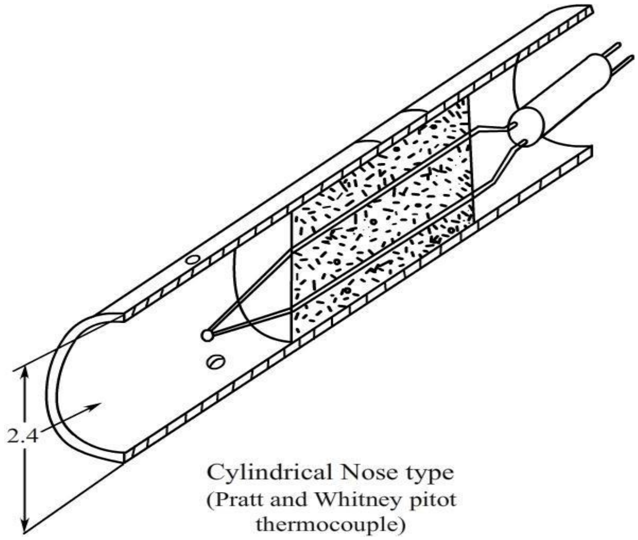
a) Low temperature sensors

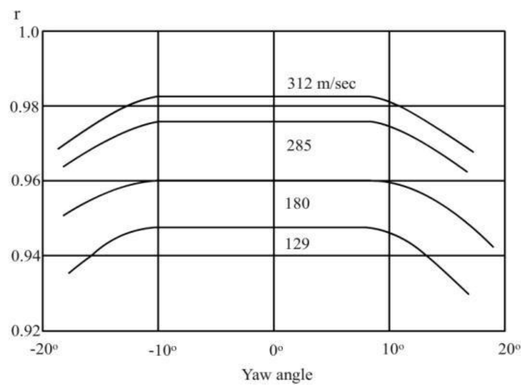
Losses due to radiation can be neglected when the probe and walls of the flow channel do not differ much in temperature. To determine the flow temperature, stagnation temperature in the settling chamber can be determined settling chamber temperature can be determined where there is no velocity. As there is no addition or removal of heat between the settling chamber and the test section, the settling chamber temperature can be assumed to be same as the test section temperature. Mercury thermometers, resistance thermometers or thermocouples could be used as the sensor.

b) Sensors for high velocities and medium temperature

For temperature range from 300 to 400^{0}C, the sensors are mounted in narrow channels. Thermocouple wires of 0.1 to 0.2mm diameter [iron =constantan or copper constantan] t are generally employed in this range of temperature. The thermal capacity of the junction of thermocouple is very small so that it responds rapidly and measurement can be done at rapidly changing temperatures. When there is no major radiant heat transfer, a thermocouple consisting of the thermocouple junction inserted lengthwise into the flowing medium will have a recovery coefficient of ~0.9 even up to sonic velocities.

Well made stagnation temperature probes will have recovery coefficients close to unity over a wide range of velocities. The gas upstream of the sensor is brought to an optimum velocity such that heat gained by the sensor due to convection will be balanced by heat lost by conduction. In order that the flow is not brought to rest completely, the tube is provided with vents of area 1/4 to 1/8 of the inlet orifice area.



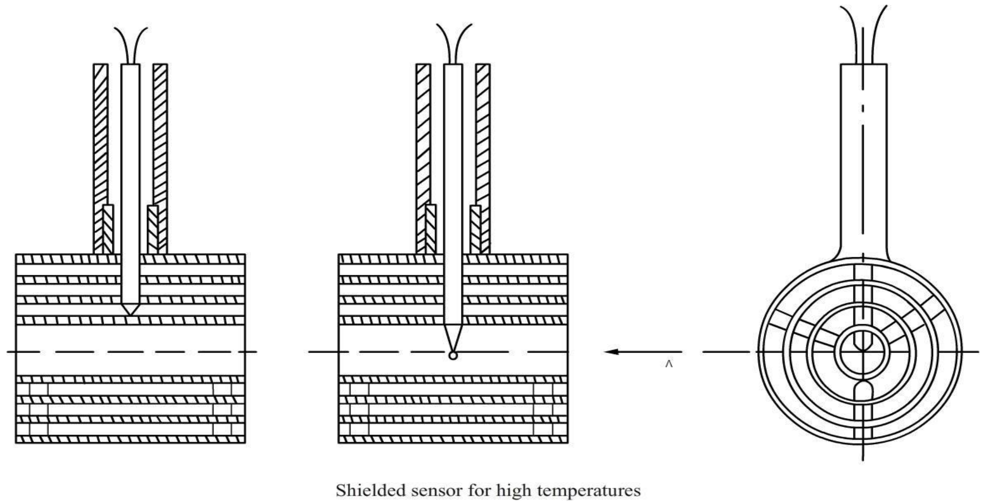


Total temperature probe and its characteristics

Figure shows one such probe. Such probes are simple to make and have recovery coefficient between 0.95 and 0.99.

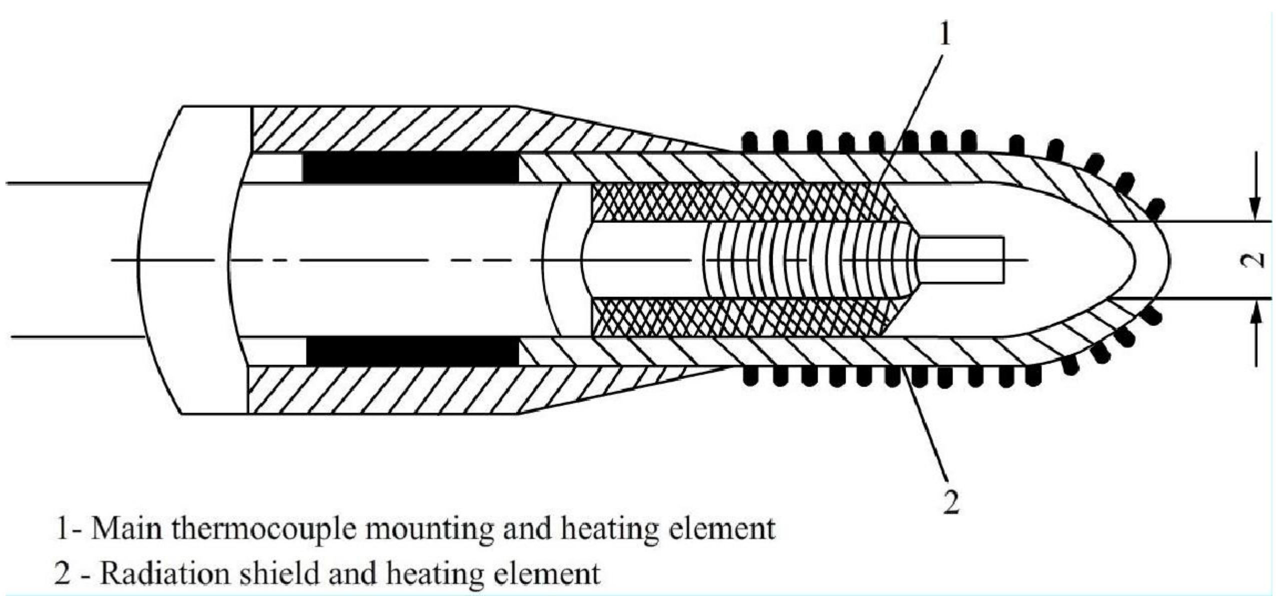
c) High temperature probes (for temperatures above 300 to 400^{0}C

In such cases, the temperature difference between surrounding medium and sensor is 50^{o}C. Hence radiant heat losses become predominant. Radiation intensity depends on area and because of this reason high temperature sensors are made very small. The radiation capacity of the body on which the sensor is mounted should be low and this is achieved by polishing. Another way to achieve good results is by shielding the sensor using concentric tubes.



Temperature probe with concentric tubes

The sensor may be welded to the innermost tube or in the centre of the inner tube. In the first case it will act as a poorly streamlined body and the recovery coefficient will be ~0.65. In the latter case the recovery coefficient may be up to 0.9.The innermost tube may be of insulator material (porcelain) and the outer tubes of heat resistant steel.



Temperature probe with heated shield

Radiation losses can be reduced by heating the shield to a temperature close to the ambient temperature of the medium. Figure gives a miniature probe with heated shied developed by California Institute of Technology. In this an electrically heated wire on the shield reduces direct radiation losses and by conduction from the shield. To reduce the heat loss by conduction through the leads from the thermocouple and its holder, the latter is also heated by electric heating.

Expansion Thermometers or Liquid in Glass Thermometers (LIG)

A liquid-in-glass thermometer is widely used due to its accuracy for the temperature range - 200 to 600°C. Compared to other thermometers, it is simple for usage. It has been used in medicine, metrology and industry. In the LIG thermometer the thermally sensitive element is a liquid contained in a graduated glass envelope. The liquid used in practical thermometers are mercury or alcohol. The principle used to measure temperature is that of the apparent thermal expansion of the liquid.

Boiling point of Mercury is 357^{o}C. Liquid in bulb Thermometers making use of Mercury has a range of -39^{0} to 350^{o}C which are freezing and melting points of Mercury. If alcohol is used the lower temperature can be upto -62^{0}C

Bimetallic thermometers

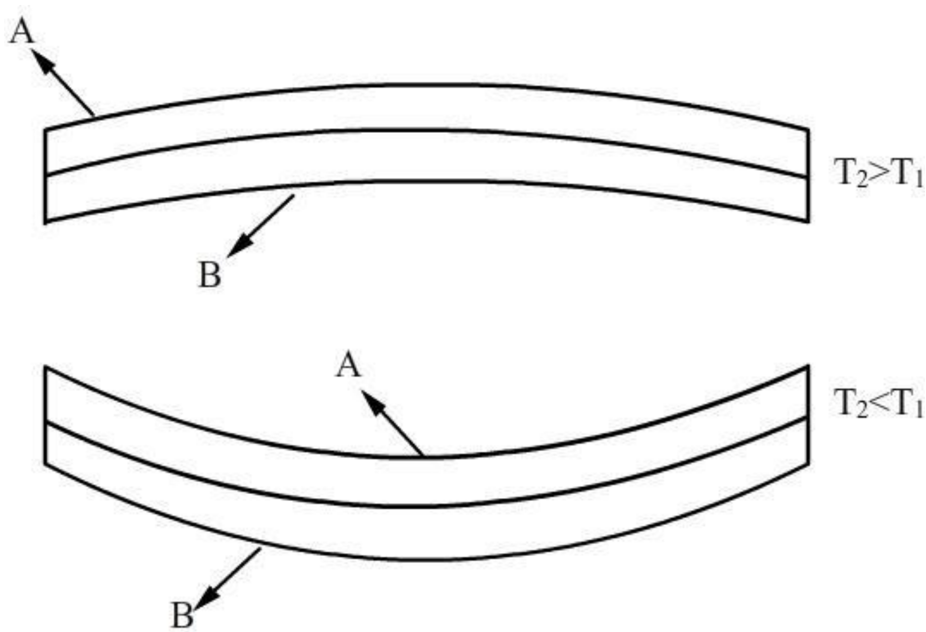
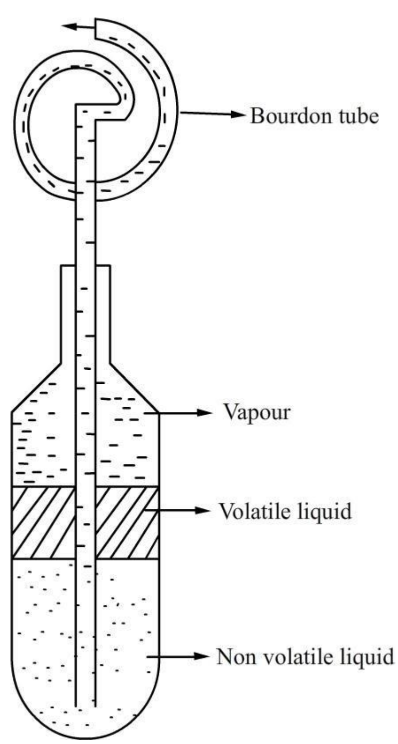


Fig. Bimetallic elements subjected to differential temperature

Bimetallic elements are used for temperature measurement and more widely for sensing and control purposes Invar rod (coefficient of expansion =2.7x 10^{-6} cm/^oC) and Brass (coefficient of expansion = 34.2x10^{-6}cm/^oC because of their large difference in the values of coefficient of expansion are used as a very useful combination.

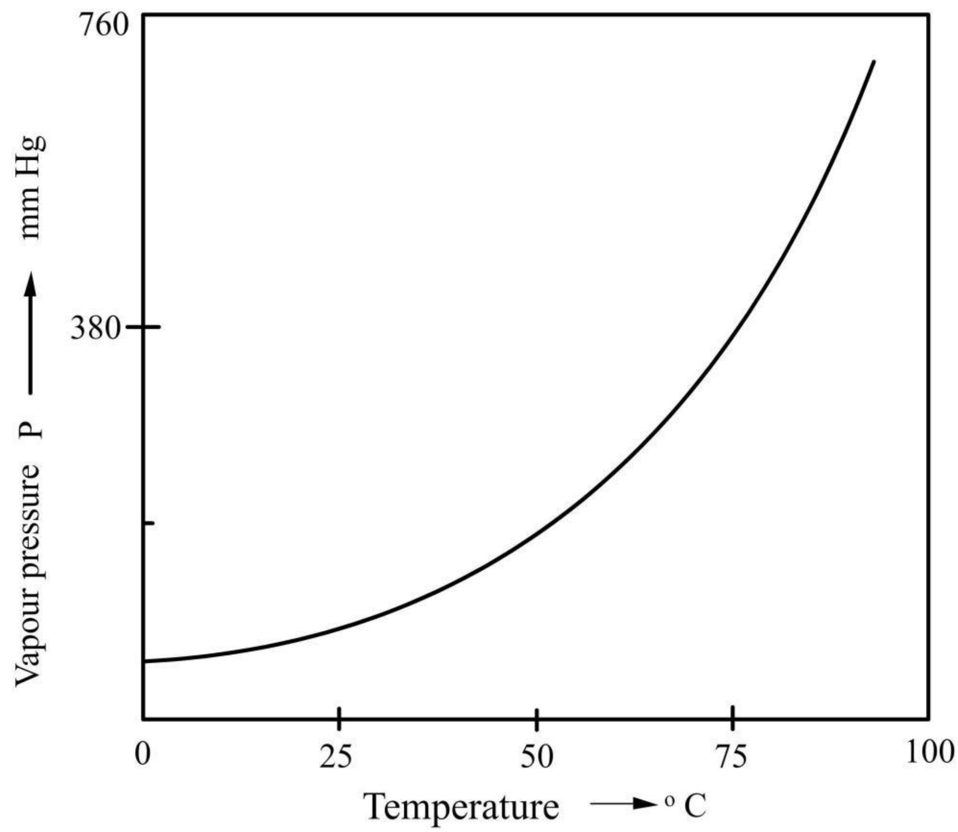
Change of state thermometers: Vapor pressure thermometer

Consider a container having a certain quantity of liquid. The molecules of liquid are in a state of random motion moving in all directions. When vertical component of kinetic energy is greater than the force of attraction at liquid surface, it escapes from the surface. On the other hand, the molecules which constitute vapour are also moving at random. The process of evaporation and condensation go on simultaneously. [When the rates of evaporation and condensation are equal, the vapour becomes saturated].



Vapor pressure thermometer

Saturated vapor pressure depends only on the temperature and properties of the liquid and is independent of the size of the container. The vapor pressure thermometer consists of a (i) bulb containing a fill liquid (ii) a capillary tube (iii) Bourdon Tube.



Saturated vapor pressure of water

The relationship between vapor pressure and temperature is non-linear. As an example, the relation between the saturated vapor pressure of water is shown in Fig.. The range of usage of the vapor pressure thermometer is dependent on the saturated vapor pressure of the liquid. Some of the commonly used fill liquids and the range of temperature in degree C (given in brackets) are Methyl chloride (0-50), Sulphur dioxide (30-120),Water (120-220), Butane (20-

80) and Toluene (150-250). The bulb of the thermometer is exposed to the temperature field to be measured.

Measurement of temperature in Flow

Measurement of the temperature of flowing gas is important in many practical cases. The state of the stationary perfect gas can be defined by two independent physical parameters one of which may be the temperature. When velocity of flow is such that compressibility effects are important, it is necessary to differentiate between static and stagnation temperatures.

Stagnation temperature is that reached by the fluid when it is brought to rest adiabatically.

A thermometer moving with the fluid and emitting no thermal radiation would measure static temperature. An intrusive sensor cannot measure static temperature. Static temperature is measured by non-intrusive methods or estimated indirectly. (by measuring static pressure and then density by optical means) or by measuring the speed of sound. The difference between stagnation temperature T_0 and free temperature T if a moving perfect gas can be determined from

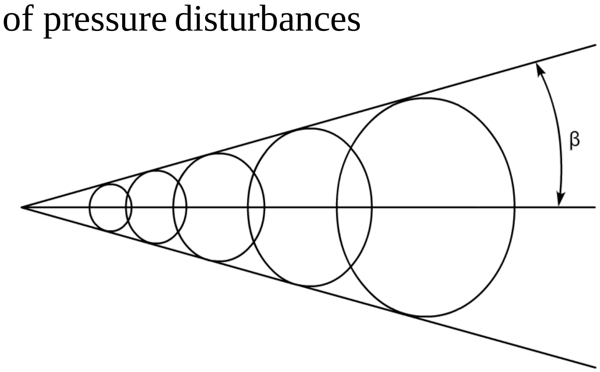
$$T_0 - T = \frac{V^2}{2C_p}$$

Since, shocks do not change the enthalpy; this equation is true for both subsonic and supersonic flows.

Measurement of supersonic velocities/Mach number

This is done by measuring inclination angles of shock waves $\beta = \sin^{-1}\frac{1}{M}$.

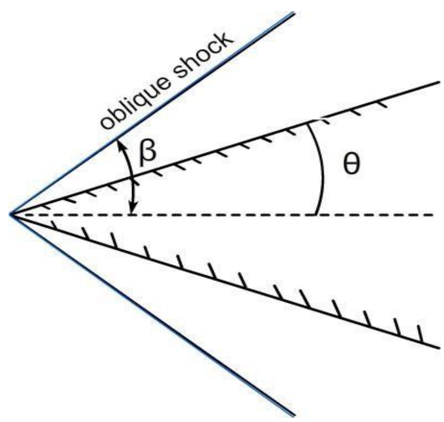
The Mach cone of pressure disturbances



A shock wave of infinitely small intensity lies along the Mach line .But, Mach lines cannot be observed directly. Mach number is best determined by measuring inclination angles of the shock wave appearing at a wedge or a cone shaped obstacle placed with its apex at the test point and axis in the flow direction.

$$\sin^2\beta - \frac{\gamma+1}{2}\frac{\sin\beta\cos\beta}{\cos(\beta-\theta)} = \frac{1}{M^2}$$

In the above equation, θ is the flow deflection angle by the wedge and β is the shock angle.



Oblique shock on a wedge

Hot Wire Anemometer (HWA)

The hot wire anemometer is used to measure fluid velocities by measuring heat loss by convection from a very fine wire which is exposed to the fluid stream. The wire is electrically heated by passing an electrical current through it. When the heated wire is cooled by a fluid stream its electrical resistance decreases, because the resistance of metal wire varies linearly with its temperature.

Assumptions

1) Cylinder is infinitely long
2) No heat loss due to radiation (valid as $T_w < 200^oC$) According to King"s Law,

$$Nu = A + BR_e^{1/2}$$

where A and B are constants

$$\bar{R}_e = \frac{ud}{\gamma_f}$$

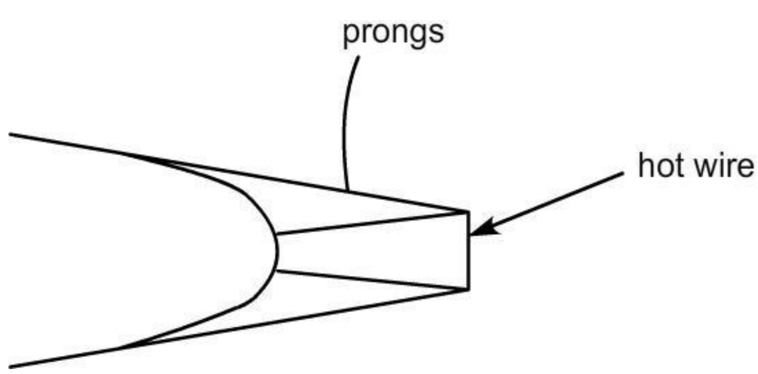
d is diameter of wire.

$\gamma_f \rightarrow$ kinematic viscosity

Advantages of HWA

1) Compared to pneumometric methods, HWA has fast response. Manometers have transmission lag to a more or less extent depending on the measurement system employed. Instantaneous measurement of velocity is important for time dependent fluid phenomena such as turbulence.
2) In pneumometric methods, sensitivity decreases as the velocity decreases. In the case of HWA, sensitivity is more at lower velocities.
3) Small probes can be made.

Probes used in HWA



Hot wire probe

The material of the hot wire is Tungsten, Platinum or Platinum Rhodium

Response to fluctuation

Response to fluctuation depends on wire diameter. Smaller the diameter faster is the response. Diameter of the hot wire is usually between 2.5 and 10μ [say~ 5μ]

To minimise heat loss to prongs

Length of wire $l_w >> d_w$

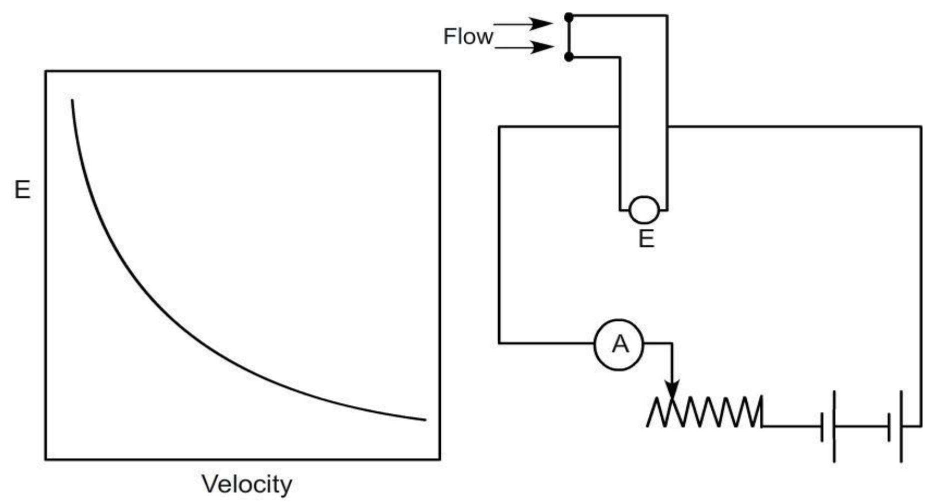
Usual length $l \simeq 1$ to $1.2mm$

$$\frac{l}{d} \simeq 240$$

Two modes of HWA

(a) Constant current anemometer

In this case, the current through the wire is kept constant. When the flow takes place over the hot wire, changes in temperature and resistance occur. The resultant change in voltage is calibrated against velocity.

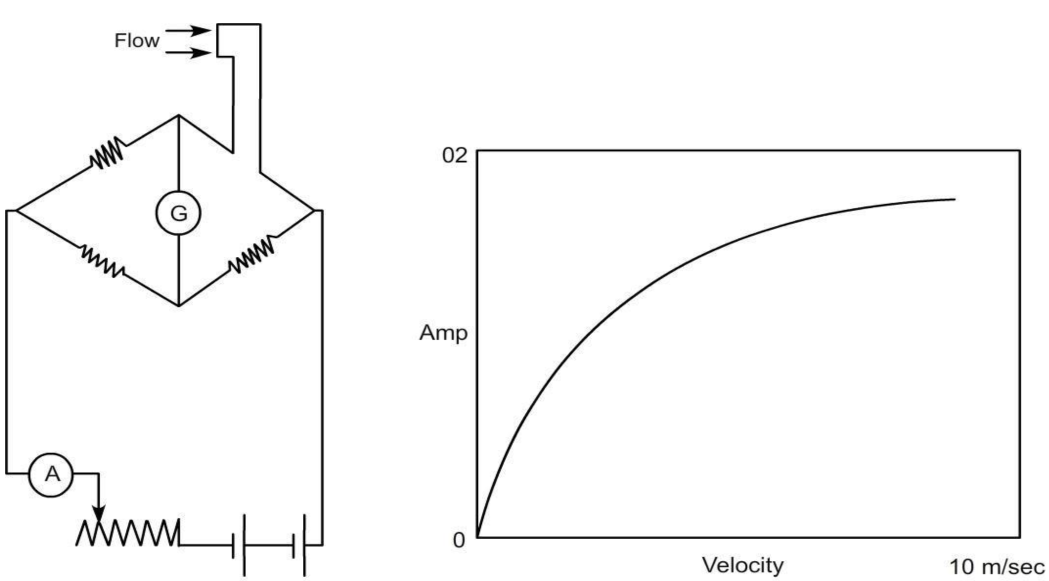


Constant current anemometer and a typical calibration curve Drawbacks

I. Due to thermal inertia the response is limited to about 1000Hz.

II. The current is usually set high to heat the wire considerably above fluid temperature. If the flow drops or velocity becomes zero the wire might damaged due to burn out as there is no convection transfer.

(b) Constant temperature anemometer



Constant temperature anemometer and a typical calibration curve

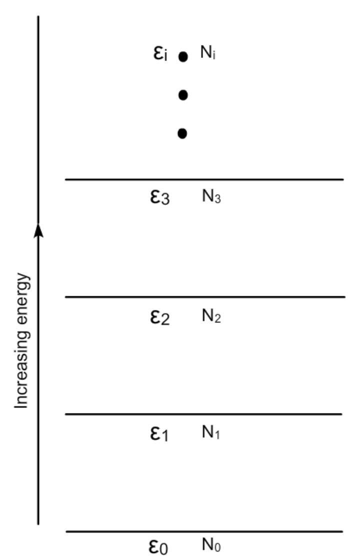
A change in velocity of the flow over the hot wire causes temperature and resistance to change. This imbalances the bridge. By adjusting the resistance of the adjacent arm the bridge is rebalanced. In other words the wire temperature is restored. In constant temperature (resistance) method, the velocity is determined in terms of current needed to maintain a constant temperature of the wire.

Elementary physics of laser action

Before the next method of velocity measurement, the Laser Doppler Anemometer, is explained it is useful to have an understanding of the basic laser action itself.

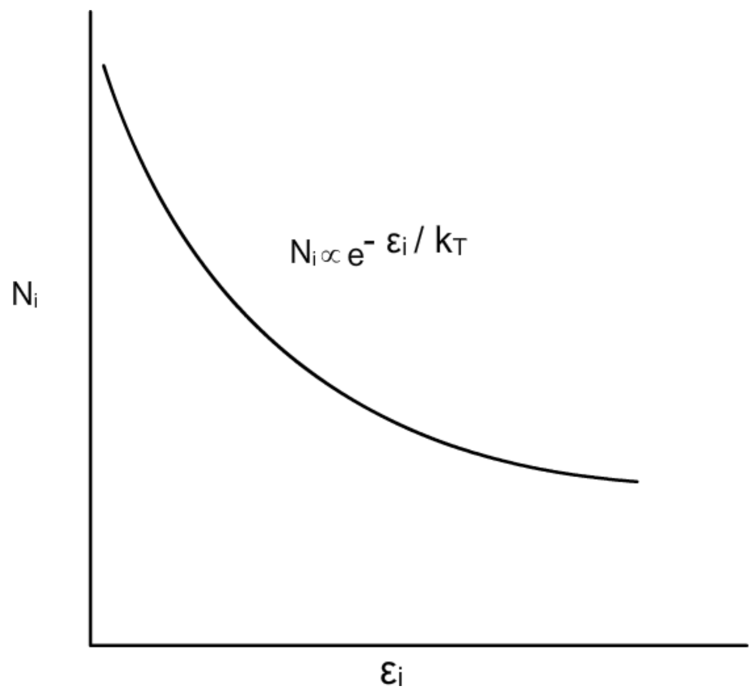
Consider a collection of molecules in a gas. Pick one of the molecules and examine it. The molecule is moving about in space – it has translational energy – it is rotating about its principal axes. So, it has rotational kinetic energy. The atoms that make up the molecule may be vibrating back and forth from some equilibrium position – it has vibrational kinetic and potential energy. Electrons move about the nuclei of the molecule hence, it has kinetic and

potential energy of electronic origin. One amazing quality of these various forms of molecular energy is that they can not be any arbitrary value. Molecule at any instant has to occupy one of the very specific set of energy levels.



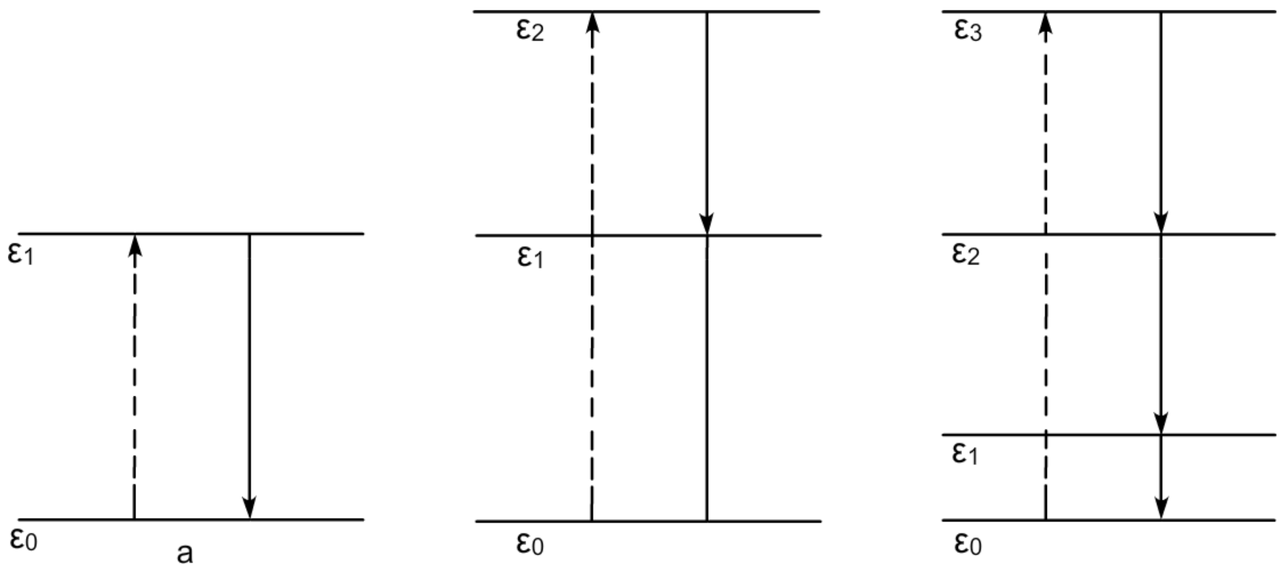
Population distribution at different energy levels

The numbers N_o, N_1, N_2, N_3 …….. N_i is called the population distribution over the energy levels ε_0 …… ε_i of the gas. Consider the vibrational energy of a molecular gas. If the gas is in thermodynamic equilibrium, the population distribution will exponentially decrease with increasing Ni that is it will follow a Boltsman distribution.

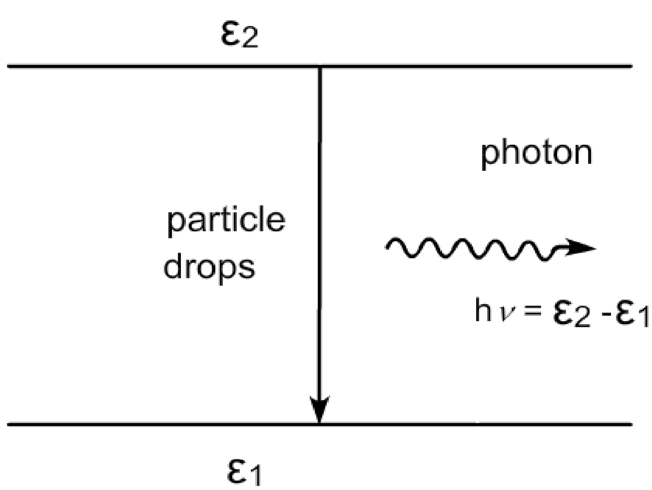


Boltsman distribution of energy

The nature of this population distribution is of vital importance for laser action. A major characteristic of the equilibrium distribution is that $N_{i+1} < N_i$. However, if the gas is disturbed at any instant say by a temperature change and by an electric discharge then the population distribution and in some cases if it is possible that $N_{i+1} > N_i$. This situation in which the number of molecules in a higher energy level is greater than the number in a lower level is called population inversion. The population inversion is the essence of laser action. The attainment of population inversion by means of rapid cooling of the gas is the essence of a G.D laser.



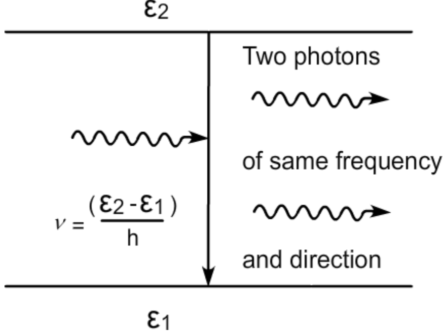
Excited energy levels



Representation of spontaneous emission

Let us consider one electron of the many in an atom E_0 is the ground state of the electron the one in which it normally resides. E_1 is the state (excited state) into which the electron can be driven by supplying it with energy. This energy can come in the form of a photon. The frequency ν of light which can excite the electron is given by $E_1 - E_0 = h\nu$.

If a light wave of frequency ν passes through a material containing these it will excite them and be absorbed. Higher energy states are unstable and after a short time the electron will spontaneously revert to the ground state emitting a photon ν in the process. The average time an atom or molecule spends in the excited state is spontaneous emission lifetime. The net result is



that light travelling in one direction will be absorbed and re-emitted in all directions. Instead of leaving the excited atom to decay naturally it is irradiated with another photon.

Representation of stimulated emission

Another possibility can however occur. A photon of frequency ν can stimulate an already excited atom to emit a second photon travelling in the same direction as the first, whilst the atom reverts to the ground state. This is the stimulated emission upon which a laser relies. If more electrons are in the excited state than the ground state, the net result is amplification. So, the problem of constructing a laser is then essentially one of creating population inversion. If there are only two levels possible for the electron, an enormous amount of energy would be required to excite the majority of the electrons into the upper state.

This is stimulated emission. If max atoms or molecules are in the excited state, the net result is amplification. Three basic requirements for any system to operate as Laser are

1. A material must be available with a suitable energy level system.
2. A means of producing population inversion must be devised.
3. A sufficiently large number of atoms in the excited level must be available if stimulated emission is to exceed spontaneous emission.

Characteristics of laser light

(1) High intensity

(2) Directionality

(3) Coherence

(4) Monochromaticity

Laser Doppler Anemometry (LDA)

Laser Doppler Anemometry is the measurement of fluid velocities by detecting frequency shift of laser light that has been scattered by small particles moving with the fluid. Determining velocity by observing the frequency shift of scattered light was first discussed in a paper by Cummins, Knable and Yeh titled „Observation of Diffusion broadening of Rayleigh Scattered light" (Phys. Rev. Lett. Vol 12 150-153, 1964). Their study was on the

Brownian motion of an aqueous suspension of micron sized particles by observing the spectrum of scattered light. They observed the net shift in the frequency of light which they attributed to the small convection currents that generated mean velocity in their cell. Shortly thereafter, Yeh and Cummins carried out experiments intended expressly to demonstrate the measurement of fluid velocities. [Y.Yeh and H.Z.Cummins „Localized fluid flow measurement with a He-Ne laser Spectrometer‟ Appl. Phy. Lett, Vol 4, pp.176-178, 1964].

Advantages of LDA for velocity measurements

i. The major advantage is that the method is non-intrusive. It could be used in flows that are hostile to material probes or that would be altered by material probe.
ii. No calibration needed.
iii. Many components can be measured.
iv. Good spatial resolution.
v. Capable of tracking very high frequency fluctuations [with fast electronics].
vi. Impressive accuracies achievable. Reported up to 0.1% absolute accuracy [Goldstein and Kreid „Measurement of Laminar flow development in a Square duct using LD flow meter‟

Versatility of LDA is illustrated by the types of flows such as the following in which it has been used successfully

- Supersonic flows
- Recirculating flows
- Natural free convection
- Flow in IC engines
- Chemically reacting flows
- Two phase flows
- Atmospheric turbulence
- High temperature plasmas

Limitations

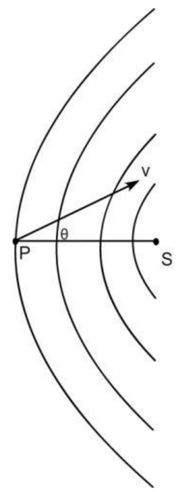
1. Weak intensities of light scattered by small particles resulted in noisy signals.
2. Random locations of the scattering particles in the fluid created new

problems of data analysis. Data arrive randomly and infrequently.

3. Optical arrangement is sensitive to vibrations.

Doppler Shift: Simplistic physical explanation

Consider a wave motion being received by a person at P



Propagation of waves from a source

In unit time the distance travelled by observer P in the direction of source S is

$v\cos\theta$ where, θ is the angle, the velocity vector makes with the direction of wave motion.

So, in unit time $\frac{v\cos\theta}{}$

would be intercepted by P than it had remained stationary. So, change

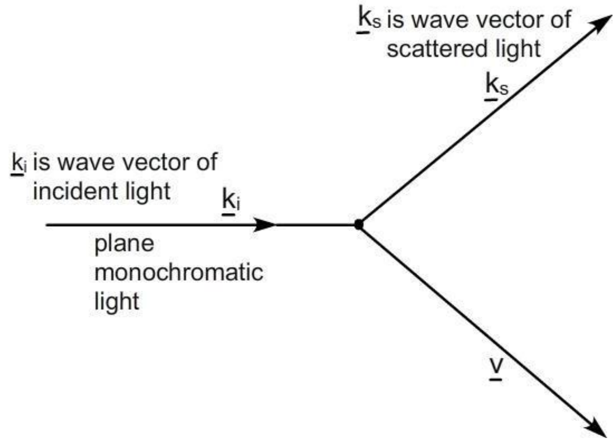
in frequency apparent to the observer is

$\Delta f = \frac{v\cos\theta}{\lambda} = \frac{f_s v\cos\theta}{c}$ c f =

Difference in frequency from the original is caused by the movement of P.

Classical approach to Doppler shift equation

An electromagnetic radiation scattered by a moving object suffers a change in frequency in proportion to the velocity of the scattering object.



Incident light scattered by a moving particle

Assume that a plane monochromatic wave is incident on a particle moving with velocity $\underline{v}$ such that $\underline{v}$ is much less than c the speed of light. For a stationary particle, the number of wave fronts incident upon it per unit time.

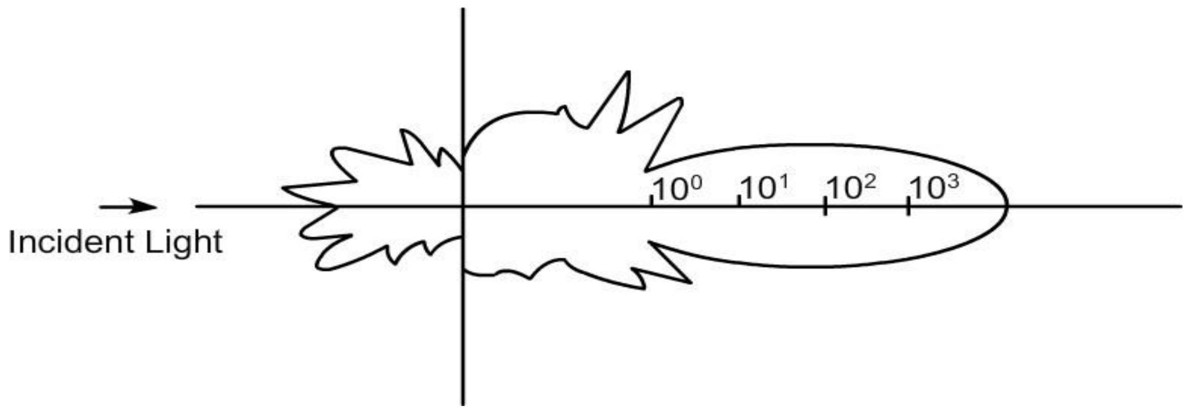
$$f_i = c / \lambda_i$$

Intensity of the scattered light

The intensity of light scattered by particles depends upon:

i. The total incident intensity illuminating the particle.
ii. The scattering angle.
iii. The normalized particle diameter where, is the wavelength of the incident radiation.
iv. The ratio m of the refractive indices of the scatterer and the surrounding medium.

In anemometer applications the diameter of particles is usually comparable to or greater then the wavelength of incident radiation. Foreman and co-workers found that, the scattering is much greater for small angles in the forward direction. For scattering angles less than 10^o the intensity is several hundred times greater than for scattering through 180^o.



Typical example of spatial intensity distribution of scattered light

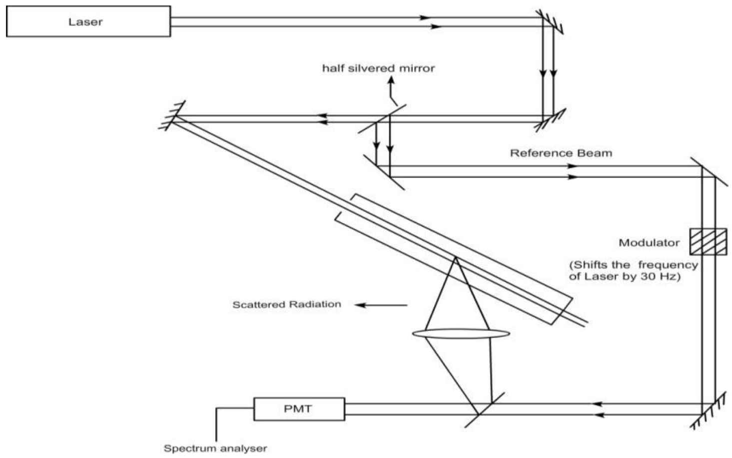
Two modes of LDA

Forward and backward scattering modes of LDA

In the forward scattering mode the scattered light is collected by the photo detector at small degrees in the forward direction. As there is higher intensity in this direction it is possible to build the LDA system using lower power laser.The drawback with this arrangement is that both sides of the test set up will be engaged with the equipments.In the case of backward scattering mode,the photo detector is also kept at the same side of the laser. As the scattered intensity is lower in this direction, the power of the laser source has to be more

Basic LDA arrangement

To understand the basic arrangement of LDA, refer to Fig.



Basic arrangement of LDA

Light from a helium Neon laser is used at a wavelength of 632.8nm which is red light. The light is scattered polystyrene spheres approximately 0.5 μm in diameter which are suspended in water at a concentration of 1 part in 30,000 by volume.

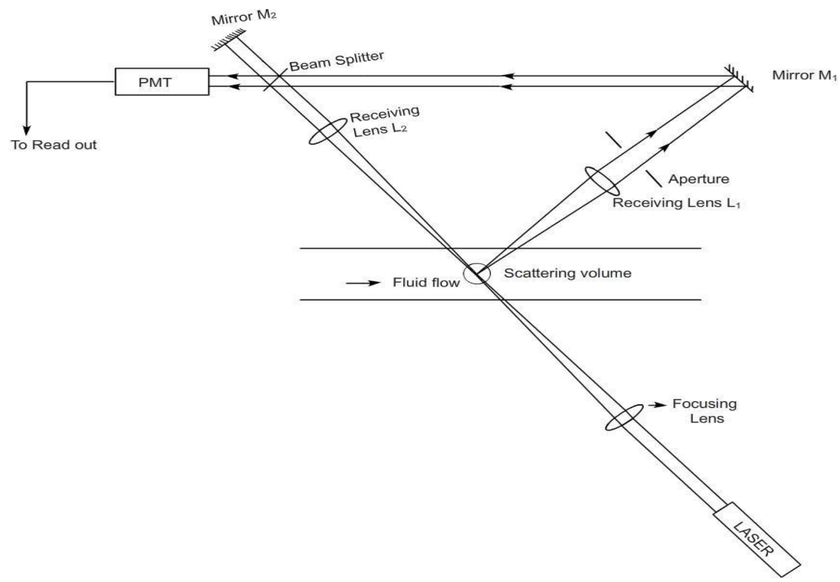
The beam is split by a half silvered mirror. One beam passes through the flow tube. This laser light is scattered by the fluid and collected through a part in the flow tube. This signal beam is focused upon the photo cathode of a photomultiplier. The other beam is passed through a single side band modulator which shifts the frequency of the laser light by 30MHz.

The reference beam is then caused to fall upon the photomultiplier and mix with the signal beam. For zero velocity a frequency shift of 30MHz will be observed. The Doppler frequency shift is added to this 30MHz. Yeh and Cummins used velocimeter to measure velocity profile of laminar flow through the flow tube.

Single beam laser anemometer

The first extensive paper on a Laser anemometer was written by Foreman, George, Lewis, Thorton, Felton and Watson IEE Jl. Quantum Electronics GE-2, 260 (1966). These researchers used what is now termed a single-beam anemometer. The schematic of the single beam laser anemometer is given in Fig..

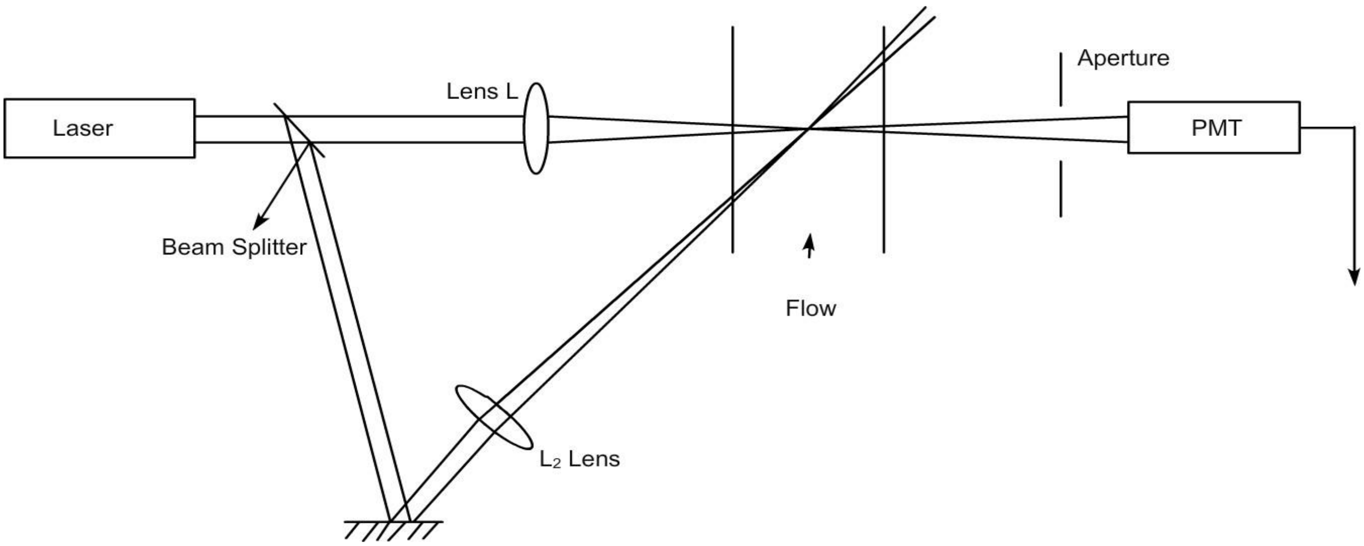
Once beam from the laser is focused upon the fluid whose velocity is to be measured, part of the beam is scattered and part is transmitted to produce the reference beam. The signal beam is collimated by a lens L_1, passes through an aperture A which defines the scattering angle and is reflected by a mirror M_1 onto a photo multiplier tube. The reference beam is collimated by a lens, L_2 and made to overlap the signal beam by means of the mirror M_2 and a beam splitter.



Single beam Laser Doppler Anemometer

Foreman and co-workers after extensive studies on the effect of angle on scattering intensity concluded that scattering at small angles gives much greater intensity. Scattering at less than 10^o was found to be several hundred times greater than scattering through 180^o. Accordingly their system and all subsequent systems used light which was scattered through only small angles.

Dual beam laser anemometer



Schematic of a dual beam anemometer

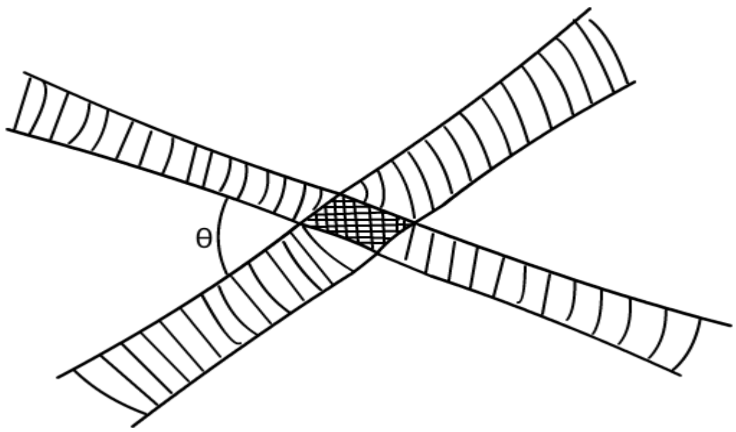
The schematic of the dual beam anemometer is given in Fig.

First reported by Goldstein and Hagen in 1967 [J.App.Mech. 34, 813 (1967)].The important features of the dual beam anemometer are the following:

1) Beam splitter splits laser output into two beams.
2) The two beams are focused nominally onto the same region of flow.
3) One of the beams falls directly on the photo multiplier tube (PMT).
4) The other beam is partially scattered by the fluid.
5) Some of this scattered beam will travel in the same direction as the reference beam.
6) It will pass the aperture and mix with the reference beam.

7.7.7 Fringe model of the LDA

M.J.Rudd in 1969 "Measurements made on a drag reducing solution with a Laser Velocitimeter". Nature 224, 587, (1969).



Fringe model of LDA

λ is the wavelength and θ is the angle between the beams. Where the two beams overlap, the two beams will interfere and produce a set of fringes. Distance between fringes $d = \frac{\lambda}{2} / \sin\frac{\theta}{2}$.

A particle crossing the section block the light. If one collects the light, it will fluctuate at the rate the particle crosses. This will modulate the light at a frequency of V/d where, V is the velocity of light particle.

Flow Visualisation

Introduction

The visualisation of complex flows has played a uniquely important role in the improvement of our understanding of fluid dynamic phenomena. Flow visualisation has been used to verify existing physical principles and has led to the discovery of numerous flow phenomena. In addition to obtaining qualitative global pictures of the flow the possibility of acquiring quantitative measurements without introducing probes that invariably disturb the flow has provided the necessary incentive for development of a large number of visualisation techniques. The methods usually depend either on

(i) the reflection or scattering of light by small solid or liquid particles introduced into the stream or

(ii) on the natural changes of refractive index which accompany the density changes of a compressible fluid.

Flow visualisation by direct injection (Tracer Methods)

In this group of methods, small particles of solid or liquid are introduced into the fluid stream and observed by reflected or scattered light. It is necessary that such particles are of sufficiently small inertia to follow the local direction of fluid motion and sufficiently light as not to be sensibly influenced by gravity. Smoke or other particles in air and dye or other particles in water provide the necessary contamination for flow visualisation. Many substances have been used to visualise the flow of air and water. Smoke, helium bubbles, dust particles and even glowing iron particles have been used in air. A variety of dyes, particles, neutrally buoyant spheres and both air and helium bubbles have been employed in water.

Smokes consist of suspension of small solid or liquid particles in a transparent gas and are usually observed by the scattering and reflection of light by these particles. The word “smoke” used in flow visualisation includes a variety of smoke like materials such as vapours, fumes and mists.

A large number of materials have been used to generate smoke eg, the combustion of tobacco, rotten wood and straw the products of reaction of various chemical substances such as titanium tetrachloride and water vapour. The smokelike materials are referred to as aerosols (since aerosols are composed of collided particles suspended in a gas).

Two very practical points must be examined before the choice of smokelike material. The particles must be as small as possible so that they will closely follow the flow pattern being studied. The particles must be large enough to scatter a sufficient amount of light. Sizes below 1μm but above 0.15μm are good for scattering sufficient light and hence for photographing.

The most popular agent for airflow visualisation in wind tunnels has been smoke. The use of smoke requires a low turbulence level to minimize diffusion. Furthermore the smoke particles are so small that they cannot be observed or photographed individually. A larger neutrally buoyant tracer agent is needed to follow the paths of individual particles and bubble methods are useful in this regard.The soap bubble is an ideal particle because its size and buoyancy can be controlled. The system for bubble method consists of a bubble generator, lighting and optical components and photographic equipments to record the paths of bubbles. Neutral buoyancy is achieved by filling the bubbles with helium. Bubbles from approximately 1 to 5mm dia can be generated at rates upto 500/sec.

Index of refraction methods

The three methods included in this category are Schlieren, Shadowgraph and Interferometric techniques. Although all three methods depend on variation of index of refraction in a transparent medium and the resulting effects on a light beam passing through the test region quite different quantities are measured with each one. All three methods are used to study density fields in transparent media.

Density is a variable in compressible fluid. Particles added in incompressible fluids for visualising flows cannot respond to the thermodynamic changes. Hence, refractive index based methods are used for visualisation of such flows.

These methods are integral. They integrate the quantity measured over the length of the light beam. So, they are suited for two dimensional flow fields where there are no density variation in the field along the light beam except at entrance and exit of test section.

Theoretical background

According to Gladstone – Dale formula

$$n-1 = K\rho$$

where, n is the

refractive index. K

values are (to a

large extent).

constant for a wavelength. Varies slightly with λ .

Table Values of K in gases

Gas	K (cm^3/gm)
CO_2	0.229
O_2	0.190
N_2	0.238
He	0.196

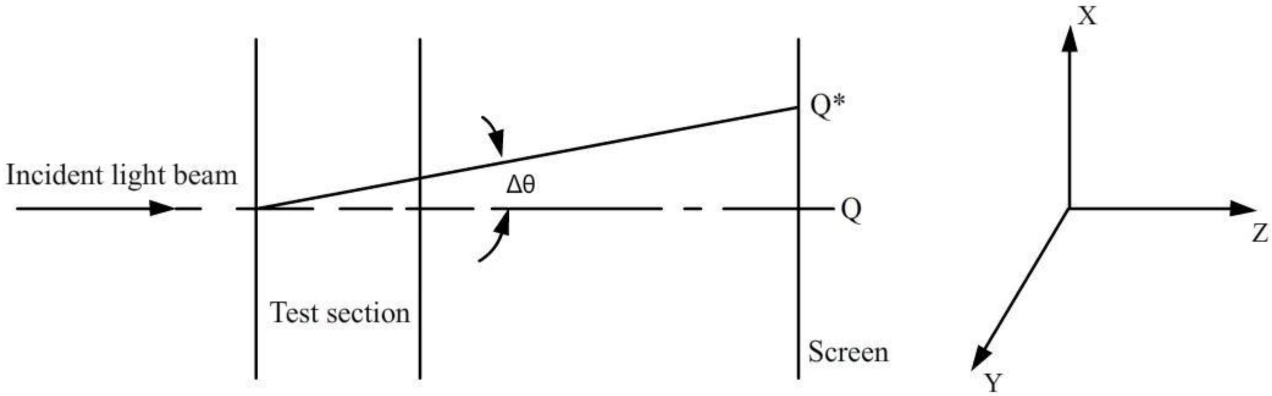
ρ is the density and K is the Gladstone–Dale constant. This equation holds quite well for gases. The constant K is a function of the particular gas and varies slightly with wave length. Index of

refraction or refractive index n is defined as and c that in the medium.

$n = \frac{c_o}{c}$, where c_o is the speed of light in vacuum

$$n = n(\rho)$$

When encountering a flow field of varying density, light passing through one part of the flow field is retarded differently from that passing through another part.



Effect of change of Refractive Index on a ray of light

As shown in Figure, light ray is deflected from original direction and reaches Q*. Q and Q* will coincide if at all planes normal to the incident ray n is constant. The optical path covered by the deflected ray is different from that of the undisturbed ray. It is possible to measure

(a) displacement QQ*

(b) the angular deflection $\Delta\theta$

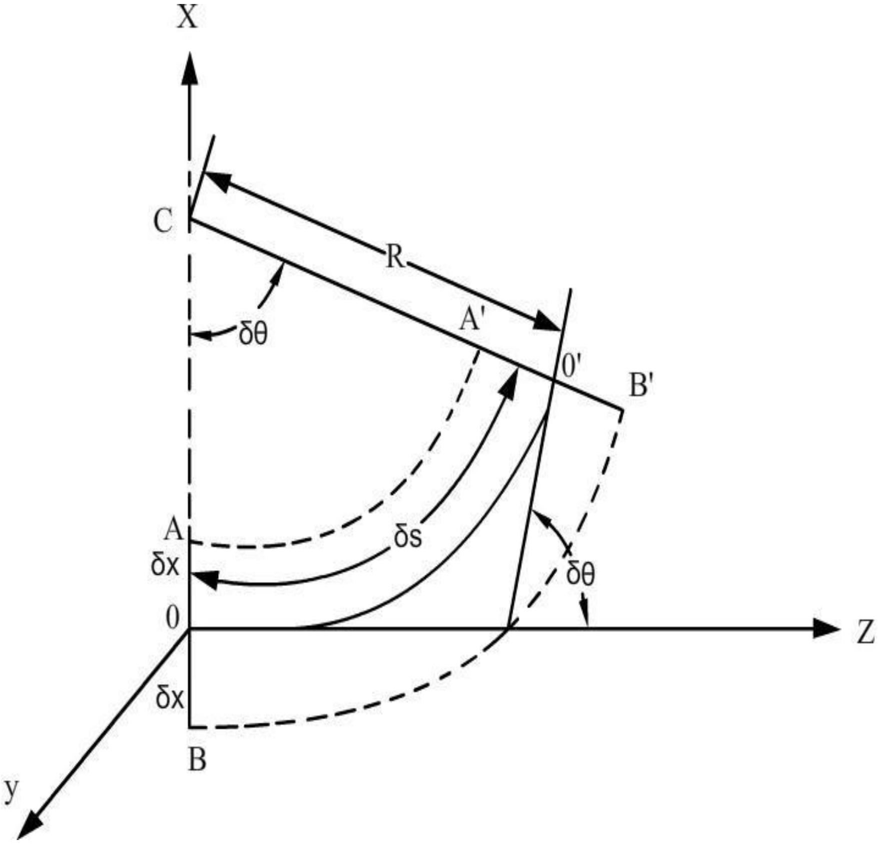
(c) the path difference between the two rays

The Table sums up the three different methods for optical flow visualisation.

Comparison of the three optical methods of flow visualisation

Method	**Quantity measured**	**Sensitive to the change of**
Shadow	Displacement	$\frac{\partial^2 n}{\partial x^2}$
Schileren	Angular deflection	$\frac{\partial n}{\partial x}$
Interferometer	Phase change	n

Deflection of light ray in a medium of constant density gradient



Effect of a constant gradient of refractive index on a wave front