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FORMULA SHEET

for

GATE-AE GAS DYNAMICS

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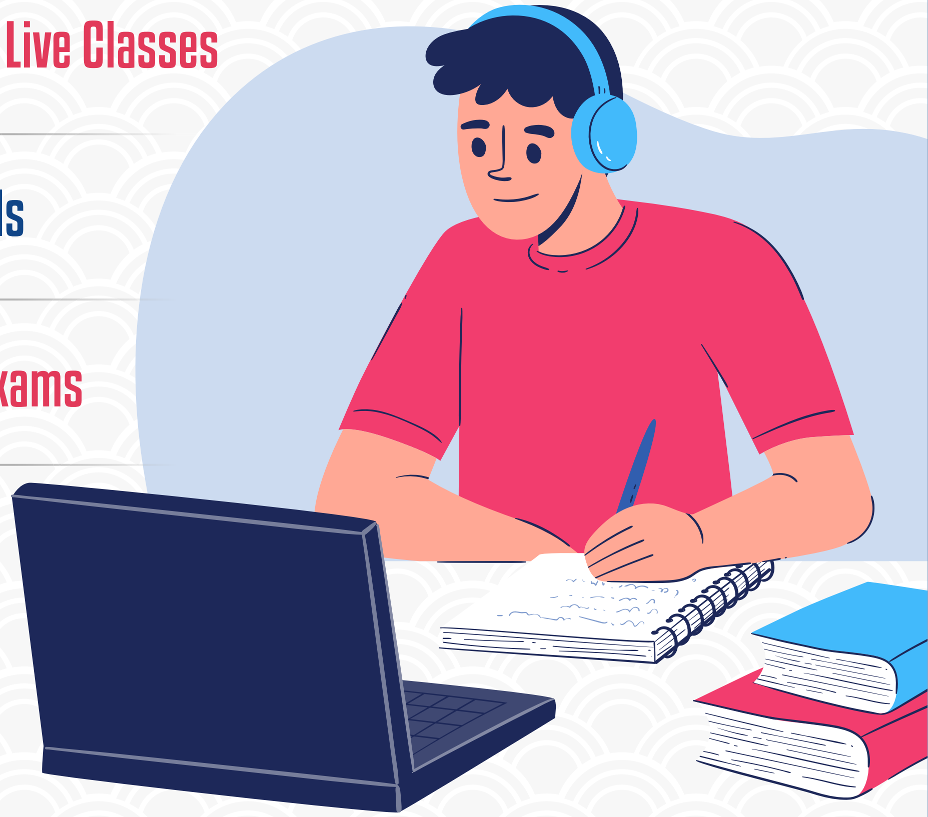

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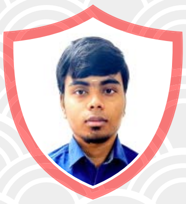

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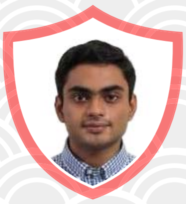

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GAS DYNAMICS

Chapter 1: Review of Thermodynamics

1st Law:

$\delta q + \delta w = de$

$q \rightarrow$ Heat transfer, $w \rightarrow$ Work transfer

$e \rightarrow$ internal energy of the system per unit mass.

Adiabatic Process:

One in which no heat is added to or taken away from the system.

Reversible Process:

One in which no dissipative phenomenon occurs, that is, where the effect of viscosity thermal conductivity, and mass diffusion are absent.

Isentropic Process:

One that is both adiabatic and reversible.

$\delta q - pdv = de \rightarrow$ For reversible process.

Where $p \rightarrow$ pressure,

$v \rightarrow$ Specific volume, $v = \frac{1}{\rho}$

$\rho \rightarrow$ density

Entropy and 2nd Law:

$$ds = \frac{\delta q_{rev}}{T}$$

where, $s \rightarrow$ Entropy per unit mass of the system.

$T \rightarrow$ Temperature of the system.

$$ds = \frac{\delta q}{T} + ds_{(irrev)} \rightarrow \text{more general form}$$

$ds_{irrev} \geq 0$

2nd Law: $ds \geq 0$

Tds Relations:

$Tds - pdv = de$

$Tds = de + pdv$

$\boxed{Tds = dh - vdp}$

$h \rightarrow$ specific enthalpy

$\boxed{h = c_p dT}$ $\boxed{e = c_v dT}$

here, $c_p \rightarrow$ Specific heat at constant pressure

$$c_p = \left(\frac{\partial h}{\partial T}\right)_{p=constant}$$

$c_v \rightarrow$ specific heat at constant volume

$$c_v = \left(\frac{\partial e}{\partial T}\right)_{v=constant}$$

Relationship Between c_p, c_v and R

$c_p - c_v = R$

$R \rightarrow$ Gas constant

$$R = \frac{R_u}{MW}$$

$R_u \rightarrow$ Universal gas constant

$MW \rightarrow$ Molecular weight

$$\left.\begin{aligned} s_2 - s_1 &= c_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{p_2}{p_1}\right) \\ s_1 - s_1 &= c_v \ln\left(\frac{T_2}{T_1}\right) + R\ln\left(\frac{v_2}{v_1}\right) \end{aligned}\right\} \left(\begin{gathered}\text{Valid for} \\ \text{Calorically} \\ \text{perfect gas}\end{gathered}\right)$$

$$\gamma = \frac{c_p}{c_v} \rightarrow \text{Ratio of specific heats}$$

Isentropic Relations:

$$s_1 - s_1 = 0$$

$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{\rho_2}{\rho_1} = \left(\frac{T_2}{T_1}\right)^{\frac{1}{\gamma-1}}$$

$$\frac{p_2}{p_1} = \left(\frac{\rho_2}{\rho_1}\right)^{\gamma} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$$

Chapter 2: Compressible Fluid Flow Basics

Compressibility:

Isothermal compressibility:

$$\tau_T = -\frac{1}{v}\left(\frac{\partial v}{\partial p}\right)_{T=\text{constant}}$$

Isentropic Compressibility:

$$\tau_s = -\frac{1}{v}\left(\frac{\partial v}{\partial p}\right)_{s=\text{constant}}$$

$$\tau_s = \frac{1}{\rho}\frac{d\rho}{dp}$$

$$d\rho = \rho\tau dp$$

Mach Number:

$$M = \frac{V}{a}$$

$V \rightarrow$ Local speed (Velocity) of the fluid Particle.

$a \rightarrow$ Local speed of sound.

Equation of State: $p = \rho RT$

Speed of Sounds:

$$a = \sqrt{\left(\frac{\partial p}{\partial \rho}\right)_{s=\text{constant}}}$$

$$a = \sqrt{\gamma RT} = \sqrt{\frac{\gamma p}{\rho}}$$

$\rightarrow$ valid for calorically perfect gas

Forms of energy equation for Steady Adiabatic Flows:

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2} = \text{Constant}$$

For 1-D Adiabatic steady flows

$$h_1 + \frac{u_1^2}{2} = h_2 + \frac{u_2^2}{2}$$

$$h + \frac{u^2}{2} = h_o$$

$$\frac{T_o}{T} = \left(1 + \frac{\gamma-1}{2}M^2\right)$$

Note: This is valid for steady adiabatic flow of a calorically perfect gas.

Isentropic Flow Relations for Steady Flow:

$$\frac{p_o}{p} = \left(\frac{T_o}{T}\right)^{\frac{\gamma}{\gamma-1}} = \left[1 + \frac{\gamma-1}{2}M^2\right]^{\frac{\gamma}{\gamma-1}}$$

$$\frac{\rho_o}{\rho} = \left(\frac{T_o}{T}\right)^{\frac{1}{\gamma-1}} = \left[1 + \frac{\gamma-1}{2}M^2\right]^{\frac{1}{\gamma-1}}$$

Characteristic Mach Number:

$$M^* = \frac{u}{a^*}$$

$u \rightarrow$ Local speed of the fluid (1- D)

$a^* \rightarrow$ Characteristic speed of sound.

$$M^* = \frac{(\gamma+1)M^2}{2 + (\gamma-1)M^2};$$

$M \rightarrow$ Local Mach number

$M^* < 1 \quad \text{if } M < 1$

$M^* = 1 \;\text{ if } M = 1$

$M^* > 1 \;\text{ if } M > 1$

$M^* \to \sqrt{\frac{\gamma+1}{\gamma-1}} \;\text{ if } M \to \infty$

Chapter 3: Normal Shock Waves

Governing Equation for Standing Normal Shockwave:

Continuity : $\rho_1 u_1 = \rho_2 u_2$

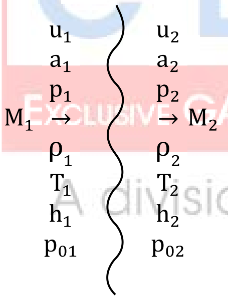
Momentum: $p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2$

Energy: $h_1 + \frac{u_1^2}{2} = h_2 + \frac{u_2^2}{2}$

$h = c_p T$

$P = \rho R T$

Property Change across the Standing Normal Shock Wave:



Shock Wave

Thickness of shockwave $\sim \frac{\nu}{a}$

$\nu \to$ Kinematic viscosity of the gas

$a \to$ Speed of sound

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{(\gamma+1)M_1^2}{2+(\gamma-1)M_1^2}$$

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1)$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)\left(\frac{\rho_1}{\rho_2}\right)$$

$$M_2^2 = \frac{1 + \left(\frac{\gamma-1}{2}\right)M_1^2}{\gamma M_1^2 - \left(\frac{\gamma-1}{2}\right)}$$

Limit Cases:

As $M_1 \to \infty$

$\frac{\rho_2}{\rho_1} \to \frac{\gamma+1}{\gamma-1}$

$\frac{p_2}{p_1} \to \infty$

$\frac{T_2}{T_1} \to \infty$

$M_2 = \to \sqrt{\frac{\gamma-1}{2\gamma}}$

$T_{01} = T_{02}$

$\frac{p_{02}}{p_{01}} = e^{-(s_2-s_1)/R}$

Measurement of Velocity in Compressible flow Using Pitot-Static Tube:

Subsonic Compressive Flow:

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

$p_{01} \to$ Total pressure; $p_1 \to$ Static pressure

[Free stream conditions]

$$u_1^2 = \frac{2a_1^2}{\gamma-1}\left[\left(\frac{p_{01}}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

Supersonic Compressible Flow (Rayleigh-Pitot Formula):

$$\frac{p_{02}}{p_1} = \left(\frac{(\gamma+1)^2 M_1^2}{4\gamma M_1^2 - 2(\gamma-1)}\right)\left[\frac{1-\gamma+2\gamma M_1^2}{\gamma+1}\right]$$

p_{02} → Total pressure downstream of the shock wave.

p_1 → Static pressure upstream of the shock wave.

M_1 → Mach number upstream of the shock wave. (Free stream Mach number).

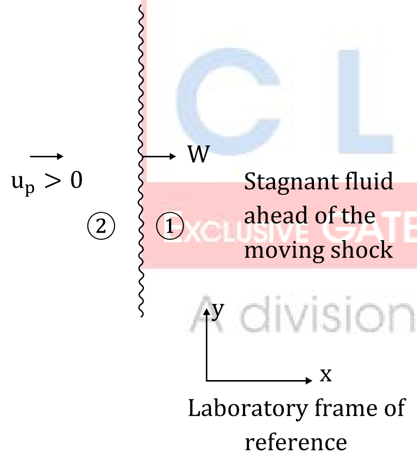
Moving Normal Shock Relations:

Hugoniot Equation:

$$e_2 - e_1 = \frac{p_1 + p_2}{2}\left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right)$$

$$\frac{p_2}{p_1} = \frac{\left(\frac{\gamma+1}{\gamma-1}\right)\left(\frac{\rho_2}{\rho_1}\right) - 1}{\left(\frac{\gamma+1}{\gamma-1}\right) - \left(\frac{\rho_2}{\rho_1}\right)}$$

Moving Shock Waves:



u_p → Mass Motion Induced by the moving shock wave (Group motion velocity)

W → Shock motion velocity.

$$M_s = \frac{W}{a_1}$$

M_s → Moving shock Mach number

a_1 → Velocity of round in region ①.

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma+1}(M_s^2 - 1)$$

$$W = a_1\sqrt{\frac{\gamma+1}{2\gamma}\left(\frac{p_2}{p_1} - 1\right) + 1}$$

$$u_p = W\left(1 - \frac{\rho_1}{\rho_2}\right)$$

$$u_p = \frac{a_1}{\gamma}\left(\frac{p_2}{p_1} - 1\right)\left(\frac{\frac{2\gamma}{\gamma+1}}{\frac{p_2}{p_1} + \frac{\gamma-1}{\gamma+1}}\right)^{\frac{1}{2}}$$

Note: $A_s \frac{p_2}{p_1} \to \infty$

$$\lim_{\frac{p_2}{p_1}\to\infty}\left(\frac{u_P}{a_2}\right) = \sqrt{\frac{2}{\gamma(\gamma-1)}}$$

$$\frac{T_2}{T_1} = \frac{p_2}{p_1}\left(\frac{\frac{\gamma+1}{\gamma-1} + \frac{p_2}{p_1}}{1 + \frac{\gamma+1}{\gamma-1}\frac{p_2}{p_1}}\right)\left(\begin{array}{c}\text{Temperature}\\ \text{Change across}\\ \text{Moving Shock}\end{array}\right)$$

$$\frac{\rho_2}{\rho_1} = \frac{1 + \frac{\gamma+1}{\gamma-1}\frac{p_2}{p_1}}{\frac{\gamma+1}{\gamma-1} + \frac{p_2}{p_1}}\left(\begin{array}{c}\text{Density change}\\ \text{Across moving shock}\end{array}\right)$$

Note: Total enthalpy and total temperature is not constant across the moving shock wave! (Since it is unsteady flow).

$h_{02} > h_{01}$

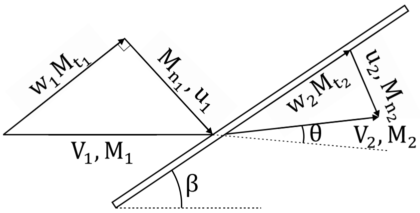
$$\rho\frac{Dh_o}{Dt} = \frac{\partial p}{\partial t} \text{ and } \frac{\partial p}{\partial t} \neq 0$$

Chapter 4: Oblique Shock and Expansion Waves

Oblique Shock Relations:

Mach Angle:

$$\mu = \sin^{-1}\left(\frac{1}{M}\right)$$



$V_1 \to$ Upstream velocity

$M_1 \to$ Upstream Mach number

$\theta \to$ Deflection angle

$\beta \to$ Shock wave angle

$V_2 \to$ Downstream velocity

$M_2 \to$ Down stream Mach number

$M_{n_1}, M_{n_2} \to$ Normal component of Mach number upstream and downstream, respectively.

$M_{t_1}, M_{t_2} \to$ Tangent component of Mach number upstream and downstream, respectively.

$u_1, u_2 \to$ Normal component of velocity vector upstream and downstream respectively.

$w_1, w_2 \to$ Tangential component of velocity vector upstream and downstream respectively.

$$w_1 = w_2$$

$$M_{n_1} = M_1 \sin \beta_1$$

$$M_{n_2}^2 = \frac{1 + \left(\frac{\gamma - 1}{2}\right) M_{n_1}^2}{\gamma M_{n_1}^2 - \left(\frac{\gamma - 1}{2}\right)}$$

$$\frac{p_2}{p_1} = \frac{(\gamma + 1) M_{n_1}^2}{2 + (\gamma - 1) M_{n_1}^2}$$

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma + 1}\left(M_{n_1}^2 - 1\right)$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)\left(\frac{\rho_1}{\rho_2}\right)$$

$$M_2 = \frac{M_{n_2}}{\sin(\beta - \theta)}$$

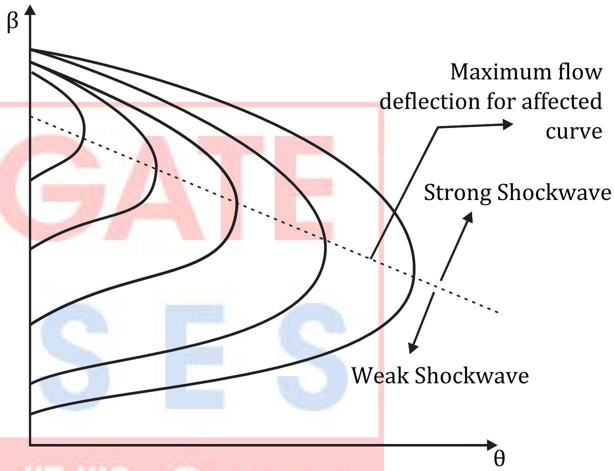
$$\tan \beta = \frac{u_1}{w_1}$$

$$\tan(\beta - \theta) = \frac{u_2}{w_2}$$

θ-β-M Relation:

$$\frac{\tan(\beta - \theta)}{\tan \beta} = \frac{u_2}{u_1} = \frac{\rho_1}{\rho_2}$$

$$\tan \theta = 2 \cot \beta \left(\frac{M_1^2 \sin^2 \beta - 1}{M_1^2 (\gamma + \cos 2\beta) + 2}\right)$$



The normal component must be supersonic ($M_1 \sin \beta > 1$)

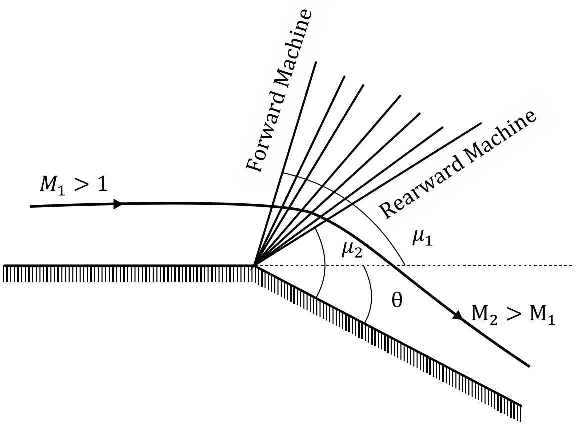
This requirement imposes the restriction on the wave angle (β) for a given M_1

$$\sin^{-1}\left(\frac{1}{M_1}\right) \le \beta \le \frac{\pi}{2}$$

$$\beta = \frac{\pi}{2} \to \text{Normal shock}$$

$$\beta = \sin^{-1}\left(\frac{1}{M_1}\right) \to \text{mach wave}$$

Prandtl-Mayor Function for Expansion waves:



Note: Applicable for isentropic flow turn.

$$\nu(m) = \sqrt{\frac{\gamma+1}{\gamma-1}}\tan^{-1}\sqrt{\frac{\gamma-1}{\gamma+1}(M^2-1)} - \tan^{-1}\sqrt{M^2-1}$$

$\nu(m) \rightarrow$ Prandtl-Mayor Function in units of angle.

$\theta = \nu(M_2) - \nu(M_1) \rightarrow$ True for Expansion corner.

$\theta = \nu(M_1) - \nu(M_2) \rightarrow$ True for isentropic compression corner.

$$\frac{T_2}{T_1} = \frac{1+\left(\frac{\gamma-1}{2}\right)M_1^2}{1+\frac{(\gamma-1)}{2}M_2^2}$$

$$\frac{p_2}{p_1} = \left[\frac{1+\left(\frac{\gamma-1}{2}\right)M_1^2}{1+\frac{(\gamma-1)}{2}M_2^2}\right]^{\frac{\gamma}{\gamma-1}}$$

$T_{02} = T_{01}$; $p_{02} = p_{01}$

Chapter 5: Flow Through Cd Nozzle

Quasi-One-Dimensional Flow:

Continuity:

$\rho_1 u_1 A_1 = \rho_2 u_2 A_2$

$A \rightarrow$ Area at any section.

Momentum:

$$p_1A_1 + \rho_1 u_1^2 A_1 + \int_{A_1}^{A_2} p\,dA = p_2A_2 + \rho_2 u_2^2 A_2$$

Energy:

$$h_1 + \frac{u_1^2}{2} = h_2 + \frac{u_2^2}{2}$$

Differential Form:

$\rho u A = \text{Constant}$

$d(\rho u A) = 0$

Continuity:

$$\frac{d\rho}{\rho} + \frac{du}{u} + \frac{dA}{A} = 0$$

Momentum:

$dp = -\rho u\,du$

Energy:

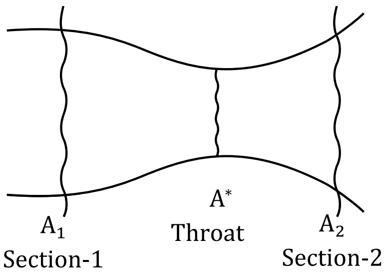
$dh + u\,du = 0$

Area Mach Number Relation:

$$\frac{dA}{A} = (M^2 - 1)\frac{du}{u}$$

Nozzle Flows: (C-D Nozzle)

$$\frac{A_1}{A_2} = \frac{M_2}{M_1}\sqrt{\left[\frac{1+\frac{\gamma-1}{2}M_1^2}{1+\frac{\gamma-1}{2}M_2^2}\right]^{\frac{\gamma+1}{\gamma-1}}}$$



$$\left(\frac{A}{A^*}\right)^2 = \frac{1}{M^2}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{\frac{\gamma+1}{\gamma-1}}$$

Choked Mass Flow Rate at the Throat:

($u^* = a^*$, $M^* = 1$) At throat

$$\dot{m} = \frac{p_o}{\sqrt{RT_O}}\sqrt{\gamma}.\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} A^*$$

Flow Through Supersonic Wind Tunnel:

$$\frac{A_{t_2}}{A_{t_1}} = \frac{p_{01}}{p_{02}}$$

A_{t_1} → Throat area of C-D nozzle

A_{t_2} → Throat area of diffuser.

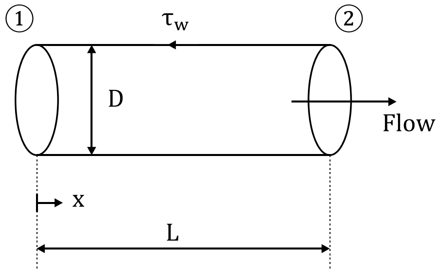
p_{01} → Stagnation pressure in the nozzle.

p_{02} → Stagnation pressure in the diffuser.

Note: This relation assumes normal shockwave standing in the test section. This to make sure that the initial shock wave (Starting shock) to pass the wind tunnel during the start of the tunnel.

Chapter 6: Rayleigh and Fanno Flows

Flow with Friction (Fanno Flow):



$$\frac{T_2}{T_1} = \frac{2+(\gamma-1)M_1^2}{2+(\gamma-1)M_2^2}$$

$$\frac{p_2}{p_1} = \frac{M_1}{M_2}\left[\frac{2+(\gamma-1)M_1^2}{2+(\gamma-1)M_2^2}\right]$$

$$\frac{\rho_2}{\rho_1} = \left(\frac{p_2}{p_1}\right)\left(\frac{T_1}{T_2}\right)$$

$$\frac{\rho_2}{\rho_1} = \frac{M_1}{M_2}\left[\frac{2+(\gamma-1)M_2^2}{2+(\gamma-1)M_1^2}\right]^{-1/2}$$

$$\frac{p_{02}}{p_{01}} = \frac{M_1}{M_2}\left[\frac{2+(\gamma-1)M_2^2}{2+(\gamma-1)M_1^2}\right]^{\frac{\gamma+1}{2(\gamma-1)}}$$

Choking in Frictional Flow:

$$\frac{T}{T^*} = \frac{\gamma+1}{2+(\gamma-1)M^2}$$

$$\frac{p}{p^*} = \frac{1}{M}\left[\frac{\gamma+1}{2+(\gamma-1)M^2}\right]^{1/2}$$

$$\frac{\rho}{\rho^*} = \frac{1}{M}\left[\frac{2+(\gamma-1)M^2}{\gamma+1}\right]^{1/2}$$

$*$→ Denotes properties at choking, i.e., where $M = 1$

T → Temperature upstream of the choking.

M → Mach number upstream of the choking

p → Pressure upstream of choking.

ρ → Density upstream of choking.

$$\frac{p_o}{p_o^*} - \frac{1}{M}\left[\frac{2+(\gamma-1)M^2}{\gamma+1}\right]$$

p_o → Total pressure upstream of chocking.

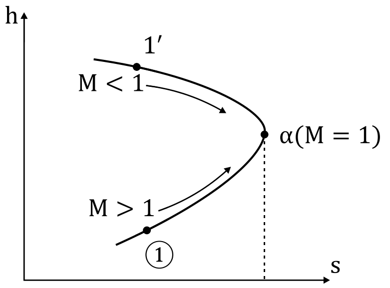
Average Friction Co-efficient:

$$\bar{f} = \frac{1}{L^*}\int_0^{L^*} f\,dx$$

L^* → Location from the origin where M = 1.

f → Local friction co-efficient f → f(x) depends on flow type.

Fano Curve:



Effect of Friction:

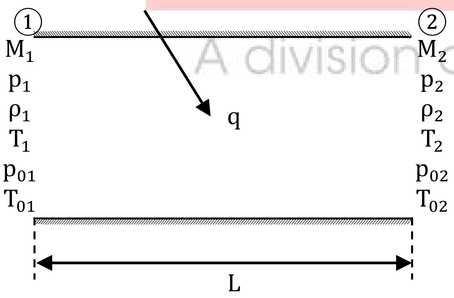
Variable	**Subsonic region**	**Supersonic Region**
Mach Number	Increases $(M_2 > M_1)$	Decreases $(M_2 < M_1)$
Pressure	decreases $(p_2 > p_1)$	Increase $(p_2 > p_1)$
Temperature	decreases $(T_2 < T_1)$	Increases $(T_2 > T_1)$
Total Pressure	decreases $(p_2 < p_1)$	decreases $(p_{02} < p_{01})$
Velocity	Increases $(u_2 > u_1)$	decreases $(u_2 < u_1)$

Flow With Heat Addition (Rayleigh Flow):

Modified Energy Equation:

$$h_1 + \frac{u_1^2}{2} + q = h_2 + \frac{u_2^2}{2}$$

q → Heat transfer per unit mass.



$$\frac{p_2}{p_1} = \frac{1+\gamma M_1^2}{1+\gamma M_2^2}$$

$$\frac{T_2}{T_1} = \left[\frac{1+\gamma M_1^2}{1+\gamma M_2^2}\right]^2 \left(\frac{M_2}{M_1}\right)^2$$

$$\frac{\rho_2}{\rho_1} = \left(\frac{1+\gamma M_2^2}{1+\gamma M_1^2}\right)\left(\frac{M_1}{M_2}\right)^2$$

$$\frac{p_{02}}{p_{01}} = \frac{1+\gamma M_1^2}{1+\gamma M_2^2}\left[\frac{1+\frac{\gamma-1}{2}M_2^2}{1+\frac{\gamma-1}{2}M_1^2}\right]^{\gamma/\gamma-1}$$

$$\frac{T_{02}}{T_{01}} = \left(\frac{1+\gamma M_1^2}{1+\gamma M_2^2}\right)^2\left(\frac{M_2}{M_1}\right)^2\left(\frac{1+\frac{\gamma-1}{2}M_2^2}{1+\frac{\gamma-1}{2}M_1^2}\right)$$

Choking Relations (at M = 1)

$$\frac{p}{p^*} = \frac{1+\gamma}{1+\gamma M^2}$$

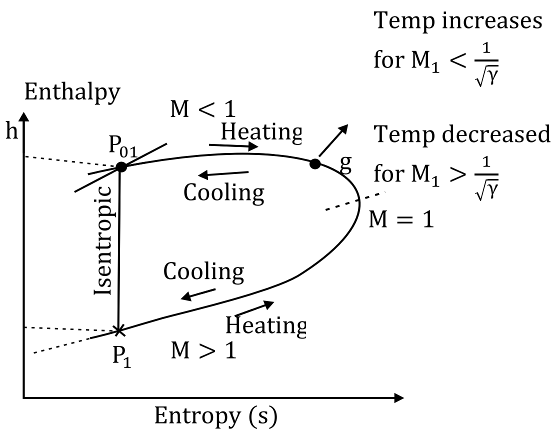
$$\frac{T}{T^*} = M^2\left(\frac{1+\gamma}{1+\gamma M^2}\right)^2$$

$$\frac{\rho}{\rho^*} = \frac{1}{M^2}\left(\frac{1+\gamma M^2}{1+\gamma}\right)$$

$$\frac{p_o}{p^*} = \frac{1+\gamma}{1+\gamma M^2}\left[\frac{2+(\gamma-1)M^2}{\gamma+1}\right]^{\gamma/\gamma-1}$$

$$\frac{T_o}{T_o^*} = \frac{(\gamma+1)M^2}{(1+\gamma M^2)}\left[2+(\gamma-1)M^2\right]$$

Rayleigh Curve:



Effect of Flow with Heat Addition:

Variable	**Subsonic Region**	**Supersonic Region**
Mach Number	Increases ($M_2 > M_1$)	Decreases ($M_2 < M_1$)
Pressure	Decreases ($p_2 < p_1$)	Increases ($p_2 > p_1$)
Temperature	Increases for $M_1 < \gamma^{-1/2}$ And decrease for $M_1 > \gamma^{-1/2}$	Increases ($T_2 > T_1$)
Total Temperature	Increases ($T_{02} > T_{01}$)	Increases ($T_{02} > T_{01}$)
Total Pressure	Decreases ($p_{02} > p_{01}$)	Decreases ($p_{02} < p_{01}$)
Velocity	Increases ($u_2 > u_1$)	Decreases($u_2 < u_1$)

Chapter 7: Flow Visualization Technique

Flow Visualization (Laser Diagnostics Techniques) For High-Speed Flows.

Method	**Quantity on which method depends**	**Sensitive to**	**Ease of Setup**
Shadowgraph	Displacement	$\frac{\partial^2 \rho}{\partial y^2}$	Easy
Schlieren	Angular deflection	$\frac{\partial \rho}{\partial y}$	Moderate
Interferometer	Phase change	ρ	Tough

Here $\rho \rightarrow$ density of the medium through which light rays travel.

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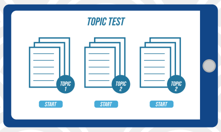
- Online Doubt Support
- Previous Year Solved Question Papers

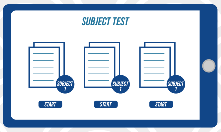
OUR COURSES

Online Test Series

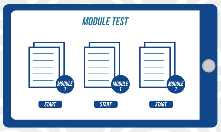
Course Features



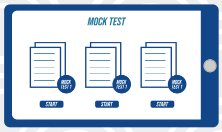
Topic Wise Tests



Subject Wise Tests



Module Wise Tests



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