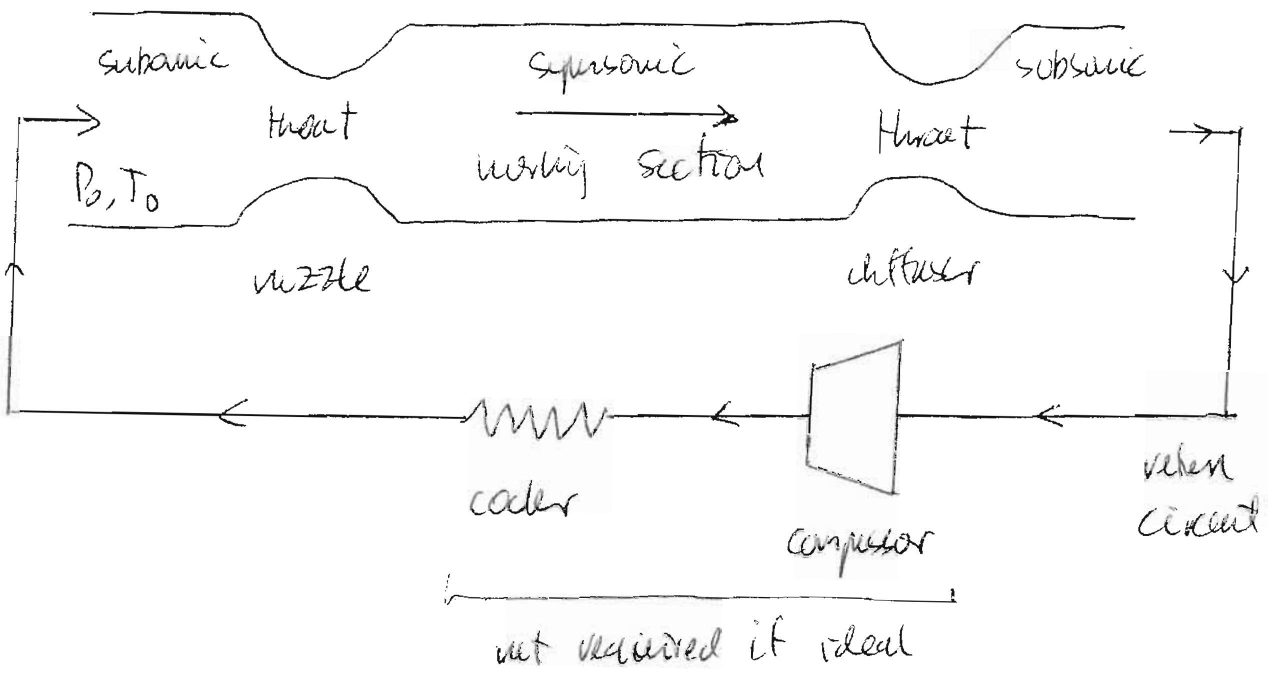
3A3 Exam 2014

RSC Draft Crib

1.a)



In isentropic operation, the flow accelerates through $M=1$ at the nozzle throat to supersonic ($M = 2\text{-}2$) in the working section, then decelerates isentropically through $M=1$ at the diffuser throat to subsonic in the return circuit. There are no losses and no need to compensate for any drop in stagnation pressure using a compressor + cooler.

This is not possible in practice since there will be (at least) friction, and a shock wave will form in the working section on start-up. The shock must be repositioned downstream of the diffuser throat in normal operation, causing a further loss of stagnation pressure and requiring a compressor + cooler to restore P_0 and T_0.

b) (i) at the nozzle throat $\frac{\dot{m}\sqrt{c_pT_0}}{A_n P_0} = 1.281$

at the entry to the W/S $\frac{\dot{m}\sqrt{c_pT_0}}{A_W P_0} = 0.6389$ [tables at M = 2.2

$A_W = 0.2^2 = 0.04 m^2$

$A_n = \frac{0.6389}{1.281} A_W = 0.499 \times 0.04 = \underline{0.01996 m^2}$

(ii) At startup have a M = 2.2 shock in the W/S.

tables at M = 2.2: $\frac{P_{0s}}{P_0} = 0.6281$

Diffuser throat $\frac{\dot{m}\sqrt{c_pT_0}}{A_D P_{0s}} \leq 1.281$ to swallow the shock.

$\frac{A_D}{A_n} \geq \frac{P_0}{P_{0s}}$; $A_D \geq \frac{0.01996}{0.6281} = \underline{0.0318 m^2}$

c) $P_{0s} = 59$ kPa at exit ; $T_0 = 288$ K unchanged.

Isentropic compression for minimum work input :

$$\frac{T_{exit}}{T_0} = \left(\frac{100}{59}\right)^{\frac{\gamma-1}{\gamma}} \quad ; \gamma = 1.4$$

$$= 1.1627$$

$$\therefore T_{exit} = 334.8 \text{ K}$$

$\therefore$ compressor work $= C_p \Delta T$ per kg flowing

$$= 1005 \times (334.8 - 288)$$

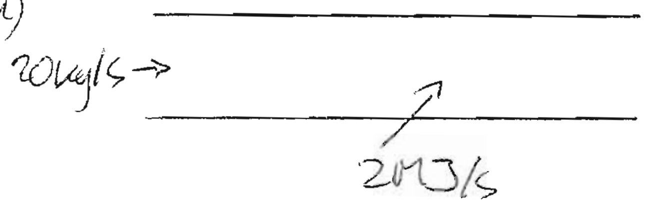
$$= 47034 \text{ J/kg}$$

In the nozzle $\dfrac{\dot{m}\sqrt{c_p T_0}}{A_n P_0} = 1.281$

$$\dot{m} = 1.281 \times \frac{0.01996 \times 1 \times 10^5}{\sqrt{1005 \times 288}} = 4.489 \text{ kg/s}$$

$\therefore$ compressor work is $4.489 \times 47034 = \underline{211 \text{ kW}}$

2 a)



330 m/s

$T_2 = 660\,K$

exit stagnation temperature : $\dfrac{T_{02}}{T_2} = \left(1 + \dfrac{\gamma-1}{2} M_2^2\right)$

$T_2 = 660K$; $a_2 = \sqrt{\gamma R T_2} = \sqrt{1{\cdot}4 \times 287 \times 660}$

$= 515\,m/s$

$\therefore M_2 = \dfrac{330}{515} = 0{\cdot}6407$

$\therefore \dfrac{T_{02}}{T_2} = 1 + \dfrac{1{\cdot}4-1}{2}(0{\cdot}6407)^2 = 1{\cdot}0821$

$\therefore T_{02} = 714\,K$ (or use tables)

(i) $\dot{Q} = \dot{m} c_p (T_{02} - T_{01})$ $\therefore$ $T_{01} = 714 - \dfrac{2\times10^6}{20\times1005}$

i.e. $\underline{T_{01} = 614{\cdot}5K}$

(ii) impulse function unchanged (no friction)

$$\frac{\dfrac{F_2}{\dot{m}\sqrt{c_p T_{02}}}}{\dfrac{F_1}{\dot{m}\sqrt{c_p T_{01}}}} = \sqrt{\frac{T_{01}}{T_{02}}} = \sqrt{\frac{614{\cdot}5}{714}}$$

$= 0{\cdot}9277$

At exit $M_2 = 0{\cdot}6407$: tables $(0{\cdot}64)$ $\dfrac{F_2}{\dot{m}\sqrt{c_p T_{02}}} = 1{\cdot}0678$

At entry $\dfrac{F_1}{\dot{m}\sqrt{c_p T_{01}}} = \dfrac{1.0678}{0.9277} = 1.151$

tables give $M_1 = 0.535$ (approx)

and $T_1/T_{01} = 0.946$ (approx)

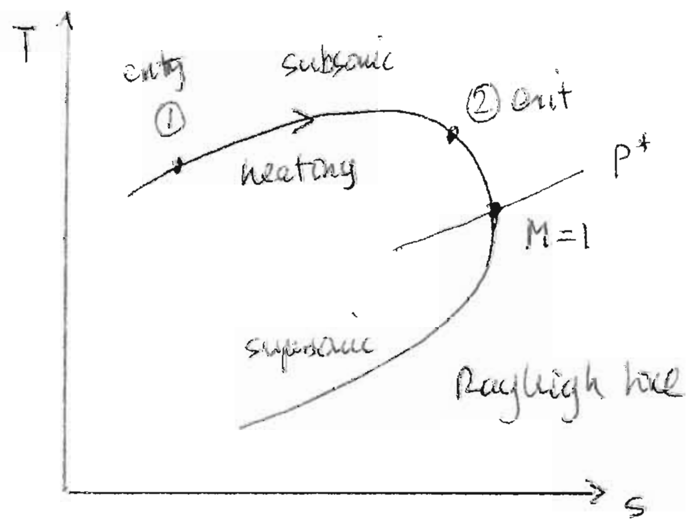
$\therefore T_1 = 0.946 \times 614.5 = 581.3\,K$

$\therefore a_1 = \sqrt{1.4 \times 287 \times 581.3} = 483.3\,m/s$

$\therefore u_1 = 0.535 \times 483.3 = \underline{258.5\,m/s}$

($M_1 = 0.535$ cha

b)



c) Choked exit $M_2 = 1$; $\dfrac{F_2}{\dot{m}\sqrt{c_p T_{02}}} = 0.9897$

$$\frac{T_{02}}{T_{01}} = \left(\frac{\dfrac{F_1}{\dot{m}\sqrt{c_p T_{01}}}}{\dfrac{F_2}{\dot{m}_2\sqrt{c_p T_{02}}}}\right)^2 = \left(\frac{1.15}{0.9897}\right)^2 = 1.35$$

(tables at $M_1 = 0.535$)

$$T_{02} = 1.35 \times T_{01} = 1.35 \times 614.5 = 829.6K$$

$$\therefore \quad \dot{Q} = 20 \times 1005 \times (829.6 - 614.5) = 4323510\,W$$

ie 2.16 times more heat required to choke.

3(a) Mention: equivalence of { speed of sound $a = \sqrt{\gamma RT}$; wave speed $c = \sqrt{gh}$ }

{ Mach number Ma ; Froude number Fr }

Riemann invariants $V \pm \frac{2a}{\gamma-1} \Leftrightarrow V \pm 2c$

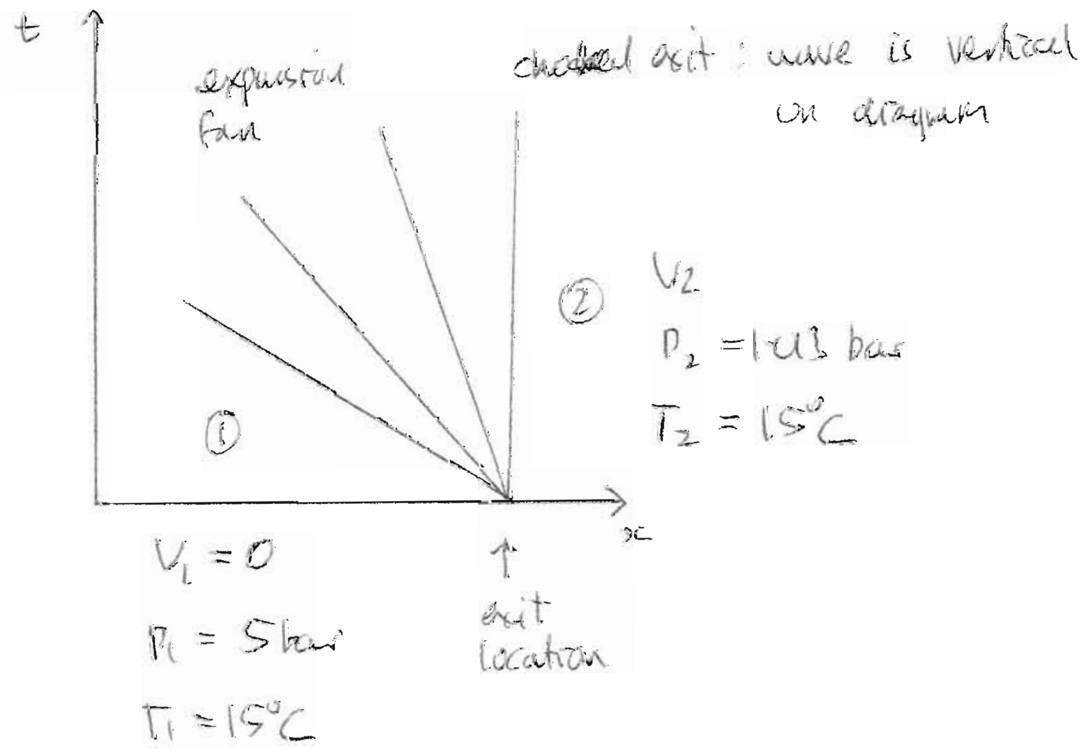
$\Rightarrow$ analogy best if $\gamma = 2$

Depth $\Leftrightarrow$ temperature ; Shock wave $\Leftrightarrow$ hydraulic jump.

Usefulness includes ease of testing esp. for unsteady flows

Limitations include 2D restriction.

b) (i)



(ii) Pressure ratio $P_1/P_2 = 4.936$

temperature ratio $T_1/T_2 = (4.936)^{\frac{\gamma-1}{\gamma}}$ isentropic waves

$$= 1.578$$

$$\therefore T_2 = \frac{288.15}{1.578} = 182.6K$$

$$a_1 = \sqrt{1.4 \times 287 \times 288.15} = 340.3 \text{ m/s}$$

$$a_2 = \sqrt{1.4 \times 287 \times 182.6} = 270.9 \text{ m/s}$$

Riemann (L-r waves) $V_1 + \frac{2a_1}{\gamma-1} = V_2 + \frac{2a_2}{\gamma-1}$

$$V_2 = \frac{2}{0.4}(340.3 - 270.9) = 347 \text{ m/s}$$

$V_2 > a_2 \therefore$ exit is choked (confirmed).

Since exit is choked, $a^* = \frac{2a_1}{\gamma+1} = \frac{2}{2.4} \times 340.3$

$$= 283.6 \text{ m/s}$$

Density at exit is $\rho^*/\rho_1 = \left(\frac{T^*}{T_1}\right)^{1/\gamma-1} = \left(\frac{a^*}{a_1}\right)^{2/\gamma-1}$

$$= \left(\frac{283.6}{340.3}\right)^{2/\gamma-1} = 0.402$$

$$\rho_1 = \frac{P_1}{RT_1} = \frac{5 \times 10^5}{287 \times 288.15} = 6.05 \text{ kg/m}^3$$

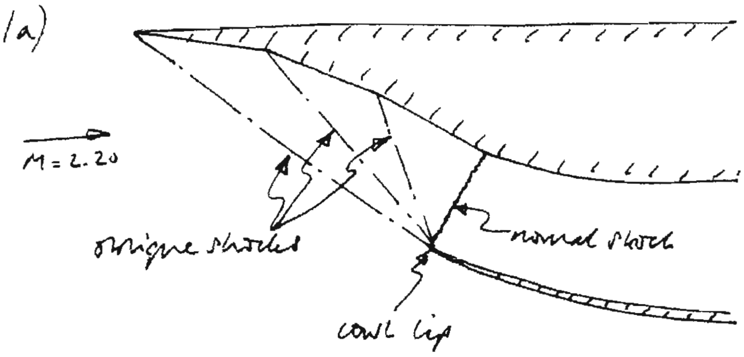
$$\therefore \rho^* = 0.402 \times 6.05 = 2.43 \text{ kg/m}^3$$

$$\dot{m} = \rho V A \quad ; \quad A = \frac{\dot{m}}{\rho V} = \frac{200}{2.43 \times 283.6} = \underline{0.29\ m^2}$$

(54cm square)

4

1a)



b)

M_1	δ	p_{02}/p_{01}	M_2
2.20	8°	0.9902	1.899
1.90	6°	0.9968	1.690
1.69	6°	0.9972	1.485
1.49	N	0.934	

from tables

∴ total pressure ratio = 0.919

i.e. 8.1 % loss

The loss through the normal is far greater than the obliques so increase angle of both 6° ramps.

c) All other things equal, the cowl lip will move forwards and upwards to retain focus. Hence expect the intake to become shorter (∴ lighter) and of reduced frontal area (∴ potentially lower drag)

d)

M_1	δ	p_{02}/p_{01}	M_1
2.05	8°	0.9915	1.761
1.76	13°	0.9716	1.289
1.29	N	0.981	

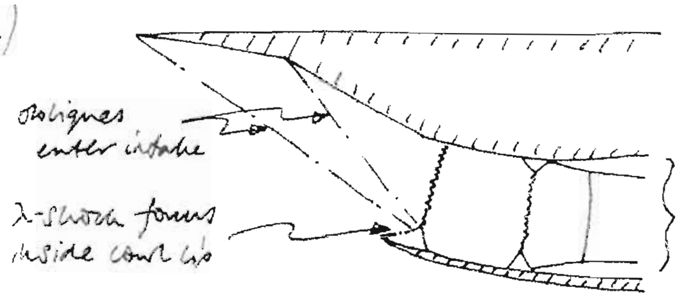
from tables

∴ total pressure ratio = 0.945

i.e. 5.5 % loss

This is a significant improvement on the initial design: the shock losses are far better matched and initial speed lower.

e)



possible shock formation in subsonic (as designed) diffuser. May lead to separation on endwalls. Resulting distortion may provoke engine surge.

5

5 a i) Elliptic - a "jury" problem which must satisfy all boundary conditions

ii) Hyperbolic - a "wave" problem: only some boundary conditions apply.

b) Subs $\tilde{x} = \frac{x}{c}$, $\tilde{y} = \beta \frac{y}{c}$ $\therefore$ b.c. $\rightarrow$ $\frac{\partial \phi}{\partial \tilde{y}} = \frac{c}{\beta} \frac{\partial \phi}{\partial y} = \frac{\tau}{\beta} U_\infty g'(\tilde{x})$

so take $\phi = \frac{\tau}{\beta} U_\infty \tilde{\phi}$ $\rightarrow$ $\frac{\partial \tilde{\phi}}{\partial \tilde{y}} = g'(\tilde{x})$ on $\tilde{y} = 0$ for $0 < \tilde{x} < 1$

hence $\beta^{-2} (1 - M_\infty^2) \frac{\partial^2 \tilde{\phi}}{\partial \tilde{x}^2} + \frac{\partial^2 \hat{\phi}}{\partial \tilde{y}^2} = 0$ $\therefore$ take $\beta = \sqrt{1 - M_\infty^2}$

$$\therefore \frac{\partial^2 \tilde{\phi}}{\partial \tilde{x}^2} + \frac{\partial^2 \tilde{\phi}}{\partial \tilde{y}^2} = 0$$

c) consider x-momentum:

$$\frac{\partial p}{\partial x} = -\rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial x} \right) \rightarrow \frac{\partial p}{\partial x} = -\rho_\infty U_\infty \frac{\partial u}{\partial x} = -\rho_\infty U_\infty \frac{\partial^2 \phi}{\partial x^2}$$

$\Rightarrow p = -\rho_\infty U_\infty \frac{\partial \phi}{\partial x} + f(y)$ but far upstream $\partial \phi / \partial x = 0$ as p is uniform $\therefore f(y) = p_\infty$

$$p - p_\infty = -\rho_\infty U_\infty \frac{\partial \phi}{\partial x} \quad \therefore C_p = \frac{p - p_\infty}{\frac{1}{2} \rho U_\infty^2} = \frac{-2}{U_\infty} \frac{\partial \phi}{\partial x} = \frac{-2}{U_\infty} \frac{\tau U_\infty}{\sqrt{1 - M_\infty^2}} \frac{1}{c} \frac{\partial \tilde{\phi}}{\partial \tilde{x}}$$

$\therefore C_p = \frac{k \tau}{c \sqrt{1 - M_\infty^2}}$ where k only depends on shape factor, g.

as: $C_{p_2} = \left(\frac{\tau_2}{\tau_1} \frac{c_1}{c_2} \frac{\sqrt{1 - M_{\infty_1}^2}}{\sqrt{1 - M_{\infty_2}^2}} \right) C_{p_1}$ hence $C_p = \frac{C_{p_0}}{\sqrt{1 - M_\infty^2}}$

d) Expect C_L & C_m to scale similarly as these are dominated by pressures but <u>not</u> C_D as also contains viscous terms.

e) Max $M_\infty \sim 0.7$ for typical airfoils beyond which mixed supersonic (hyperbolic) and subsonic (elliptic) flow is likely to occur.

6 a) $$\frac{\partial\phi}{\partial t} + F(x,t) = 0$$

Taylor series $$\phi^{n+1} = \phi^n + \Delta t \left.\frac{\partial\phi}{\partial t}\right|^n + \frac{\Delta t^2}{2!}\left.\frac{\partial^2\phi}{\partial t^2}\right|^n + \frac{\Delta t^3}{3!}\left.\frac{\partial^3\phi}{\partial t^3}\right|^n + O(\Delta t^4) \quad (1)$$

$$F^{n-1} = F^n - \Delta t \left.\frac{\partial F}{\partial t}\right|^n + \frac{\Delta t^2}{2!}\left.\frac{\partial^2 F}{\partial t^2}\right|^n - \frac{\Delta t^3}{3!}\left.\frac{\partial^3 F}{\partial t^3}\right|^n + O(\Delta t^4)$$

Scheme is $\phi^{n+1} = \phi^n - \Delta t\left(\frac{3}{2}F^n - \frac{1}{2}F^{n-1}\right)$

$$= \phi^n - \Delta t\left[\frac{3}{2}F^n - \frac{1}{2}\left(F^n - \Delta t\left.\frac{\partial F}{\partial t}\right|^n + \frac{\Delta t^2}{2!}\left.\frac{\partial^2 F}{\partial t^2}\right|^n + \dots\right)\right]$$

$$= \phi^n - \Delta t F^n - \frac{\Delta t^2}{2}\left.\frac{\partial F}{\partial t}\right|^n + \frac{\Delta t^3}{2.2!}\left.\frac{\partial^2 F}{\partial t^2}\right|^n + \dots \quad (2)$$

but $\left.\frac{\partial\phi}{\partial t}\right|^n = -F^n$ and $\left.\frac{\partial^2\phi}{\partial t^2}\right|^n = -\left.\frac{\partial F}{\partial t}\right|^n$ from original equation.

$\therefore$ (1) and (2) match to second order ! QED.

b) Subtract the series (1) − (2):

$$0 = 0 + \Delta t\left.\frac{\partial\phi}{\partial t}\right|^n + \frac{\Delta t^2}{2!}\left.\frac{\partial^2\phi}{\partial t^2}\right|^n + \frac{\Delta t^3}{3!}\left.\frac{\partial^3\phi}{\partial t^3}\right|^n$$

$$+ \Delta t F^n + \frac{\Delta t^2}{2!}\left.\frac{\partial F}{\partial t}\right|^n - \frac{\Delta t^3}{2.2!}\left.\frac{\partial^2 F}{\partial t^2}\right|^n + O(\Delta t^4)$$

$$\frac{\partial\phi}{\partial t}\Big|^n + F^n = -\frac{\Delta t}{2!}\left(\frac{\partial^2\phi}{\partial t^2}\Big|^n + \frac{\partial F}{\partial t}\Big|^n\right) - \frac{\Delta t^2}{3!}\left(\frac{\partial^3\phi}{\partial t^3}\Big|^n - \frac{\partial^2 F}{\partial t^2}\cdot\frac{3!}{2.2!}\right) + O(\Delta t^3)$$

Approximate $\frac{\partial\phi}{\partial t} = -F \simeq -A\frac{\partial\phi}{\partial x}$

then $\frac{\partial F}{\partial t} = -\frac{\partial^2\phi}{\partial t^2} \simeq A^2\frac{\partial^2\phi}{\partial x^2}$ since A is constant,

and $\frac{\partial^2 F}{\partial t^2} = -\frac{\partial^3\phi}{\partial t^3} \simeq -A^3\frac{\partial^3\phi}{\partial x^3}$

$$\therefore \frac{\partial\phi}{\partial t}\Big|^n + F^n = -\frac{\Delta t}{2!}\left(\cancelto{0}{-A^2\frac{\partial^2\phi}{\partial x^2} + A^2\frac{\partial^2\phi}{\partial x^2}}\right)$$

$$- \frac{\Delta t^2}{3!}\left(A^3\frac{\partial^3\phi}{\partial x^3} + A^3\frac{\partial^3\phi}{\partial x^3}\frac{3}{2}\right) + O(\Delta t^3)$$

$\therefore$ Leading error term is $-\frac{5}{12}A^3\frac{\partial^3\phi}{\partial x^3}$

This contains an odd-order derivative

$\therefore$ The error is likely to be dispersive

$\therefore$ false convection.

5(a) $$\frac{\partial \phi}{\partial t} + A\frac{\partial \phi}{\partial x} = 0$$

$$\frac{\phi_i^{n+1} - \phi_i^n}{\Delta t} + A\left(\frac{\phi_{i+1}^n - \phi_{i-1}^n}{2\Delta x}\right) = 0$$

Forward time Centred space (FTCS)

b) The original equation is hyperbolic and information is transferred along the characteristic lines $\left.\frac{\partial x}{\partial t}\right|_n = A$. The FTCS scheme fails to mimic the correct behaviour by transferring information from downstream, as well as from upstream.

c) Use upwinding: $$\frac{\phi_i^{n+1} - \phi_i^n}{\Delta t} + A\left(\frac{\phi_i^n - \phi_{i-1}^n}{\Delta x}\right) = 0$$

Forward time Backwards space

$\Rightarrow$ only 1st order accurate and suffers from false diffusion, but stable if $\frac{A\Delta t}{\Delta x} \leq 1$

HALF QUESTION

1/2

b) i) $T\frac{ds}{dr} = \frac{dh}{dr} - \frac{1}{\rho}\frac{dp}{dr}$

$\boxed{\text{ISENTROPIC FLOW}} \Rightarrow \frac{dh}{dr} = \frac{1}{\rho}\frac{dp}{dr}$

FOR STEADY, STATIONARY FRAME, CONSTANT RADIUS ($V_r = 0$) FLOW (ie NO MERIDIONAL CURVATURE):

$$\frac{1}{\rho}\frac{dp}{dr} = \frac{V_\theta^2}{r}$$

$$\Rightarrow \frac{d}{dr}\left(h_0 - \tfrac{1}{2}(V_x^2 + V_\theta^2)\right) = \frac{1}{\rho}\frac{dp}{dr} = \frac{V_\theta^2}{r}$$

$$\frac{dh_0}{dr} - V_x\frac{dV_x}{dr} - V_\theta\frac{dV_\theta}{dr} = \frac{V_\theta^2}{r}$$

$$\frac{dh_0}{dr} = V_x\frac{dV_x}{dr} + V_\theta\frac{dV_\theta}{dr} + \frac{V_\theta^2}{r}$$

NOW: $V_\theta\frac{dV_\theta}{dr} + \frac{V_\theta^2}{r} = \frac{V_\theta}{r}\left(r\frac{dV_\theta}{dr} + V_\theta\frac{dr}{dr}\right) = \frac{V_\theta}{r}\frac{d}{dr}(rV_\theta)$

$\Rightarrow$ SRE: $\underline{\underline{\frac{dh_0}{dr} = V_x\frac{dV_x}{dr} + \frac{V_\theta}{r}\frac{d}{dr}(rV_\theta)}}$ $\boxed{30\%}$

b) ii) $\frac{dh_0}{dr}$ = Radial distribution of work transfer.

$\frac{dV_x}{dr}$ = Radial distribution of axial velocity (flow)

(rV_θ) = Vortex-Law — Very important in determining blade shapes & flow type.

$\boxed{10\%}$

b) iii) Free-Vortex when $\boxed{rV_\theta = \text{Constant}}$

Thus : $$\frac{dh_0}{dr} = V_x \frac{dV_x}{dr}$$

Provided uniform work transfer across the radius ie $\boxed{\frac{dh_0}{dr} = 0}$ (achieved by appropriate choice of blade shape)

Then : $V_x \frac{dV_x}{dr} = 0$ so obtain uniform distribution of axial velocity.

$\boxed{10\%}$

a) $C_p \Delta T_0 = \Delta h_0 = U \Delta V_\theta$ (constant radius)

$$U = \frac{C_p \Delta T_0}{\Delta V_\theta} = \frac{1149(1500 - 1347.1)}{(413.4 - -145.6)} = \underline{\underline{314.3\ m/s}}$$ $\boxed{5\%}$

b) $$\rho_1 = \frac{P_1}{RT_1} = \frac{1469.9 \times 10^3}{287 \times 1492.4} = \underline{3.4318\ kg/m^3}$$

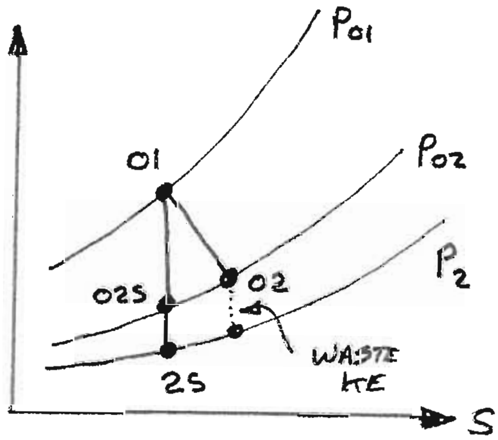
$$\dot{m}_1 = \rho_1 A_1 V_{x1} = 3.4318 \times 0.15 \times 132.0 = \underline{67.95\ kg/s}$$

$$\text{POWER} = \dot{m} \Delta h_0 = 67.95 \times 1149 \times (1500 - 1347.1)$$

$$= \underline{\underline{11.94\ MW}}$$ $\boxed{10\%}$

c) $$T_{02s} = T_{01} \left(\frac{P_{02}}{P_{01}}\right)^{\frac{1-\gamma}{\gamma}}$$

$$= 1500 \left(\frac{944.0}{1500}\right)^{\frac{0.333}{1.333}} = 1336.1\ K$$



$$\eta_{tt} = \frac{T_{01} - T_{02}}{T_{01} - T_{02s}} = \frac{1500 - 1347.1}{1500 - 1336.1}$$

$\eta_{tt} = 93.29\%$ — Relevant to Turbo jet as exit KE used!

$$T_{2s} = T_{01}\left(\frac{P_2}{P_{01}}\right)^{\frac{1-\gamma}{\gamma}} = 1500\left(\frac{887.4}{1500}\right)^{\frac{0.333}{1.333}} = 1315.7\ K$$

$$\eta_{ts} = \frac{T_{01} - T_{02}}{T_{01} - T_{2s}} = \frac{1500 - 1347.1}{1500 - 1315.7} = \underline{\underline{82.96\%}}$$

Relevant to land based as exit KE is wasted. $\boxed{20\%}$

d) $$\frac{\Delta h_0}{U^2} = \frac{C_p \Delta T_0}{U^2} = \frac{1149(1500 - 1347.1)}{314.3^2} = \underline{\underline{1.78}}$$

Measures the amount of work exchange, 1.78 is a sensible value for a turbine.

$$\text{REACTION} = \frac{\Delta h_{rotor}}{\Delta h_{stage}} = \frac{1414.9 - 1326.4}{1492.4 - 1326.4} = \underline{\underline{53.3\%}}$$

Reaction is an approximate measure of pressure drop across the rotor compared to the stage. 53.3% says the two blade rows have similar pressure drops.

$\boxed{15\%}$

e) $$Y_p\big|_{STATOR} = \frac{P_{01} - P_{02}}{P_{02} - P_2} = \frac{1500.0 - 1480.3}{1480.3 - 1171.7} = \underline{\underline{0.0638}}$$

For rotor need P_{02}^{REL} and P_{03}^{REL}.

$$V_{\theta 2}^{REL} = 413.4 - 314.3 = \underline{99.1\ m/s}$$

$$T_{02}^{REL} = 1414.9 + (157.0^2 + 99.1^2)/(2 \times 1149) = \underline{1429.9\ K}$$

$$P_{02}^{REL} = P_2\left(\frac{T_{02}^{REL}}{T_2}\right)^{\frac{\gamma}{\gamma-1}} = 1171.7\left(\frac{1429.9}{1414.9}\right)^{\frac{1.333}{0.333}} = \underline{1222.2\ kPa}$$

$$V_{\theta 3}^{REL} = -145.6 - 314.3 = \underline{-459.9\ m/s}$$

$$T_{03}^{REL} = 1326.4 + (162.0^2 + 459.9^2)/(2 \times 1149) = \underline{1429.9\ K}$$

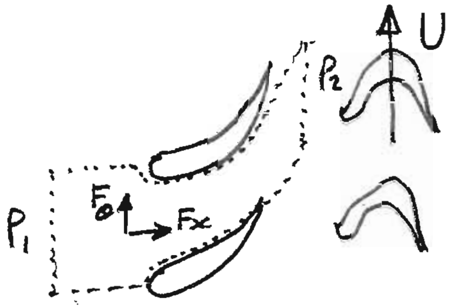
(SAME RADIUS = Constant)

$$P_{03}^{REL} = 887.4\left(\frac{1429.9}{1326.4}\right)^{\frac{1.333}{0.333}} = \underline{1198.8\ kPa}$$

$$Y_p\big|_{ROTOR} = \frac{P_{02}^{REL} - P_{03}^{REL}}{P_{03}^{REL} - P_3} = \frac{1222.2 - 1198.8}{1198.8 - 887.4} = \underline{\underline{0.0751}}$$

$\boxed{25\%}$

f) F_x, F_θ Force on flow through the stator passage.



TOTAL FORCE = Δ(MOM. FLUX)

AXIAL $\quad P_1A_1 + F_x - P_2A_2 = \dot{m}V_{x2} - \dot{m}V_{x1}$ $\qquad$ N.B. $A_1 = A_2$

$$F_x = (P_2 - P_1)A_1 + \dot{m}(V_{x2} - V_{x1})$$

$$= (1171.7\times10^3 - 1469.9\times10^3)\times 0.15 + 67.95(157.0 - 132.0)$$

$$F_x = -43.03 \text{ kN}$$

Axial component of force in the flow is in the upstream direction.

[NOTE: VERY IMPORTANT THAT $A_1 = A_2$ SO CAN IGNORE ANNULUS WALL FORCES.]

$$F_\theta = \dot{m}(V_{\theta2} - V_{\theta1}) = 67.95(413.4 - 0) = 28.09 \text{ kN}$$

Tangential component of force on the flow is in the same direction as rotor rotation.

ROTOR

Since $A_3 = 0.18\,m^2 > A_2 = 0.15\,m^2$ the axial component of the force on the flow has a contribution from the annulus wall pressure distribution. This either has to be approximated $\approx \frac{1}{2}(P_2 + P_3)$ or obtained from CFD etc.

25%