NATIONAL EXAMINATIONS

December 2016

98-Mar-B5 FLUID MACHINERY

Three hours duration

Notes to Candidates

1. This is a **Closed Book** examination.

2. Examination consists of two Sections: **Section A is Calculative (5 questions)** and **Section B is Descriptive (3 questions).**

3. **Do four (4) questions (including all parts of each question) from Section A (Calculative) and two (2) questions from Section B (Descriptive).**

4. **Six questions constitute a complete paper.** (Total 60 marks).

5. Note that Question 2 is on two pages.

6. **All questions are of equal value.** (Each 10 marks).

7. If doubt exists as to the interpretation of any question, the candidate is urged to submit, with the answer paper, a clear statement of any assumptions made.

8. Read the entire question before commencing the calculations and take note of hints or recommendations given.

9. If any initial parts of a multi-part question cannot be solved the remaining parts may be worked by making appropriate assumptions for the first parts from the technical data given.

10. Candidates may use one of the approved **Casio** or **Sharp** calculators.

11. **Reference data** for particular questions are given in the Attachments on pages 11 to 15. **All pages from which data has been obtained or on which answers have been written are to be returned with the answer booklet to show any working. Candidate's names must be on these sheets.**

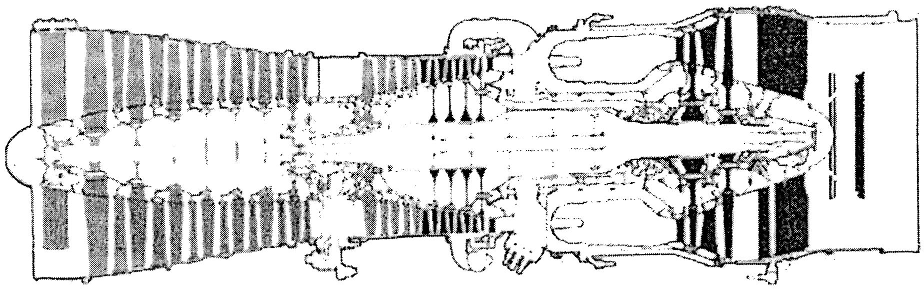
12. **Reference formulae and constants** are given on pages 16 to 20.

13. **Drawing Instruments** (scale ruler, protractor and sharp pencil) are required for vector diagrams. While calculation of velocities by trigonometric ratios with reference to a sketch is acceptable it is longer and more time consuming.

SECTION A CALCULATIVE QUESTIONS

Show all steps in the calculations and state the units for all intermediate and final answers.

QUESTION 1 COMPRESSOR STAGE PERFORMANCE



Rolls-Royce/SNECMA Olympus 593 Mark 610 Afterburning Turbojet

The diagram above (for illustration only) shows a cross section of the engine of the Concorde supersonic aircraft (without the variable geometry intake and variable area nozzle). Relevant specifications and assumed operational conditions are as follows:

LP compressor stages	7
LP compressor pressure ratio	3
HP compressor stages	7
HP compressor pressure ratio	5
LP and HP isentropic efficiencies	0.90
Mach number at compressor inlet	0.49
Effective area at compressor inlet	0.80 m
Air inlet pressure	80 kPa
Air inlet temperature	80°C

(a) Sketch the compression process on a T-s diagram and label all key points that will be required and referred to in the calculations. (1)

(b) Calculate the air temperature at the LP compressor exit and at the HP compressor exit. (4)

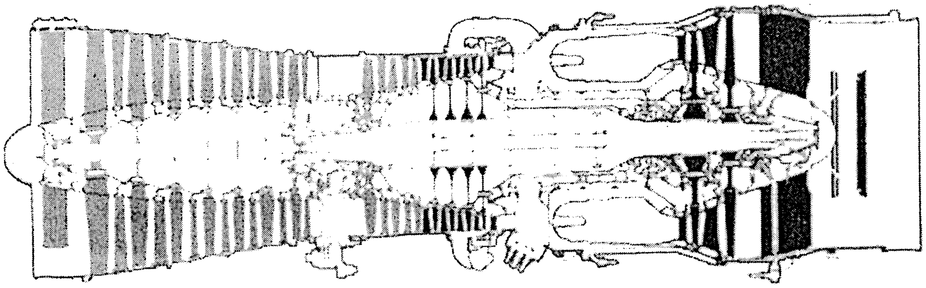
(c) Some air is drawn off after the fifth HP compressor stage for cooling of the turbine blades. Calculate the temperature of this air. (2)

(d) Calculate the air velocity at the compressor inlet. (1)

(e) Calculate the mass flow through the compressor (neglecting that extracted for cooling) and hence the power required to drive the compressor. (2)

[10 marks]

QUESTION 2 COMPRESSOR BLADE ANGLES



Rolls-Royce/SNECMA Olympus 593 Mark 610 Afterburning Turbojet

The diagram above (for illustrative purposes only) shows a cross section of the engine of the Concorde supersonic aircraft (without the variable geometry intake and variable area nozzle). Basic specifications and assumed operational conditions are as follows:

LP compressor stages	7
LP compressor pressure ratio	3
LP compressor speed	6500 rev/min
HP compressor stages	7
HP compressor pressure ratio	5
HP compressor speed	8500 rev/min
HP and LP isentropic efficiency	0.9
LP first stage moving blade tip diameter	1.12 m
LP first stage moving blade hub diameter	0.38 m
Inlet air temperature to first stage	80°C
Inlet air velocity to first stage	184 m/s
Air mass flow rate	116 m/s

Consider the first stage moving blade conditions and assume no prewhirl at the inlet (air enters in a purely axial direction to give maximum flow). Refer to the Examination Paper Attachments Page 11 **Compressor Velocity Diagram** and Page 12 **Compressor Inlet Blades** for guidance and reference.

This question is continued on the next page

Question 2 Continued

(a) Calculate the blade velocity at the tip and hub of the first stage moving blade. (1)

(b) Calculate the temperature at the exit of the first stage. (2)

(c) Calculate the work done (J/kg) by the first stage and hence determine the values of the components (in the direction of blade motion) of the absolute air velocities (C_{Y1} and C_{Y2}). (2)

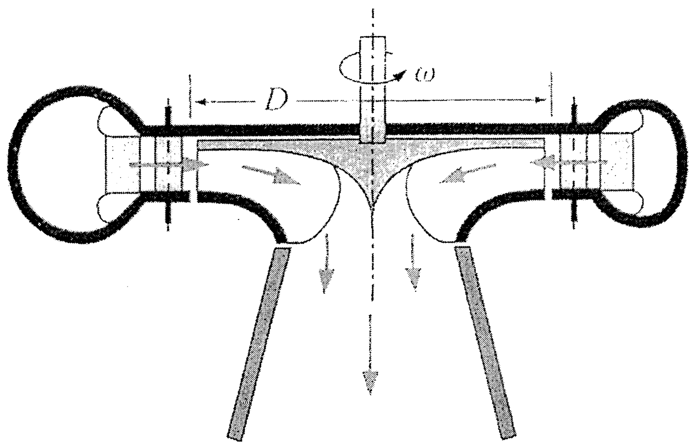
(d) Draw to scale the velocity (vector) diagrams for the first stage moving blades at both the tip and hub and determine the inlet and outlet blade angles for these blades. *A scale of 1mm = 5 m/s is suggested.* (4)

(e) Refer to the photograph of the first stage inlet blades on Page 12 and assess whether the blade angles determined in (d) above are reasonably correct. Justify your answer. (1)

[10 marks]

QUESTION 3 HYDRO TURBINE DESIGN

Refer to the Examination Paper Attachments Page 13 **Hydro Turbine Parameters**.



In the preliminary stages in the design of a hydro power plant some basic dimensions need to be established. The conditions suggest a turbine of the Francis type as shown in the figure above. Each turbine has to have a power output under the available head as indicated below:

Electrical power output	200 MW
Available net head	110 m

A typical Francis turbine has the following characteristics:

Efficiency	See chart on Page 13
Specific speed	$N_S = 0.9$
Runner blade inlet angle	$\alpha_1 = 22°$ (relative to tangent to runner)
Flow velocity ratio	$V_{absolute}/V_{jet} = 0.77$
Blade velocity ratio	$V_{blade}/V_{jet} = 0.6583$

Note that V_{jet} is the free jet velocity when subject to the given head.

(a) Determine, from the diagram of efficiencies for hydro turbines, the expected efficiency and hence the hydraulic power input to achieve the specified electrical output. (1)

(b) Calculate the rotational speed of the turbine and hence the runner diameter. (4)

(c) Draw a velocity (vector) diagram of the flow conditions at the runner inlet and determine the radial inlet velocity. *A scale of 10 mm = 2.5 m is suggested.* (3)

(e) Calculate the water flow rate and hence the height of the runner inlet (vertical height of flow area). (2)

[10 marks]

QUESTION 4 HYDRO TURBINE MODEL

Technical specifications for the hydro turbines at Vanderkloof Hydro Power Station are as follows:

Generator design output	120 MW (at 0.90 power factor lagging)
Speed of machine	125 rev/min
Electrical frequency	50 Hz
Generator voltage	11 kV
Design net head	65 m
Design water flow	200 m^3/s
Maximum water flow	213 m^3/s
Turbine runner diameter	5.462 m
Turbine runner material	stainless cast steel

(a) Calculate the specific speed of the machine. (2)

(b) Calculate the overall efficiency of the turbine based on the design parameters. (1)

Prior to construction, a model test is required to prove the performance of the prototype machine. Assume that an homologous (scaled to be geometrically identical) model runner 200 mm in diameter is a available and can be tested in an instrumented hydraulic system under a head of 10 m. Use the turbine affinity laws or similarity rules to do the following:

(c) Determine the speed at which the model should run. (2)

(d) Determine the necessary flow through the model. (2)

(e) Determine the ideal (no friction) power developed by the model. (1)

Due to scaling differences, the efficiency of the model and the prototype are not identical. The Moody equation allows the hydraulic efficiencies of the model and prototype to be compared.

(f) Assuming that the prototype has an electrical efficiency of 98%, determine the efficiency that should be measured on the model to ensure that the prototype will meet its specified efficiency. (2)

[10 marks]

QUESTION 5 STEAM TURBINE BLADE EFFICIENCY

Refer to the Examination Paper Attachments Page 14 **Steam Turbine Velocity Diagram**

The attached diagram clarifies the nomenclature used in the question below. Use this same nomenclature in your answer

One stage of a steam turbine operating on the impulse principle has the following blade characteristics:

Moving blade velocity	V_B	=	100 m/s
Inlet steam velocity	V_{S1}	=	300 m/s
Nozzle exit angle	θ	=	25°
Steam mass flow rate	M	=	24 kg/s

The moving blades are assumed to be symmetrical and frictionless, that is:

Blade outlet angle γ = Blade inlet angle Φ
Relative velocity V_{R2} = Relative velocity V_{R1}

Draw a velocity (vector) diagram (see note below) to a scale of 1 cm = 20 m/s to show the absolute and relative velocities within the turbine blades. By measuring from this diagram determine the following:

(a)	Absolute exhaust steam velocity.	(5)
(b)	Impulse force on the moving blades.	(1)
(c)	Energy transferred to the moving blades in kJ/kg.	(1)
(d)	Inlet and exhaust kinetic energies in kJ/kg.	(1)
(e)	Blade efficiency.	(1)
(f)	Power developed by the turbine stage.	(1)

Note: While calculation of velocities by trigonometric ratios with reference to a sketch is acceptable it is longer and more time consuming.

[10 marks]

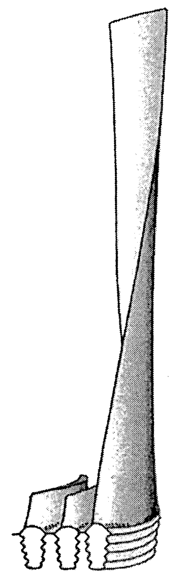
SECTION B DESCRIPTIVE QUESTIONS

Note that each five mark part of each question requires a full page answer with complete explanations with sketches, if appropriate, to support the explanation.

QUESTION 6 COMPRESSOR AND TURBINE BLADE SHAPE

Refer to the Examination Paper Attachments Page 12 **Compressor Inlet Blades**.

Compressor blades at and near the inlet of large compressors have twisted blades as shown in the photograph on Page 12. Similarly turbine blades at or near the exhaust of large turbines also have twisted blades as shown in the adjacent sketch.



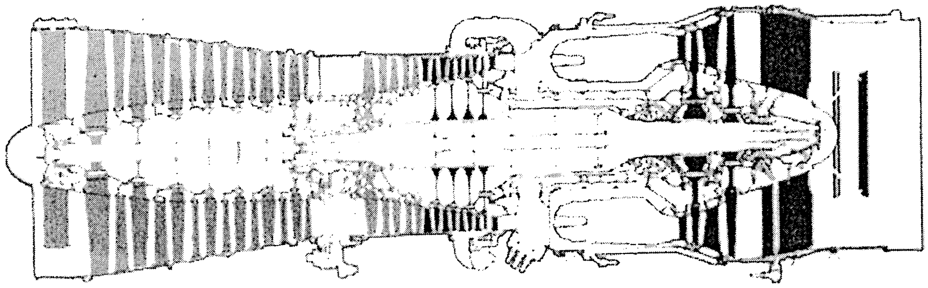
(a) Explain why it is necessary to have twisted blades on large machines. (3)

(b) For large steam turbines show with the aid of sketches how the velocity diagrams are different at the base and at the tip of twisted blades. (4)

(c) For large steam turbines explain how the degree of reaction changes from the base to the tip of twisted blades. Clarify what is meant by the degree of reaction. (3)

[10 marks]

QUESTION 7 TURBINE AND COMPRESSOR STAGE LIMITATIONS



Rolls-Royce/SNECMA Olympus 593 Mark 610 Afterburning Turbojet

The diagram of the gas turbine turbojet engine above shows a high pressure turbine with just one stage driving a high pressure compressor with seven stages and similarly a low pressure turbine also with just one stage driving a low pressure compressor with seven stages. The two turbines drive the respective compressors through separate shafts at different speeds. *The diagram is for orientation only and no specific information need be obtained from it.*

(a) Explain why the compressors require so many stages compared with the turbines for an equivalent transfer of energy. Clarify the limiting factors in compressor design and operation. (4)

(b) Explain how with only one stage each the turbines can produce sufficient power to drive the compressors. (4)

(c) Explain why the low pressure and high pressure turbine-compressor shafts run at different speeds:

LP turbine-compressor shaft speed = 6500 rev/min
HP turbine-compressor shaft speed = 8500 rev/min

(2)

[10 marks]

QUESTION 8 PUMP AND SYSTEM CHARACTERISTICS

Refer to the Examination Paper Attachments Page 15 **Pump and System Characteristics**.

This page (Page 15) for (a) and (b) must be returned with the answer booklet.

(a) On the top axes given sketch the following:

(i) Head versus flow characteristics of one centrifugal pump supplying water to a typical pipe system. Identify the operating point.

(ii) Head versus flow characteristic of a second identical pump in parallel supplying the same system. Identify the operating point.

(3)

(b) On the bottom axes given sketch the following:

(i) Head versus flow characteristics of one centrifugal pump supplying water to a typical pipe system as in (a) above. Identify the operating point.

(ii) Head versus flow characteristic of the pump and system when a control valve in the system is closed to reduce the flow. Identify the operating point.

(iii) Head versus flow characteristic of the pump and system when the pump speed is raised to increase the flow. Identify the operating point.

(3)

(c) In the answer booklet do the following:

(i) Explain what factors govern the setting (elevation with respect to the surface level of the liquid supply to the pump) of a centrifugal pump.

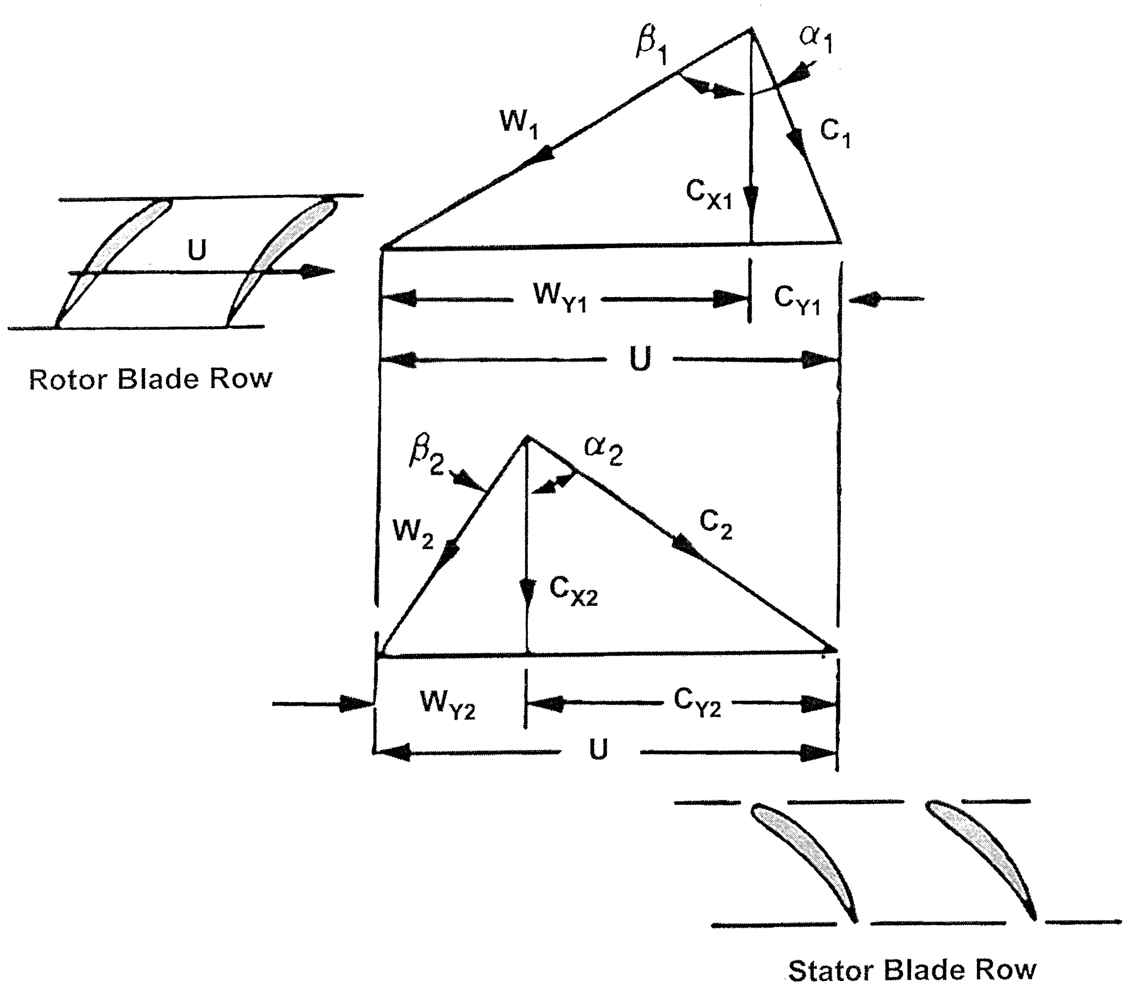
(ii) Explain the consequences if the setting limitations have not been met and how and where the pump may suffer damage or not perform properly.

(4)

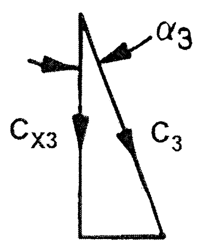
[10 marks]

EXAMINATION PAPER ATTACHMENTS

QUESTION 2 COMPRESSOR VELOCITY DIAGRAM

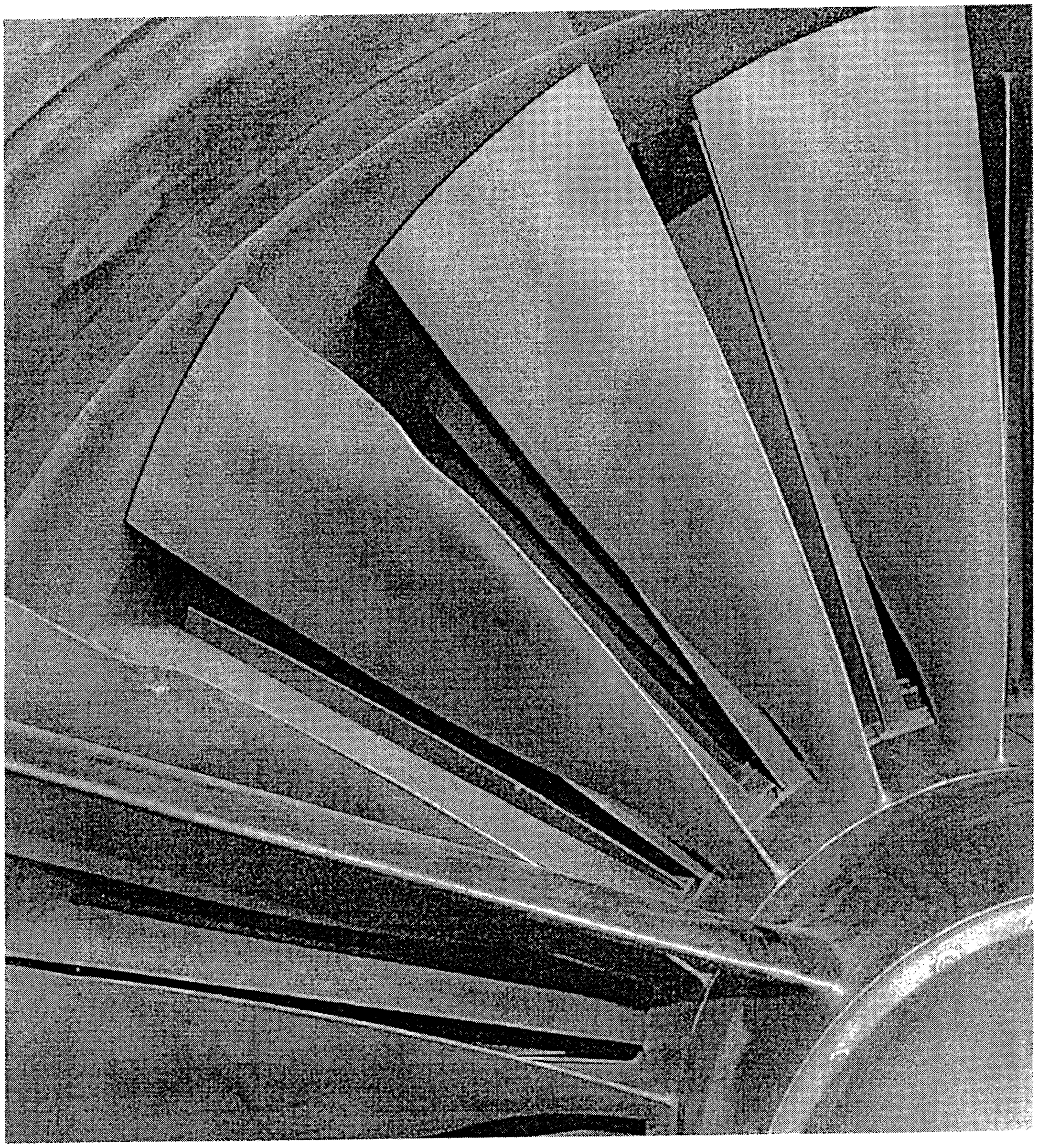


U Blade velocity
C_1 Rotor blade absolute inlet velocity
W_1 Rotor blade relative inlet velocity
C_2 Rotor blade absolute outlet velocity
W_2 Rotor blade relative outlet velocity
C_3 Stator blade absolute outlet velocity



EXAMINATION PAPER ATTACHMENTS

QUESTION 2 & QUESTION 6 COMPRESSOR INLET BLADES

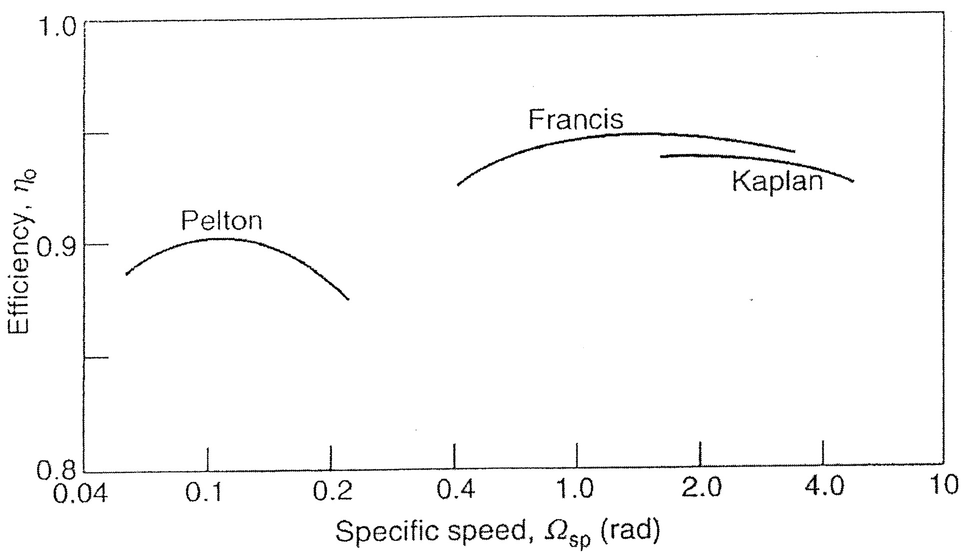


Rolls-Royce Olympus 593-610 first stage low pressure compressor blades

EXAMINATION PAPER ATACHMENTS

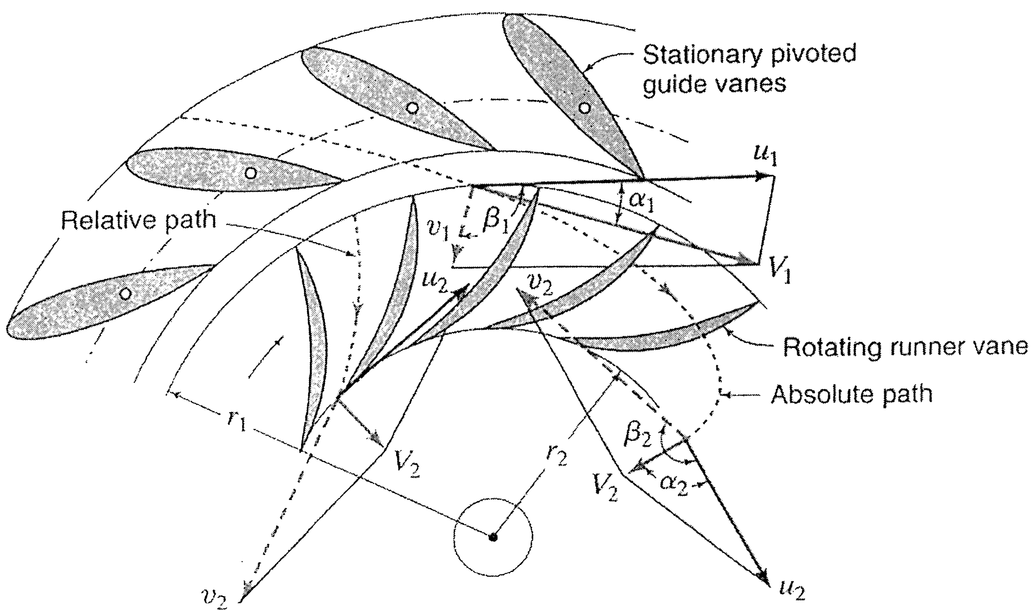
QUESTION 3 HYDRO TURBINE PARAMETERS

Turbine Efficiencies



Typical design point efficiencies for Pelton, Francis and Kaplan turbines

Velocity Diagram

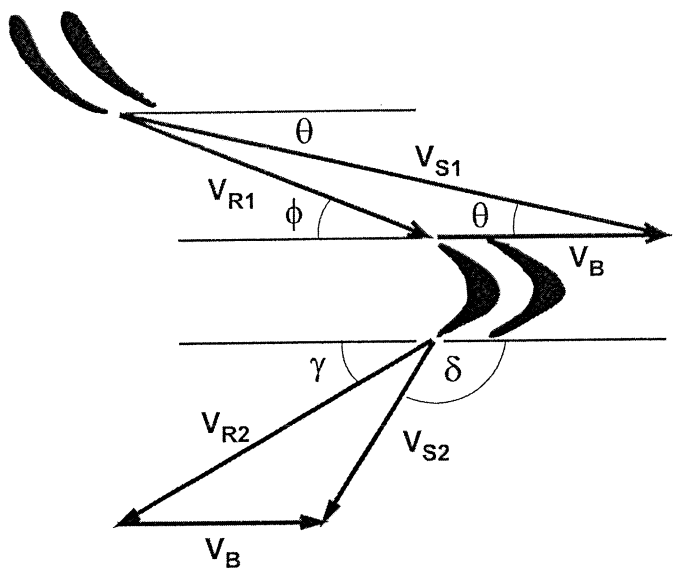


Velocity vectors for radial inward flow hydraulic turbine (Francis type)

EXAMINATION PAPER ATTACHMENTS

QUESTION 5 STEAM TURBINE VELOCITY DIAGRAM

Nomenclature for velocity vectors and angles



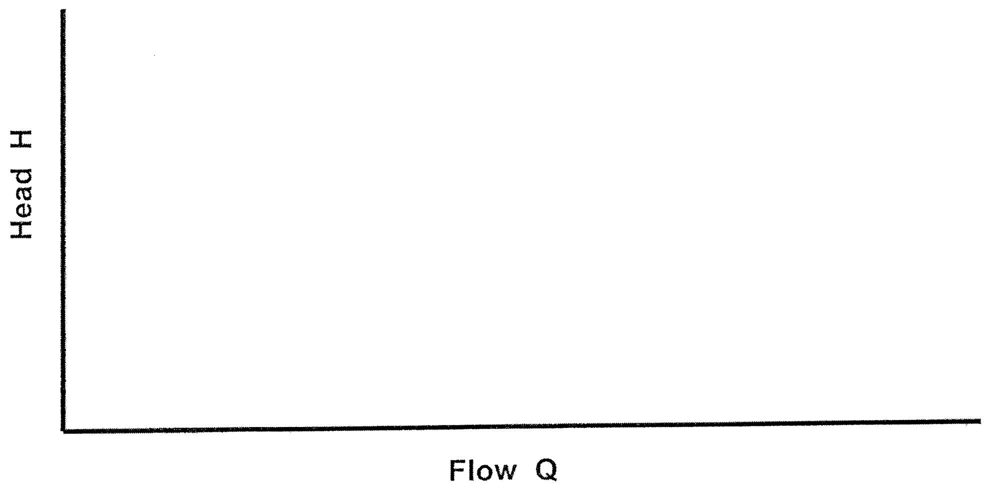
V_{S1}	Absolute steam velocity entering moving blades
V_{R1}	Relative steam velocity entering moving blades
V_B	Moving blade velocity
V_{R2}	Relative steam velocity leaving moving blades
V_{S2}	Absolute steam velocity leaving moving blades

EXAMINATION PAPER ATTACHMENTS NAME ....

QUESTION 8 PUMP AND SYSTEM CHARACTERISTICS

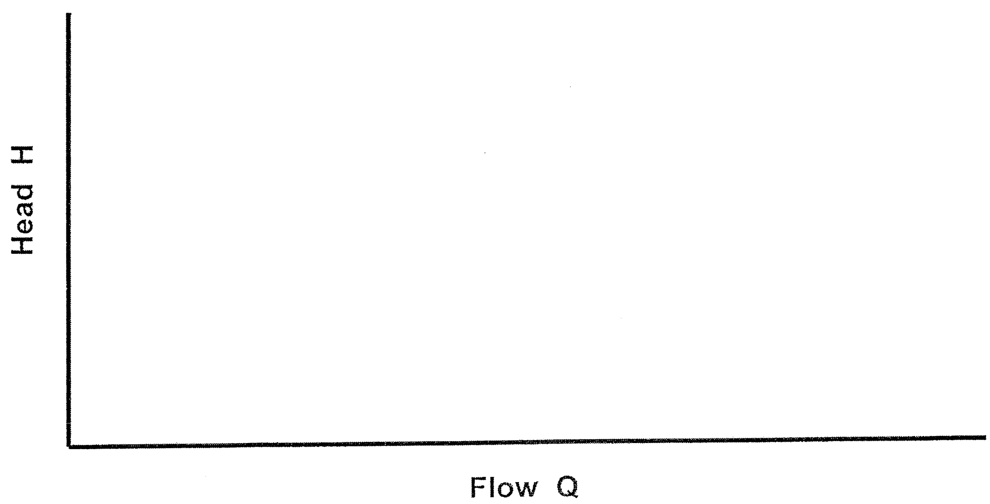
(a) Parallel Pumps

On the axes below plot head versus flow characteristics for cases (i) and (ii).



(b) Flow Control

On the axes below show the effect of a control valve and pump speed change for cases (ii) and (iii) compared with case (i).



EXAMINATION REFERENCE MATERIAL

NOMENCLATURE FOR REFERENCE EQUATIONS (SI UNITS)

a	Sonic velocity	m/s
A	Flow area, Surface area	m^2
c_p	Specific heat at constant pressure	J/kg°C
c_v	Specific heat at constant volume	J/kg°C
b	Width	m
C	Velocity	m/s
D	Diameter	m
E	Energy	J
F	Force	N
g	Gravitational acceleration	m/s^2
h	Specific enthalpy	J/kg
h	System head	m
h_L	Head loss	m
H	Pump or turbine head	m
k	Ratio of specific heats	
L	Length	m
m	Mass	kg
M	Mass flow rate	kg/s
M_A	Mach number	
N	Rotational speed	rev/s
N_S	Specific Speed	
p	Pressure	Pa (N/m^2)
P	Power	W (J/s)
q	Heat transferred	J/kg
Q	Heat	J
Q	Flow rate	m^3/s
r	Radius	m
R	Specific gas constant	J/kg K
s	Entropy	J/kg K
T	Temperature	K
u	Specific internal energy	J/kg
U	Internal Energy	J
U	Velocity	m/s
v	Specific volume	m^3/kg
V	Velocity	m/s
w	Specific work	J/kg
W	Work	J
W	Velocity	m/s
x	Length	m

z	Elevation	m
α	Pump blade angle	°
α	Compressor blade angle	°
β	Pump blade angle	°
β	Compressor blade angle	°
γ	Turbine blade angle	°
φ	Turbine blade angle	°
δ	Turbine blade angle	°
η	Efficiency	
θ	Nozzle angle	°
μ	Dynamic viscosity	Ns/m^2
ν	Kinematic viscosity	m^2/s
ρ	Density	kg/m^3
σ_C	Critical cavitation parameter	
T	Thrust	N
T	Torque	Nm
φ	Peripheral velocity factor	
ω	Rotational speed	rad/s
Ω	Heat transfer rate	J/s

GENERAL CONSTANTS

Use unless otherwise specified

Acceleration due to gravity:	$g = 9.81\ m/s^2$	
Atmospheric pressure:	$p_{atm} = 100$ kPa	
Water vapour pressure:	$p_{vapour} = 2.34$ kPa	(at 20°C)
Density of water:	$\rho_{water} = 1000\ kg/m^3$	
Density of air:	$\rho_{air} = 1.21\ kg/m^3$	(at 15°C)
Density of air:	$\rho_{air} = 1.19\ kg/m^3$	(at 20°C)
Specific heat of air:	$c_p = 1.005$ kJ/kg°C	
Specific heat of air:	$c_v = 0.718$ kJ/kg°C	
Specific heat of water:	$c_p = 4.19$ kJ/kg°C	

GENERAL REFERENCE EQUATIONS

Basic Thermodynamics

First Law:	$dE = \delta Q - \delta W$
Enthalpy:	$h = u + pv$
Continuity:	$\rho VA = \text{constant}$
Potential Energy:	$E_{PE} = mgz$
Kinetic Energy:	$E_{KE} = V^2/2$
Internal Energy:	$E_{IN} = U$
Flow Work:	$w = \Delta(pv)$
Energy Equation:	$zg + V^2/2 + u + pv + \Delta w + \Delta q = \text{constant}$

Ideal Gas Relationships

Gas Law:	$pv = RT$
Specific Heat at Constant Pressure:	$c_p = \Delta h/\Delta T$
Specific Heat at Constant Volume:	$c_v = \Delta u/\Delta T$
Specific Gas Constant:	$R = c_p - c_v$
Ratio of Specific Heats	$k = c_p / c_v$
Isentropic Relations:	$p_1/p_2 = (v_2/v_1)^k = (T_1/T_2)^{k/(k-1)}$

FLUID MACHINERY REFERENCE EQUATIONS

Fluid Mechanics

Pressure	$p = \rho gh$
Continuity Equation	$\rho_1 V_1 A_1 = \rho_2 V_2 A_2 = M$
Bernoulli's Equation	$p_1/\rho g + z_1 + V_1^2/2g = p_2/\rho g + z_2 + V_2^2/2g$
Momentum Equation	$F = p_1 A_1 - p_2 A_2 - \rho VA(V_2 - V_1)$ (one dimensional)

Energy Equation

Pump and Turbine	$p_1/\rho g + z_1 + V_1^2/2g + w_{in}/g = p_2/\rho g + z_2 + V_2^2/2g + w_{out}/g$
Pipe Flow	$p_1/\rho g + z_1 + V_1^2/2g = p_2/\rho g + z_2 + V_2^2/2g + h_L$

Compressible Flow

Mach Number	$M_A = V/a$
Sonic Velocity	$a = [kRT]^{1/2}$

Steam Turbines

Nozzle Equation:	$h_1 - h_2 = (V_2^2 - V_1^2) / 2$
Work:	$w = [(V_{1\,absolute}^2 - V_{2\,absolute}^2) + (V_{2\,relative}^2 - V_{1\,relative}^2)] / 2$
Work:	$w = (V_{S1}\cos\theta - V_{S2}\cos\delta)\, V_{blade}$
Power:	$P = wM$
Force on Blades:	$F = M\,(V_{S1}\cos\theta - V_{S2}\cos\delta)$
Power to Blades:	$P = M\,(V_{S1}\cos\theta - V_{S2}\cos\delta)\, V_B$
Power to Blades:	$P = M\,[(V_{S1}^2 - V_{S2}^2) + (V_{R2}^2 - V_{R1}^2)] / 2$

Gas Turbines

State Equation:	$pv = RT$	
Isentropic Equation:	$(T_2/T_1) = (p_2/p_1)^{(k-1)/k}$	
Enthalpy Change:	$h_1 - h_2 = c_p(T_1 - T_2)$	(ideal gas)
Nozzle Equation:	$h_1 - h_2 = (V_2^2 - V_1^2) / 2$	
Work:	$w = (C_1\sin\alpha_1 + C_2\sin\alpha_2)\, U$	
Work:	$w = [(C_1^2 - C_2^2) + (W_2^2 - W_1^2)] / 2$	
Power:	$P = wM$	

Compressors

Work	$W = U(C_{Y2} - C_{Y1})$
Rotor Enthalpy Change	$h_1 + ½W_1^2 = h_2 + ½W_2^2$
Stator Enthalpy Change	$h_2 + ½C_2^2 = h_3 + ½C_3^2$
Isentropic Equation	$(T_3/T_1) = (p_3/p_1)^{(k-1)/k}$

Hydraulic Machines

Similarity Equations:	$Q_M/Q_P = (\omega_M/\omega_P)\,(D_M/D_P)^3$
	$H_M/H_P = (\omega_M/\omega_P)^2\,(D_M/D_P)^2$
	$P_M/P_P = (\rho_M/\rho_P)\,(\omega_M/\omega_P)^3\,(D_M/D_P)^5$
Pump Specific Speed:	$N_S = \omega\, Q^{1/2} / (gH)^{3/4}$
Turbine Specific Speed:	$N_S = \omega\, P^{1/2} / [\rho^{1/2}\,(gH)^{5/4}]$
Critical Cavitation Parameter:	$\sigma = [\{(p_{atmosphere} - p_{vapour}) / \rho g\} - \Delta z] / H$
Moody Efficiency Relationship:	$\eta_P = 1 - (1 - \eta_M)\,(D_M/D_P)^{1/4}\,(H_M/H_P)^{1/10}$
Approximate Moody Efficiency:	$(1 - \eta_M)/(1 - \eta_P) \approx (D_P/D_M)^{1/5}$
Power:	$P = \rho g Q H$

Pumps

Hydraulic Torque:	$\tau = \rho Q\,(r_2V_{2T} - r_1V_{1T})$
Hydraulic Torque:	$\tau = \rho Q\,(r_2V_2\cos\alpha_2 - r_1V_1\cos\alpha_1)$
Power:	$P = 2\pi N \tau$
Net Positive Suction Head:	$NPSH = [(p_{atmosphere} - p_{vapour}) / \rho g] - \Delta z - h_L$
Peripheral Velocity Factor:	$\varphi = V_{B2} / (2gh)^{1/2}$
Critical Cavitation Parameter:	$\sigma_C = NPSH / H$
Approximate Moody Efficiency:	$(1 - \eta_P)/(1 - \eta_M) \approx (D_M/D_P)^{1/5}$

Jet Propulsion

Thrust:	$\tau = M(V_{jet} - V_{aircraft})$
Thrust Power:	$\tau V_{aircraft} = M(V_{jet} - V_{aircraft})V_{aircraft}$
Jet Power:	$P = M(V_{jet}^2 - V_{aircraft}^2) / 2$
Propulsion Efficiency:	$\eta_p = 2V_{aircraft}/(V_{jet} + V_{aircraft})$

Wind Turbines

Maximum Ideal Power:	$P_{max} = 8\,\rho\,AV_1^3 / 27$