NATIONAL EXAMINATIONS

May 2015

FLUID MACHINERY

Three hours duration

Notes to Candidates

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

2. Exam 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).** Note that Question 1 is on two pages.

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

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

6. 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.

7. 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.

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

9. **Reference data** for particular questions are given in the Attachments on pages 10 to 14. **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.**

10. **Reference formulae and constants** are given on pages 15 to 19.

11. **Drawing Instruments** (scale ruler, protractor and sharp pencil) are required for vector diagrams.

SECTION A CALCULATIVE QUESTIONS

QUESTION 1 HYDRO TURBINES

PART I KAPLAN TURBINE EFFICIENCY

Refer to the Examination Paper Attachments Page 10 **Kaplan Turbine** for illustrative purposes only.

Hydro turbines of the Kaplan type are installed at Mactaquac on the Saint John River. In order to determine the efficiency of the Mactaquac turbines the following hypothetical measurements are considered:

Turbine-generator speed	112.5 rev/min
Generator electrical output	110 MW
Water flow rate	354 m^3/s
Inlet pipe diameter (not in picture)	6.4 m
Outlet pipe diameter (bottom of picture)	7.0 m
Inlet water pressure	226 kPa gauge
Outlet water pressure	-4.5 m H_2O

The elevation of the outlet pressure measuring point is 5.0 m below that of the inlet pressure measuring point.

Determine the following:

(a) Hydraulic power produced by the water (input to turbine-generator).

(b) Electrical power output.

(c) Efficiency of turbine-generator.

(5 marks)

This question is continued on the next page

Question 1 Continued

PART II HYDRO TURBINE PLANT

Refer to the Examination Paper Attachments Page **11 Hydro Power Plant**.

The figure shows a cross section of a small hydro power plant utilizing a Kaplan turbine in a low head application. The maximum power output of the turbine generator is 4 MW. Select an appropriate value for the turbine efficiency but assume that there is negligible hydraulic friction in the rest of the system:

(a) Determine the flow rate of water when operating at maximum power between normal low water level in the reservoir and full load water level in the tail race.

(b) Determine the velocity of the water in the penstock when operating under the conditions in (a) above. Note that the penstock is circular in cross section and its diameter must be estimated from the information given on the drawing.

(c) Should normal high water level in the reservoir be reached while that in the tailrace remains unchanged, state with reasons whether the velocity in the penstock will be greater or less than that given in (b) to achieve full power.

(d) Determine the velocity of the water in the penstock when operating under the conditions in (c) above.

(5 marks)

[10 marks]

QUESTION 2 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.

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

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.

(d) Determine the necessary flow through the model.

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

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.

[10 marks]

QUESTION 3 MULTI-JET PELTON TURBINE

Consider the design of a multi-jet Pelton wheel with parameters and operating conditions as given below:

Head	$H = 200$ m
Flow rate	$Q = 4$ m^3/s
Nozzle velocity coefficient	$K = 0.99$
Wheel diameter	$D = 1.47$ m
Mechanical efficiency	$\eta = 88\%$

The following conditions are desirable:

Blade speed to jet speed ratio	0.47
Jet diameter to wheel diameter ratio	0.113

(a) Calculate the wheel rotational speed.

(b) Calculate the power output.

(c) Determine the number of nozzles required.

(d) Calculate the specific speed of the machine.

[10 marks]

QUESTION 4 CURTIS TYPE IMPULSE TURBINE

Refer to the Examination Paper Attachments Page 12 **Steam Turbine Velocity Diagram** (one stage only) for nomenclature of velocities and angles.

Steam exits the nozzles and enters the first stage moving blades of a velocity compounded two stage (Curtis) impulse turbine at 1411 m/s. The nozzle angle is 20° and the fixed blade exit angle is the same as its inlet angle, that is, the fixed blades are symmetrical. The moving blades of both stages are also symmetrical but with different angles. Assume zero fluid friction in nozzles and blades.

(a) Determine a blade velocity to give optimum work (minimum exit kinetic energy).

(b) Draw to scale, as recommended below, the velocity diagrams for the two stages.

(c) Determine all the actual and relative steam velocities and blade angles and show them on the diagrams.

(d) Calculate the work done by each stage, in kJ/kg of steam.

(e) Calculate the total power output for a steam flow of 100 kg/s.

(f) Calculate the blade efficiency.

Note: The scale drawing should be to a large enough scale for accurate measurements (a scale of 1 mm = 10 m/s is suggested). While calculation of velocities by trigonometric ratios is acceptable it is longer and more time consuming.

[10 marks]

QUESTION 5 GAS TURBINE BLADES

Refer to the Examination Paper Attachments Page 13 **Acacia and Port Rex Power Stations** and Page 14 **Gas Turbine Velocity Diagram**.

Each power station has three units. Each unit has a nominal output of 60 MW and is powered by twin back to back gas turbines driving a common electrical generator. The diagram on Page 13 is for <u>one</u> gas turbine only while the specifications are for <u>both</u> gas turbines combined. The net power output and exhaust gas flow rate as given must therefore be <u>divided by two</u> for the purposes of this question.

Consider conditions on the <u>power turbine</u> (free turbine with N3 rotor) at <u>peak load</u>.

The power turbine has the following approximate blade dimensions for the first stage:

Stator blade inlet angle α_0	30°	Blade tip diameter	1500 mm
Stator blade exit angle α_1	60°	Blade root (hub) diameter	1050 mm
Rotor blade inlet angle β_1	30°		
Rotor blade exit angle β_2	60°		

The exhaust gas has parameters slightly different from those of cold air, so use the following values for its specific heat:

c_p = 1.148 kJ/kg°C $\qquad\qquad$ c_v = 0.861 kJ/kg°C

Based on these dimensions and conditions for the first stage and, assuming that the gas flow conditions are the same for the second and third stages of the power turbine, determine the following:

(a) Mean blade velocity (velocity at mid-height of blades).

(b) The velocity diagram for the first stage of the turbine drawn to scale as recommended below.

(c) Relative and absolute gas velocities from the velocity diagram

(d) Power turbine output based on gas velocities and gas mass flow rate.

(e) Power turbine output based on actual temperature change and gas flow rate.

(f) Difference between answers to (d) and (e) above and specified value and comment on any discrepancy.

Note: The scale drawing should be to a large enough scale for accurate measurements (a scale of 10 m/s = 4 mm is suggested). While calculation of velocities by trigonometric ratios 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 PUMP AND TURBINE SPECIFIC SPEED

PART I PUMP SPECIFIC SPEED

Explain how specific speed is used to identify the type of pump to be installed for a particular application. Show by means of sketches how impeller shape varies with specific speed. Clarify the direction of flow through the impeller and how this may change with specific speed. Explain how specific speed is related to the head and flow of the pump.

(5 marks)

PART II TURBINE SPECIFIC SPEED

Explain how specific speed is used to identify the type of hydraulic turbine to be installed for a particular application. Show by means of sketches how impeller shape varies with specific speed. Explain how specific speed is related to the head and flow of the turbine. Give the common names of hydraulic turbines and match these with sketches of impeller shape.

(5 marks)

[10 marks]

QUESTION 7 CAVITATION AND EROSION

PART I HYDRAULIC CAVITATION

Describe what determines the formation and collapse of vapour bubbles in a liquid. With reference to the mode of collapse, explain the phenomenon of cavitation and the mechanism of damage to the surface of hydraulic machine components. Clarify with reasons which parts of pumps and turbines could be damaged due to cavitation.

(5 marks)

PART II MOISTURE EROSION

Describe the mechanism of moisture erosion in steam turbines. Explain how and where this occurs and what effect it has on the integrity and performance of the turbine. Indicate which parts are most affected and how this can be prevented.

(5 marks)

[10 marks]

QUESTION 8 FLOW CONTROL

PART I FANS

Describe two of the three methods commonly used for flow control in large centrifugal fans (as for example those installed in large boiler plants). Show in head versus flow diagrams (graphs) for fan and system how the operating point (flow) can be changed in each case and explain why the change has occurred.

(5 marks)

PART II HYDRO TURBINES

Explain how water flow and hence power output is changed in a typical hydro turbine of the Francis type. Show in a sketch the typical arrangement of components to effect this control. Describe any hydraulic concerns in the penstock or draught tube regarding rapid load changes or low load (low flow) operation of a fixed speed (power generating) machine.

(5 marks)

[10 marks]

EXAMINATION PAPER ATTACHMENTS

QUESTION 1 I KAPLAN TURBINE

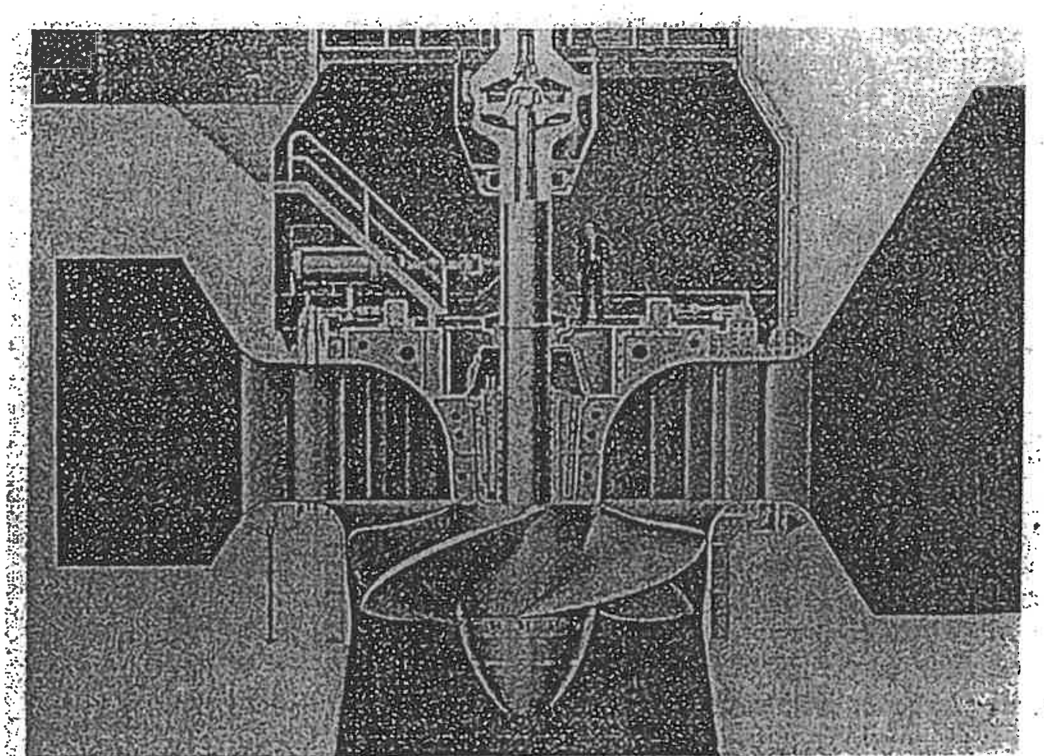
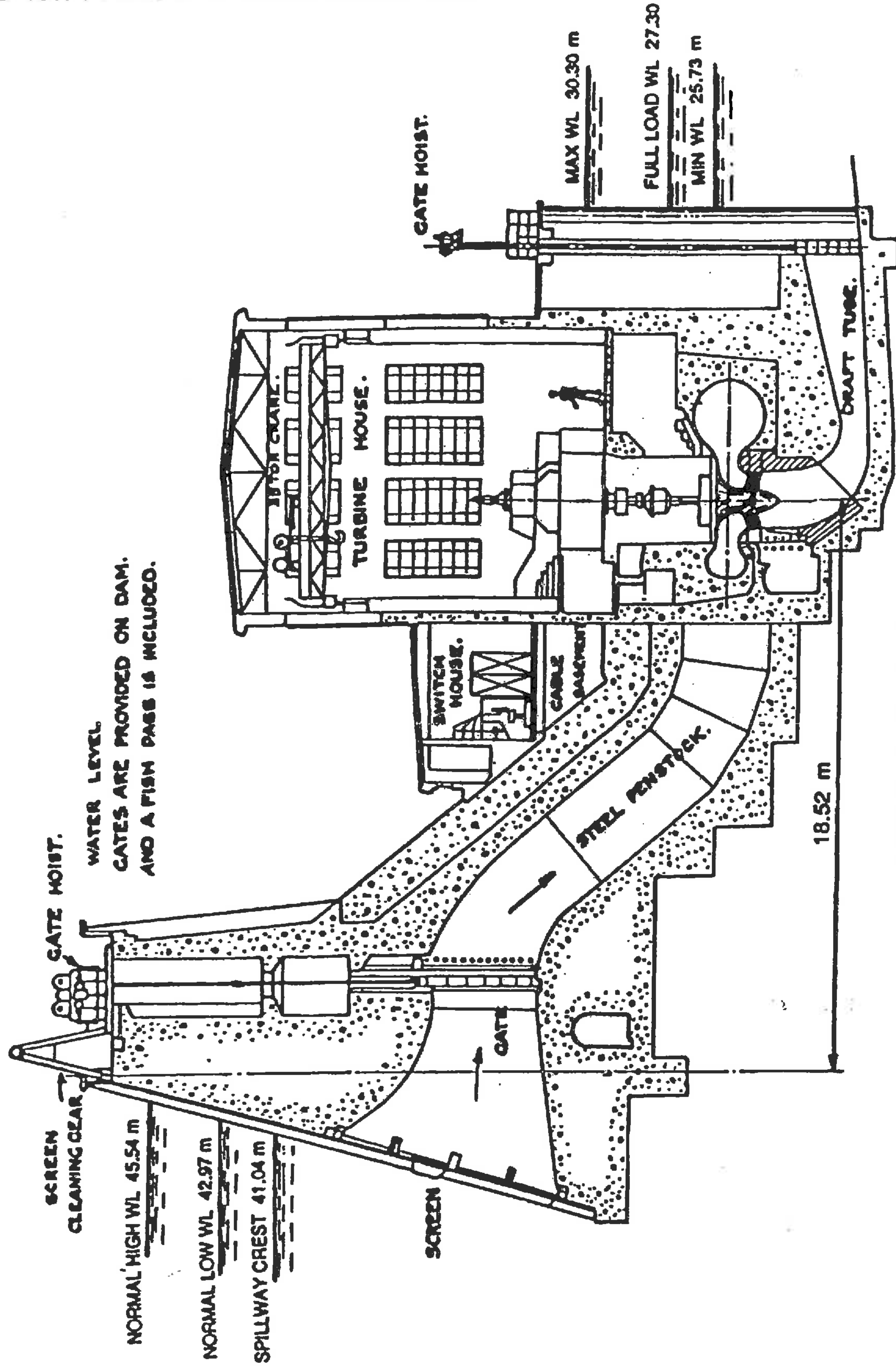


Figure 16.7 Kaplan turbine at Watts Bar Dam. 42,000 hp at 94.7 rpm under a head of 52 ft.

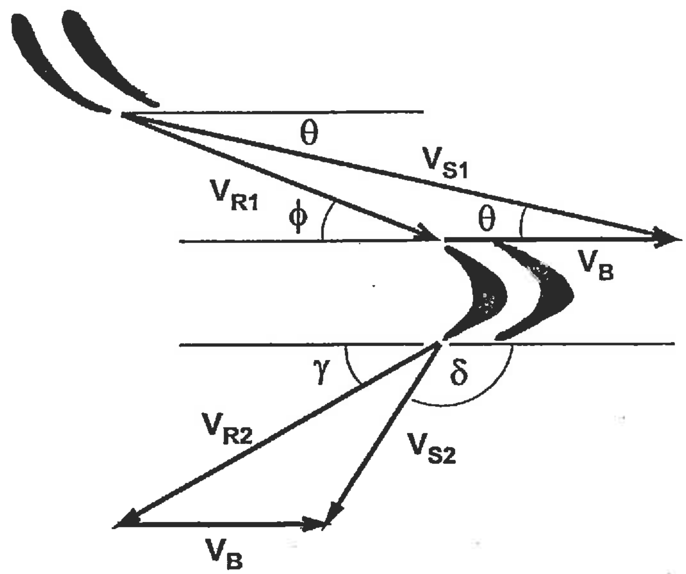
QUESTION 1 PART II HYDRO POWER PLANT



4 MW Kaplan Turbine Setting.

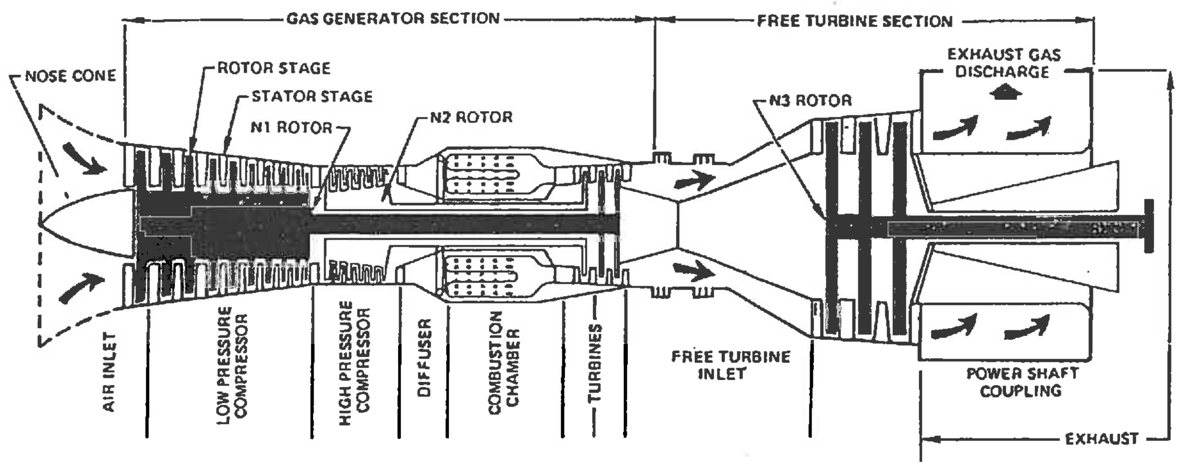
QUESTION 4 STEAM TURBINE VELOCITY DIAGRAM

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

QUESTION 5 ACACIA AND PORT REX POWER STATIONS

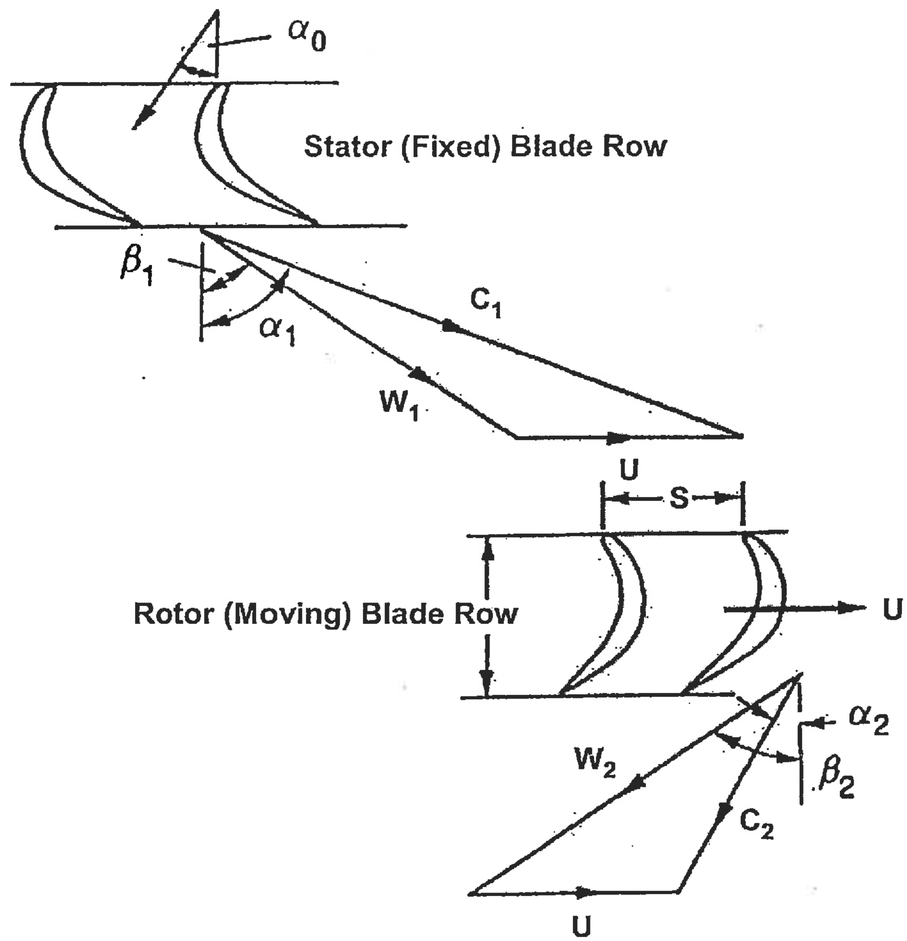


Technical Specifications		Peak Load	Base Load
Net Output	(kW)	60 860	57 100
Heat Rate	(kJ/kWh)	11 791	11 887
Speed - N1 Rotor	(rev/min)	6 805	6 640
Speed - N2 Rotor	(rev/min)	8 395	8 320
Speed - Power Turbine	(rev/min)	3 000	3 000
Temperature - Gas Generator Turbine Inlet	(°C)	1 077	1 043
Temperature - Power Turbine Inlet	(°C)	682	657
Temperature - Power Turbine Exhaust	(°C)	483	467
Exhaust Gas Flow Rate	(kg/s)	278	272
Gas Generator Pressure Ratio		14.1	13.6

N1 Low Speed Compressor and Turbine
N2 High Speed Compressor and Turbine

Inlet Air Conditions 15°C

QUESTION 5 GAS TURBINE 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 REFERENCE MATERIAL

NOMENCLATURE FOR REFERENCE EQUATIONS (SI UNITS)

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
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
v	Kinematic viscosity	m^2/s
ρ	Density	kg/m^3
σ_C	Critical cavitation parameter	
τ	Thrust	N
τ	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)

Steam Turbines

Nozzle Equation:	$h_1 - h_2 = (V_2^2 - V_1^2) / 2$
Work:	$w = [(V_1^2{}_{absolute} - V_2^2{}_{absolute}) + (V_2^2{}_{relative} - V_1^2{}_{relative})] / 2$
Work:	$w = (V_{S1}\cos\theta - V_{S2}\cos\delta)\, V_{blade}$
Power:	$P = wM$

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	$h_1 + \frac{1}{2}W_1^2 = h_2 + \frac{1}{2}W_2^2$
Stator Enthalpy Change	$h_2 + \frac{1}{2}C_2^2 = h_3 + \frac{1}{2}C_3^2$
Isentropic Equation:	$(T_3/T_1) = (p_3/p_1)^{(k-1)/k}$

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 Turbine

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

Energy Equation

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

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:	$P = \rho gQH$

Pumps

Hydraulic Torque:	$\tau = \rho Q\,(r_2 V_{2T} - r_1 V_{1T})$
Hydraulic Torque:	$\tau = \rho Q\,(r_2 V_2 \cos\alpha_2 - r_1 V_1 \cos\alpha_1)$
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:	$(1 - \eta_P)/(1 - \eta_M) \approx (D_M/D_P)^{1/5}$

Steam Turbines

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:	$P = M\,[(V_{S1}^2 - V_{S2}^2) + (V_{R2}^2 - V_{R1}^2)]\,/\,2$