NATIONAL EXAMINATIONS

May 2012

98-Mar-B5 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 also that Question 6 and Question 7 are on the same page.

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 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 9 to 16.

10. **Reference formulae and constants** are given on pages 17 to 20.

11. **Drawing Instruments** (scale ruler, protractor and sharp pencil) are required for vector diagrams. Alternatively the questions may be solved mathematically using trigonometric ratios.

SECTION A CALCULATIVE QUESTIONS

QUESTION 1 WIND AND WATER POWER

PART I WIND TURBINE

Refer to the Examination Paper Attachments Page 9 **Vestas Wind Turbine** and Page 10 **Wind Power Efficiencies**.

The tables and graphs give information for the Vestas V80 1.8 MW Wind Turbine as well as efficiencies for ideal and actual wind turbines. Determine the following for a wind speed of 10 m/s and compare with the specified output.

(a) (i) Kinetic energy and (ii) potential power available in the wind passing through a flow area equivalent to the area swept out by the rotor at the wind speed given above.

(b) (i) Maximum theoretical power and (ii) efficiency that can be obtained at the wind speed given above based on energy and momentum theoretical equations.

(c) (i) Ideal efficiency and (ii) power based on ratio of blade tip speed to wind speed as given (from graph of efficiency on page 10).

(d) (i) Actual efficiency and (ii) power based on ratio of blade tip speed to wind speed as given (from graph of efficiency on Page 10).

(e) Actual power output at the given wind speed as specified by the manufacturer (from graph on page 9).

(6 marks)

PART II HYDRO POWER PLANT

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

The figure shows a cross section of the plant in Brazil. By taking scaled measurements from this figure determine (i) the water flow rate through the turbine and (ii) the corresponding velocity in the penstock for the maximum power output of 50 MW. Note that the penstock leading to the turbine is circular in cross section. Note also that all levels are in metres.

(4 marks)

[10 marks]

QUESTION 2 STEAM TURBINE BLADE FLOW

Refer to Examination Paper Attachments Page 12 **Turbine Velocity Diagram.**

The attached diagram, for one stage only, clarifies the nomenclature to be used in answering the question.

A velocity compounded steam turbine (Curtis wheel) consisting of two stages receives 1.6×10^6 kg/h of steam at 726 m/s. The fixed blade outlet angles are 20° each and the moving blades are symmetrical (equal inlet and outlet angles). The blade speed is 168 m/s. The velocity coefficients in the moving and stationary blades are 0.905 and 0.932 respectively.

Draw to a scale of 1 cm = 50 m/s the velocity diagram and find the following:

(a) Inlet and outlet angles of both rows of moving blades

(b) Absolute and relative velocities of both stages

(c) Power developed in each stage and total power in MW

(d) Blade efficiency of both stages combined (Blade efficiency is defined as mechanical power out over steam power in)

[10 marks]

QUESTION 3 PUMP PERFORMANCE

Refer to the Examination Paper Attachments page 13 **Pump Velocity Diagram**

The attached diagram clarifies the nomenclature to be used in answering the question.

The picture below the velocity diagram shows a pump impeller of a radial flow centrifugal pump for pumping water. The key dimensions are as follows:

Blade inner diameter	$D_1 = 130$ mm	
Blade outer diameter	$D_2 = 300$ mm	
Blade inner height	$h_1 = 20$ mm	(in axial direction)
Blade outer height	$h_2 = 10$ mm	(in axial direction)
Blade inlet angle	$\beta_1 = 20°$	
Blade outlet angle	$\beta_2 = 25°$	
Pump speed	$N = 1750$ rev/min	
Water flow rate	$Q = 0.030\ m^3/s$	
Hydraulic head	$H = 35$ m	

For the given speed and a flow rate draw to a scale of 1 cm = 2 m/s the velocity diagrams at inlet and outlet and determine the following neglecting the vane thickness:

(a) Tangential blade velocities at inlet and outlet

(b) Radial water velocity at inlet and outlet

(c) Tangential water velocity at inlet and outlet

(d) Torque and power required to drive the impeller

(e) Hydraulic power and efficiency of pump

[10 marks]

QUESTION 4 PUMP APPLICATION

Refer to the Examination Paper Attachments Page 14 **Pump Characteristics** and Page 15 **Cavitation Parameter.**

A centrifugal pump is required to pump potable water from a water treatment plant to a reservoir for subsequent distribution. The required flow is 85 L/s and the head 30 m. The pump will be driven by an induction motor operating at 60 Hz and 400 V with a slip of 3% and electrical losses of 4%. To ensure satisfactory operation basic preliminary design information is required.

Assuming that the head loss in the pump inlet piping is 1.0 m and that the vapour pressure under the prevailing conditions is 2 kPa, determine the flowing:

(a) Pump specific speed

(b) Type of pump and sketch of impeller

(c) Diameter of impeller

(d) Critical cavitation parameter

(e) Desired net positive suction head

(f) Maximum elevation of pump relative to supply level

(g) Efficiency of pump

(h) Electric power consumption

[10 marks]

QUESTION 5 GE CF6-80C2 TURBOFAN ENGINE THRUST

Refer to the Examination Paper Attachments Page 16 **Aircraft Engine Operating Parameters**

Refer to the attached Aircraft Engine Operating Parameters for the Boeing 747-400. Note that the cruising conditions are very different from the take-off conditions (maximum or design conditions). For actual <u>cruising</u> conditions (Canadian Airlines Flight 8 Hong Kong to Vancouver) determine the following, noting the assumptions given below:

(a) Bypass nozzle exit temperature assuming isentropic expansion down to atmospheric conditions

(b) Core nozzle exit temperature assuming isentropic expansion down to atmospheric conditions

(c) Bypass nozzle exit velocity

(d) Core nozzle exit velocity

(e) Total thrust of engine (N)

(f) Rate of heat input to engine (kJ/s)

(g) Jet power (rate of kinetic energy production) (kW)

(h) Thrust power (kW)

(i) Thermodynamic Efficiency

(j) Propulsion Efficiency

(k) Overall Efficiency

Assume the following (which have been calculated from thermodynamic conditions):

Fan exhaust pressure	94 kPa
Fan exhaust temperature	14°C
Turbine exhaust pressure	51 kPa
Turbine exhaust temperature	518°C

Assume that the working fluid has the properties of cold air.

[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 TURBOFAN ENGINE DESIGN

(i) Explain the reasons for employing twin spools (two shafts) in an aircraft turbofan engine. (ii) Explain also why the axial flow compressors in a turbofan (or turbojet) engine have more stages than the axial flow turbines. (iii) Clarify the advantage of turbofan engines (with bypass airflow) as opposed to simpler turbojet engines (no bypass). (iv) Explain the technical difficulty in developing very high bypass ratio engines.

[10 marks]

QUESTION 7 CAVITATION AND EROSION

PART I HYDRAULIC CAVITATION

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

(5 marks)

PART II MOISTURE EROSION

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

(5 marks)

[10 marks]

QUESTION 8 EFFICIENCY OF PUMPS AND TURBINES

PART I CENTRIFUGAL PUMPS

With reference to the figure below explain the following:

(a) Why the hydraulic efficiency (water horsepower) rises from zero to a peak and then declines towards zero

(b) Why the difference between the hydraulic power (water horsepower) and the mechanical power (brake horsepower) decreases to a low value and then increases to a value greater than the initial value.

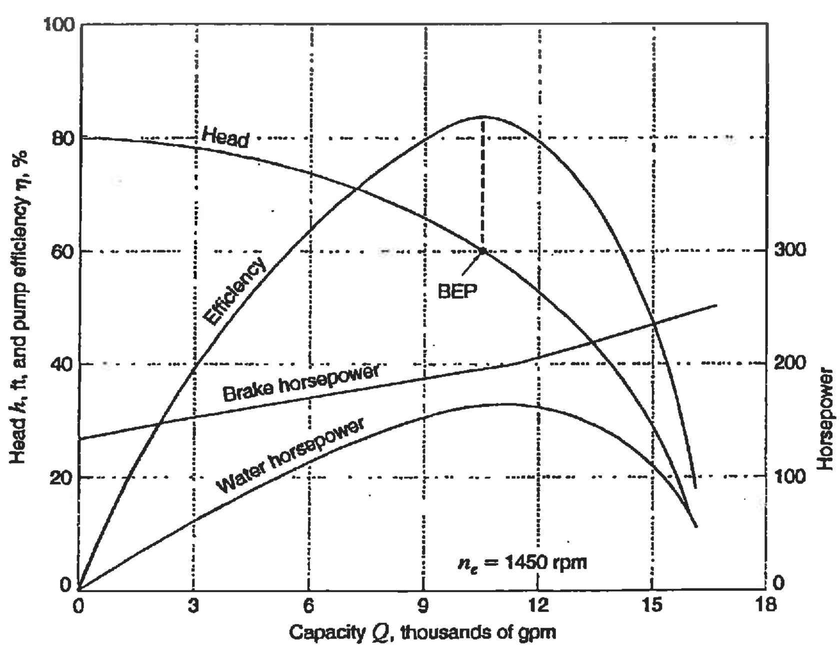
(5 marks)

PART II WIND AND HYDRO TURBINES

Wind and hydro turbines draw energy from flowing fluids. (i) Compare the theoretical efficiency of each and note the practical efficiencies generally obtained. (ii) Give realistic values for each type of machine. (iii) Describe the fluid flow through each and (iv) explain why there is a marked difference in efficiency between two machines operating on similar principles.

(5 marks)

[10 marks]



Characteristic curves for a typical mixed-flow centrifugal pump.

EXAMINATION PAPER ATTACHMENTS

QUESTION 1 PART I VESTAS WIND TURBINE

Vestas®

V80 – 1.8 MW

Pitch regulated wind turbine with OptiSlip® and OptiTip®

ROTOR	
Diameter:	80 m
Swept area:	5,027 m²
Speed of revolution:	15.7 RPM
Number of blades:	3
Power regulation:	Pitch + OptiSlip®
Air brake:	3 separate pitch settings

TOWER:	
Hub height (approx.):	60 – 67 – 78 m

OPERATIONAL DATA:	
Cut-in wind speed:	4 m/s
Nominal wind speed:	16 m/s
Stop wind speed:	25 m/s

GENERATOR:	
Type:	Asynchronous with OptiSlip®
Nominal output:	1.8 MW
Operational data:	60 Hz 690V 1,800 -1,980 RPM

GEARBOX:	
Type:	Planet/parallel gear

CONTROL:	
Type:	Microprocessor-based control of all turbine functions with the option of remote monitoring. OptiSlip® output regulation and OptiTip® pitch regulation of the blades.

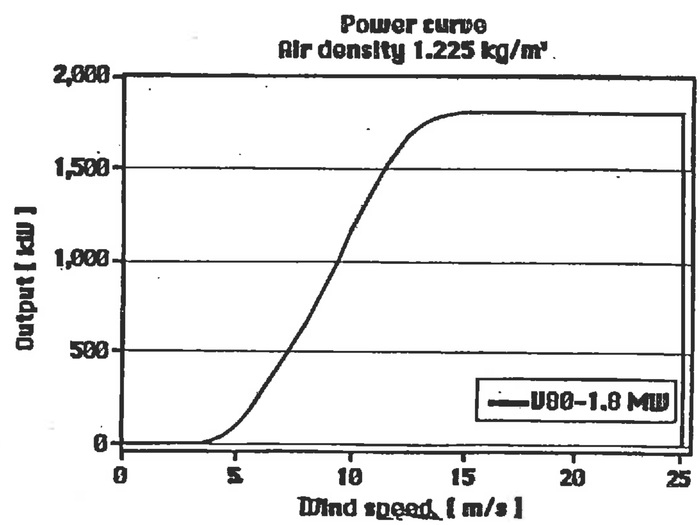
WEIGHT: (APPROX.)	(60 m)	(67 m)	(78 m)
Nacelle:	63 t	63 t	63 t
Rotor:	38 t	38 t	38 t

Ideal for moderate wind conditions

The V80-1.8 MW is particularly well suited for installation in areas with moderate to high wind conditions, and thanks to OptiSlip®, the turbine can adapt to wind conditions in almost any location. In this way, Vestas continues to strive for excellence by taking firm steps towards the full exploitation of wind energy.

Advanced Vestas technology

The Vestas V80-1.8 MW is based on the well-known technology from the V66-1.65 MW turbine. The turbine is a three blade 60 Hz pitch-regulated wind turbine with OptiSlip® and OptiTip®. The turbine's rotor diameter is 80 meters – and the turbine can be delivered with tower heights of up to 78 meters.



QUESTION 1 PART I WIND POWER EFFICIENCIES

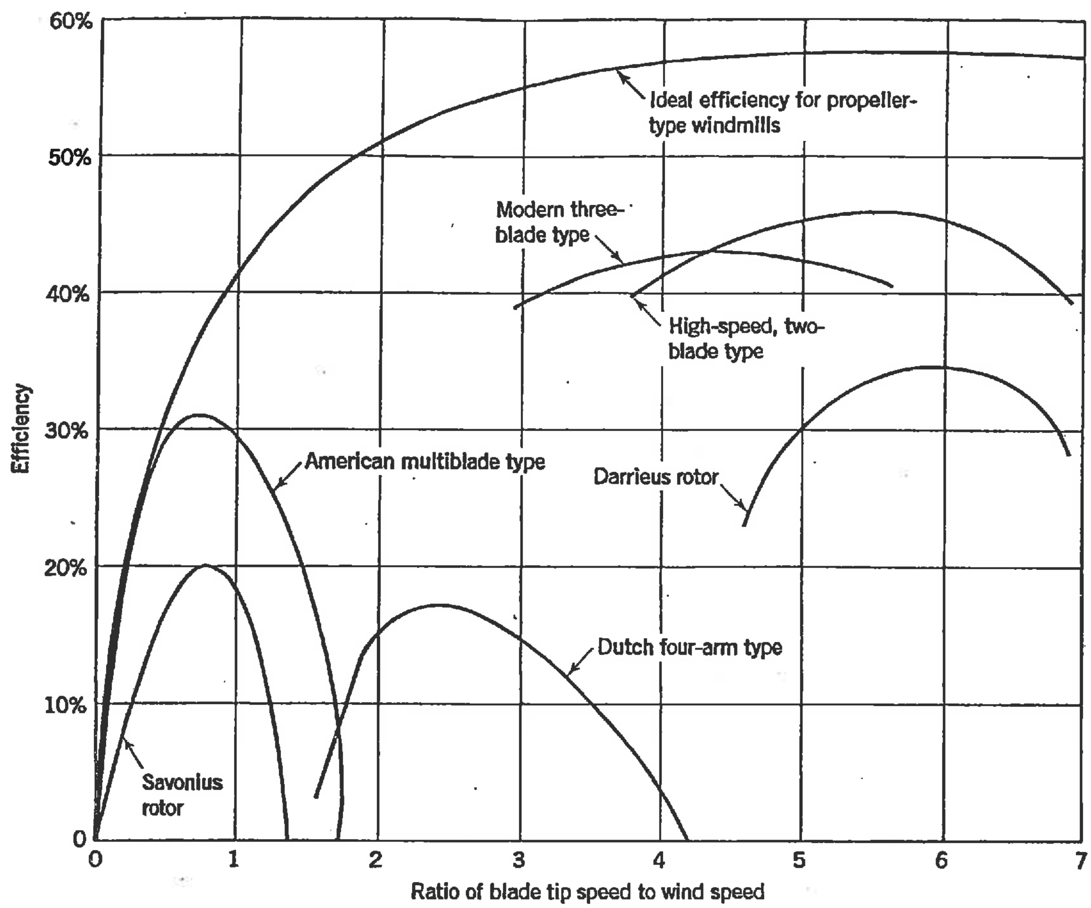


Figure 5.6 Typical efficiencies of several types of windmills plotted against their tip-speed ratio. The maximum efficiencies are seen to vary from about 16 to 46%. The ideal efficiency shown is a mathematical ideal, never to be achieved in practice. (*Source*: Basic data from R. Wilson and P. Lissaman, *Applied Aerodynamics of Wind Power Machines*, Oregon State University.)

QUESTION 1 PART II JURUMIRIM HYDRO POWER PLANT

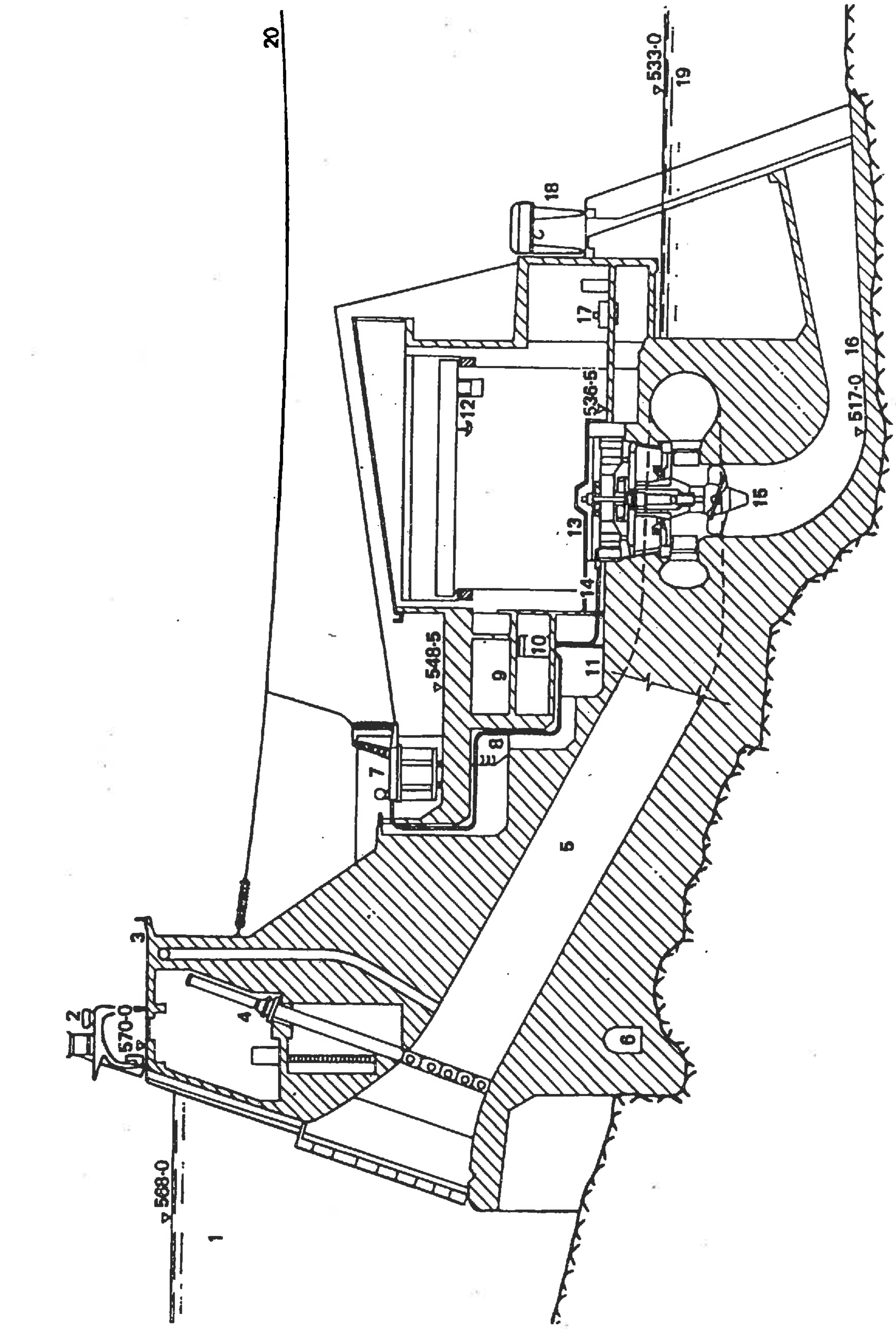
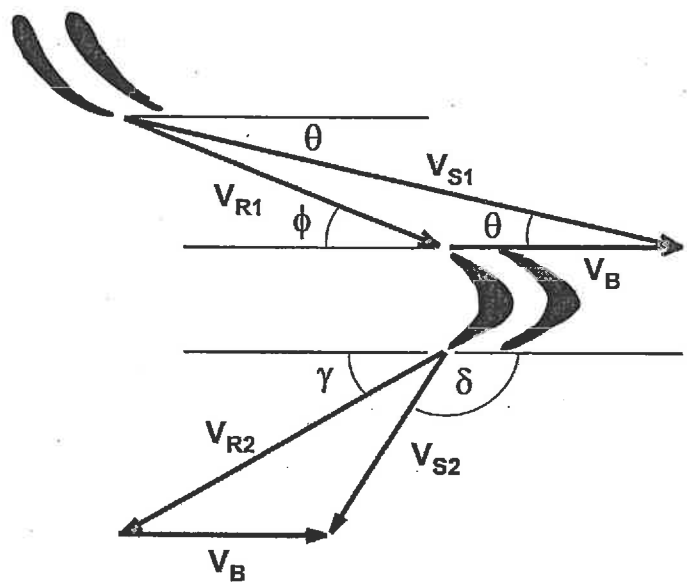


Fig. 2. Cross section through the powerhouse and turbine. Key: 1, storage reservoir; 2, rake cleaning device; 3, road; 4, turbine intake gates; 5, penstock; 6, control passage; 7, 13·8/230kV transformers; 8, cable duct; 9, control room; 10, 13·8kV switching installation; 11, cable distribution room; 12, crane; 13, 50MVA generator; 14, generator busbars; 15, Kaplan turbine; 16, draft tube; 17, turbine regulator; 18, crane for shut-off device; 19, downstream side; and 20, 230kV overhead line

QUESTION 2 TURBINE VELOCITY DIAGRAM

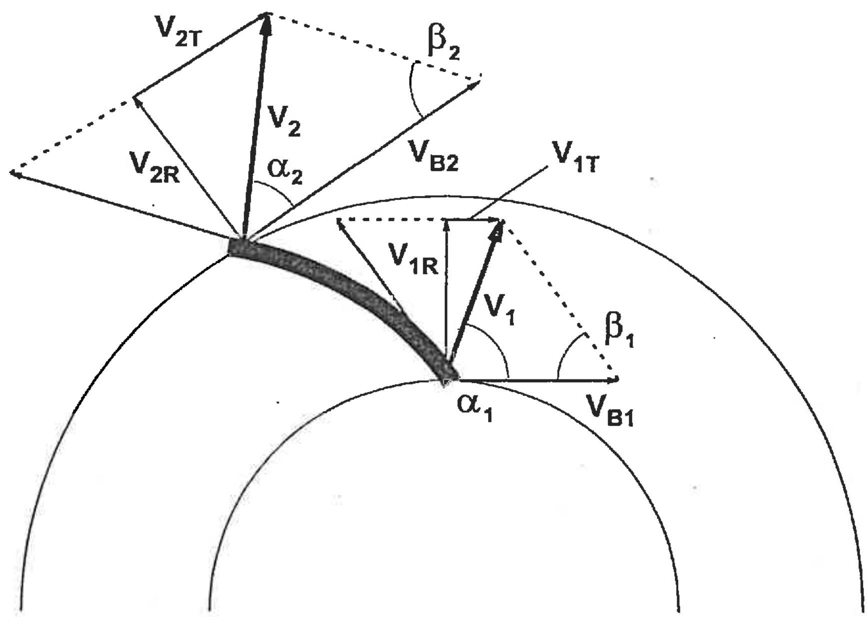
Nomenclature for velocity vectors and angles

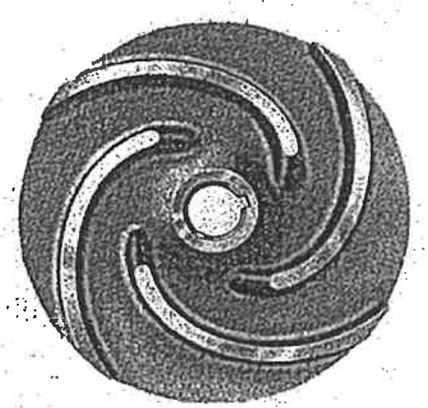


V_{S1}	Absolute steam velocity entering moving blades
V_{R1}	Relative steam velocity entering moving blades
V_B	Moving blade velocity
V_{R2}	Relative steam velocity leaving moving blades
V_{S2}	Absolute steam velocity leaving moving blades

QUESTION 3 PUMP VELOCITY DIAGRAM

Nomenclature for velocity vectors and angles





B

V_1	Absolute water velocity at inlet
V_{B1}	Blade velocity at inlet
V_{1R}	Radial water velocity at inlet
V_{1T}	Tangential water velocity at inlet
V_2	Absolute water velocity at outlet
V_{B1}	Blade velocity at outlet
V_{2R}	Radial water velocity at outlet
V_{2T}	Tangential water velocity at outlet

QUESTION 4 PUMP CHARACTERISTICS

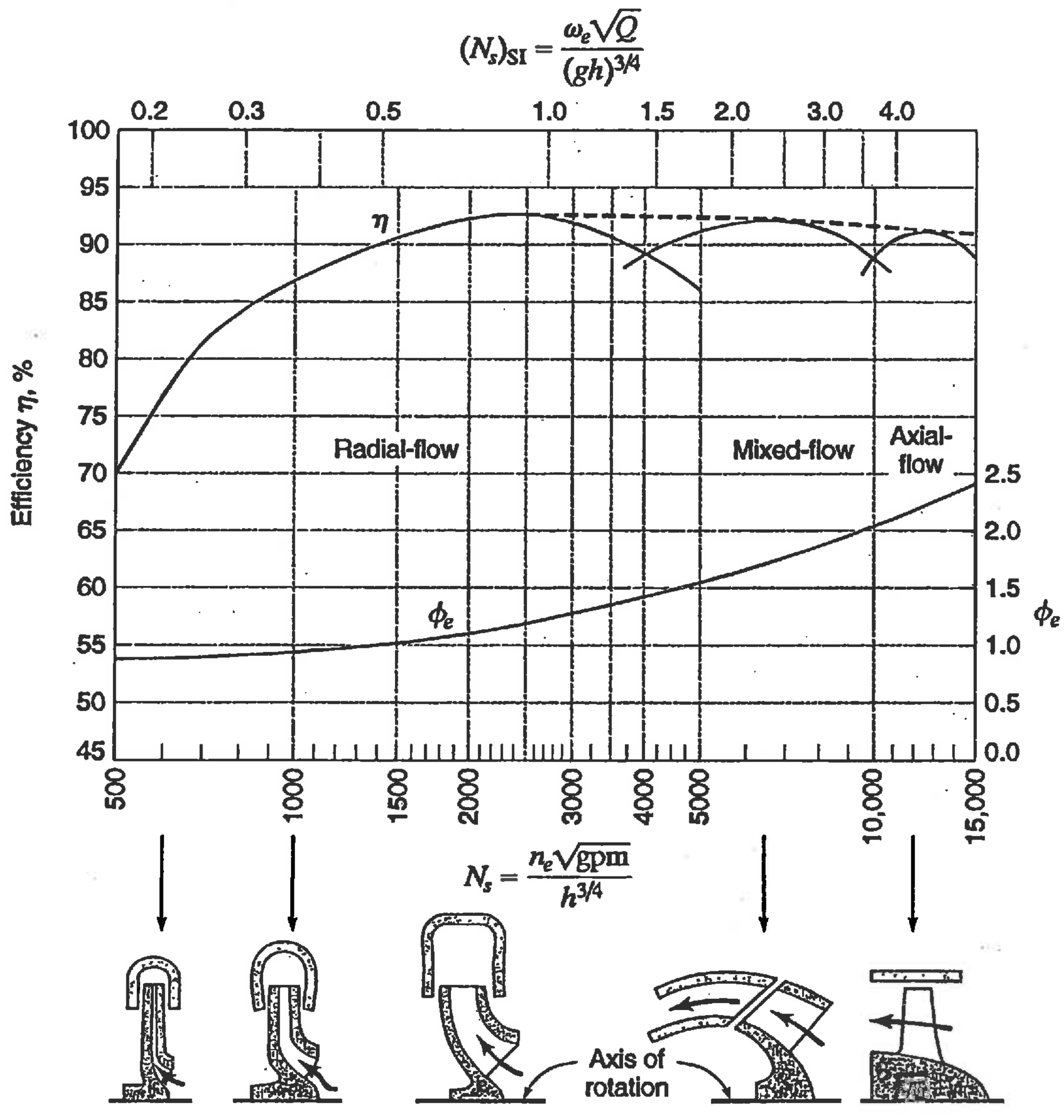


Figure 15.11
Optimum efficiency and typical values of ϕ_e for water pumps as a function of specific speed.

QUESTION 4 CAVITATION PARAMETER

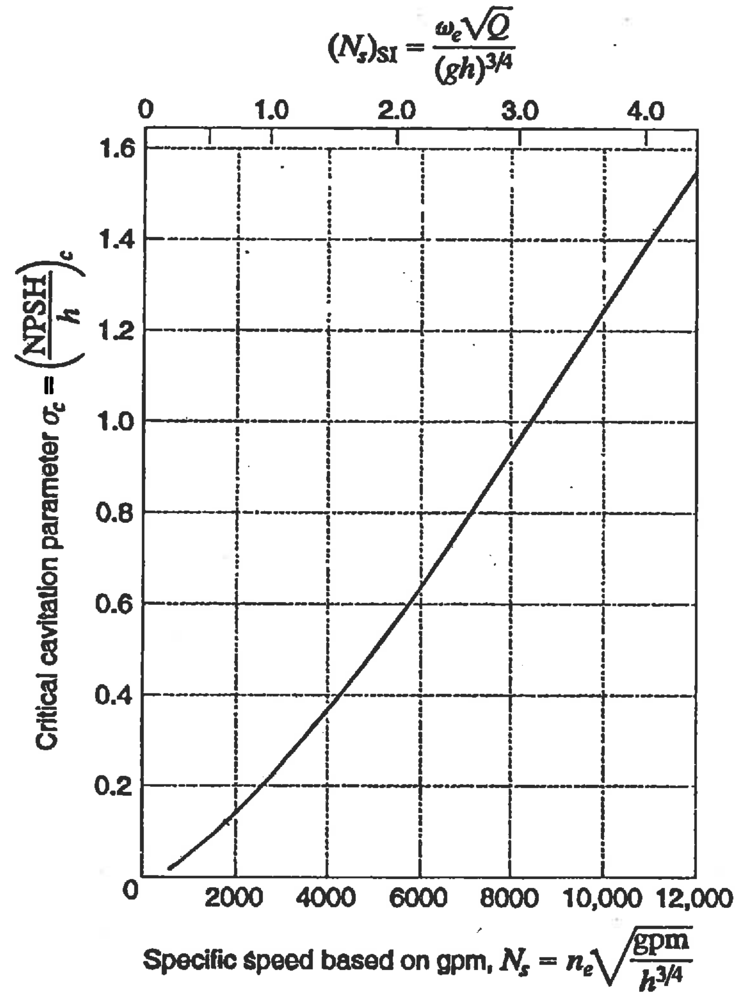


Figure 15.12
Approximate values of critical cavitation parameter σ_c as a function of specific speed.

QUESTION 5 AIRCRAFT ENGINE OPERATING PARAMETERS

BOEING 747-400
GE CF6 80 C2 B1F
High By-pass Twin Spool

Engine Design Parameters:

By-pass ratio	5.15	
Fan	1 stage	
LP Compressor	4 stages	
HP Compressor	14 stages	
HP Turbine	2 stages	
LP Turbine	5 stages	
Combustor	30 nozzles	
Fan Diameter	2.362 m	(93 in)
Engine Length	4.087 m	(161 in)
Core Pressure Ratio (max.)	30.4	
Fan Pressure Ratio (max.)	1.69	
Fan Flow Rate (max.)	802 kg/s	(1769 lb/s)
Core Flow Rate (max.)	154 kg/s	(340 lb/s)
Take-off Thrust (max.)	257.6 kN	(57 900 lbf) ideal nozzle
Take-off Thrust (max.)	253.1 kN	(56 900 lbf) real nozzle
Cruise Thrust	50.4 kN	(11 330 lbf) ideal nozzle
Specific Fuel Consumption 9.	32 mg/Ns	(0.329 lb/hr/lb st)
Fuel Calorific Value (estimated)	44 000	kJ/kg.

Engine Operating Parameters (*Data from on-board computer):

*Altitude	37 000 ft	
Atmospheric Pressure (estimated)	22 kPa	
*Static Air Temperature (atmospheric)	-51°C	
*Total Air Temperature (stagnation)	-20°C	
*Calibrated Air Speed	276 m/s	
True Air Speed	252 m/s or 909 km/hr	
*Ground Speed	1076 km/hr	(581 knots)
*Mach Number	0.845	
*HP Turbine Speed	98% of max.	
*LP Turbine Speed	95% of max.	
*Fuel Flow (average per engine)	0.71 kg/s	(5.65 klb/hr)
Fan Flow (estimated)	264 kg/s	(582 lb/s)
Core Flow (estimated)	50 kg/s	(110 lb/s)
*Combustion Chamber Pressure	921 kPa	(134 lbf/1bf/in^2)

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
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
v	Specific volume	m^3/kg
V	Velocity	m/s
w	Specific work	J/kg
W	Work	J
x	Length	m
z	Elevation	m
α	Pump blade angle	
β	Pump 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	
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:	$p_{atm} = 100\ kPa$
Density of water:	$\rho_{water} = 1000\ kg/m^3$
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:	$c_v = \Delta u / \Delta T$
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:	$w = [(V_1^2{}_{absolute} - V_2^2{}_{absolute}) + (V_2^2{}_{relative} - V_1^2{}_{relative})] / 2$

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:	$h_1 - h_2 = (V_2^2 - V_1^2) / 2$	

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:	$N_S = \omega P^{1/2} / [\rho^{1/2} (gH)^{5/4}]$
Moody Efficiency Relationship:	$\eta_P = 1 - (1 - \eta_M)(D_M/D_P)^{1/4} (H_M/H_P)^{1/10}$
Power:	$p = \rho g Q H$

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:	$\sigma_C = NPSH / H$.

Steam Turbine

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