NATIONAL EXAMINATIONS

May 2017

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

8. 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.

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

10. **Reference data** for particular questions are given in the Attachments on pages 9 to 11. **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.**

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

12. **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 AND TURBINE

Consider a simple single shaft gas turbine power plant having the following specifications:

Compressor pressure ratio	12.0
Ambient pressure	100 kPa
Ambient temperature	15°C
Turbine inlet temperature	1077°C
Compressor efficiency	0.86
Turbine efficiency	0.89
Mechanical (shaft) efficiency	0.98
Air/fuel ratio	50

(a) Sketch a T-s diagram showing the complete thermodynamic cycle and identify by number all key points in the cycle.

(b) Determine and identify by number the temperatures at all key points in the cycle.

(c) Calculate the specific work output from the unit in kWs/kg of gas flow.

(d) Calculate the specific fuel consumption of the unit in kg/kWh.

[10 marks]

QUESTION 2 COMPRESSOR DESIGN

Refer to the Examination Paper Attachments Page 9 **Compressor Velocity Diagram**.

In the preliminary stages in the design of a compressor for a gas turbine plant the following boundary conditions have been specified:

Air mass flow rate	50 kg/s
Inlet air temperature	20°C
Inlet air pressure	100 kPa
Outlet air pressure	500 kPa
Mean axial air velocity	160 m/s
Rotational speed	8000 rev/min

Based on experience the following design parameters are considered to be favourable for good performance:

Rotor hub diameter (at blade root) = 0.6 rotor tip diameter (at blade tip)
Stator exit angle α_1 = 30° (relative to axial direction)
Degree of reaction = 0.5 (50%)
All stages have similar velocity diagrams and require the same work input.

Assume that the axial air velocity is constant throughout all stages and that the mean blade diameter is also constant throughout all stages.

Do the following:

(a) Calculate the blade hub and tip diameters and hence the mean blade diameter at the inlet to the compressor.

(b) Calculate the mean blade velocity.

(c) Draw a velocity diagram at the mean blade diameter to determine the absolute and relative air velocities within the first stage.
A scale of 10 mm = 20 m/s is recommended.

(d) From the diagram determine the work required by the first stage.

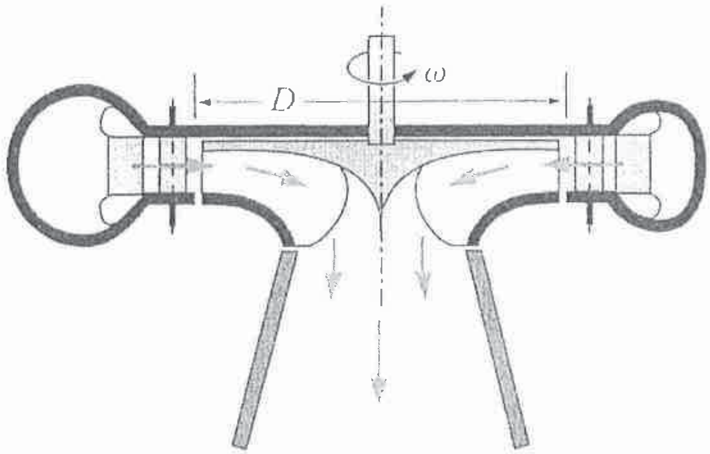
(e) From (d) above calculate the number of stages required.

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

[10 marks]

QUESTION 3 HYDRO TURBINE DESIGN

Refer to the Examination Paper Attachments Page 10 **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. It has the following basic parameters:

Specific speed	$N_s = 0.9$
Effective (net) head	$H = 160$ m
Required speed	$N = 750$ rev/min
Hydraulic efficiency	$\eta = 0.94$
Runner blade inlet angle	$\alpha_1 = 18°$ (relative to tangent to runner)
Runner tip speed	$U_1 = 0.7\ V_{jet}$

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

(a) Calculate the turbine power output.

(b) Calculate the water flow rate.

(c) Calculate the runner diameter.

(d) Sketch the velocity diagram at the runner inlet and, by scale drawing or calculation, determine the radial flow velocity.

(e) Calculate the runner height at the inlet.

[10 marks]

QUESTION 4 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	$K = 0.98$
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 (rev/min).

(b) Calculate the power output (MW).

(c) Determine the number of nozzles required.

(d) Calculate the specific speed of the machine.

[10 marks]

QUESTION 5 BOILER DRAUGHT FANS

Two induced draught (ID) fans are employed in parallel at the exhaust of a large coal fired boiler to extract the combustion gases. Each fan has the following head versus flow characteristic where H is in kPa and Q is in m^3/s:

$$H = K_1 - K_2 Q - K_3 Q^2$$

The complete exhaust system has the following head versus flow characteristic where h is in kPa and Q is in m^3/s

$$h = K_4 Q^2$$

The constants and speed of the fans at full load on the boiler are as follows where rotational speed N is in rev/min:

$K_1 = 4.5 \times 10^{-6} N^2$
$K_2 = 0.0$
$K_3 = 16.0 \times 10^{-6}$
$K_4 = 5.5 \times 10^{-6}$
$N = 1155$ rev/min

Sketch the following:

(a) Head versus flow characteristics with one fan in operation and with both fans in operation. In each case identify the operating point of the system.

Calculate the following:

(b) Volume flow rate of exhaust gas with only one fan in operation.

(c) Volume flow rate of exhaust gas with both fans in operation.

(d) Load possible on the boiler with one fan in operation (as a percentage of maximum load as calculated in (c) above).

(e) Speed requirement of both fans to give together the same load as is possible with only one fan in operation (as in (b) above).

[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 BLADE DESIGN

PART I VANE CHARACTERISTICS

Describe with the aid of sketches the difference between forward curved and backward curved vanes in a centrifugal pump or fan. Explain how these configurations affect the velocity of the fluid leaving the impeller and hence the pressure rise in the diffuser. Sketch a typical head versus flow diagram (graph) for forward and backward curved vanes in a pump or fan.

(5 marks)

PART II NUMBER OF VANES

Centrifugal pump impellers are usually designed for an optimum number of vanes. Explain the effect on performance of a pump having both too many vanes or too few vanes. Explain the reasons for these effects.

(5 marks)

[10 marks]

QUESTION 7 PUMP AND TURBINE CAVITATION AND SETTING

PART I PHENOMENON OF 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. Show the process of collapse and surface damage with the aid of sketches. Clarify with reasons which parts of pumps and turbines could be damaged due to cavitation.

(5 marks)

PART II PUMP AND TURBINE SETTING

Explain the importance of pump and turbine setting (elevation of machine with respect to lower water surface level). Identify and clarify what parameters need to be taken into account in determining the required setting. Explain how the setting may be different for different types of pumps and turbines. Explain the consequences of incorrect setting.

(5 marks)

[10 marks]

QUESTION 8 FAN CONTROL

Refer to the Examination Paper Attachments Page 11 **Fan Control Methods**.

The diagrams show (as dotted lines) the system and fan characteristics and operating point for normal design conditions of a typical air flow system.

The volume flow rate through the system can be controlled (reduced) by three methods:

- Dampers in the ducting which may be progressively closed.
- Vanes at the fan inlet which can create increasing pre-whirl.
- Speed of driving motor which can progressively reduce fan speed.

(a) For each of these three methods show on the diagrams how the system or fan characteristics change to give a new operating point.

(i) Control by duct dampers.
(ii) Control by inlet vanes.
(iii) Control by fan speed.

In each case show the new operating point.

Return Page 11 with the examination answer booklet.

(5 marks)

(b) Explain, with reference to the diagrams, why and how the flow is reduced in each case.

(i) Effect of duct dampers.
(ii) Effect of inlet vanes.
(iii) Effect of fan speed.

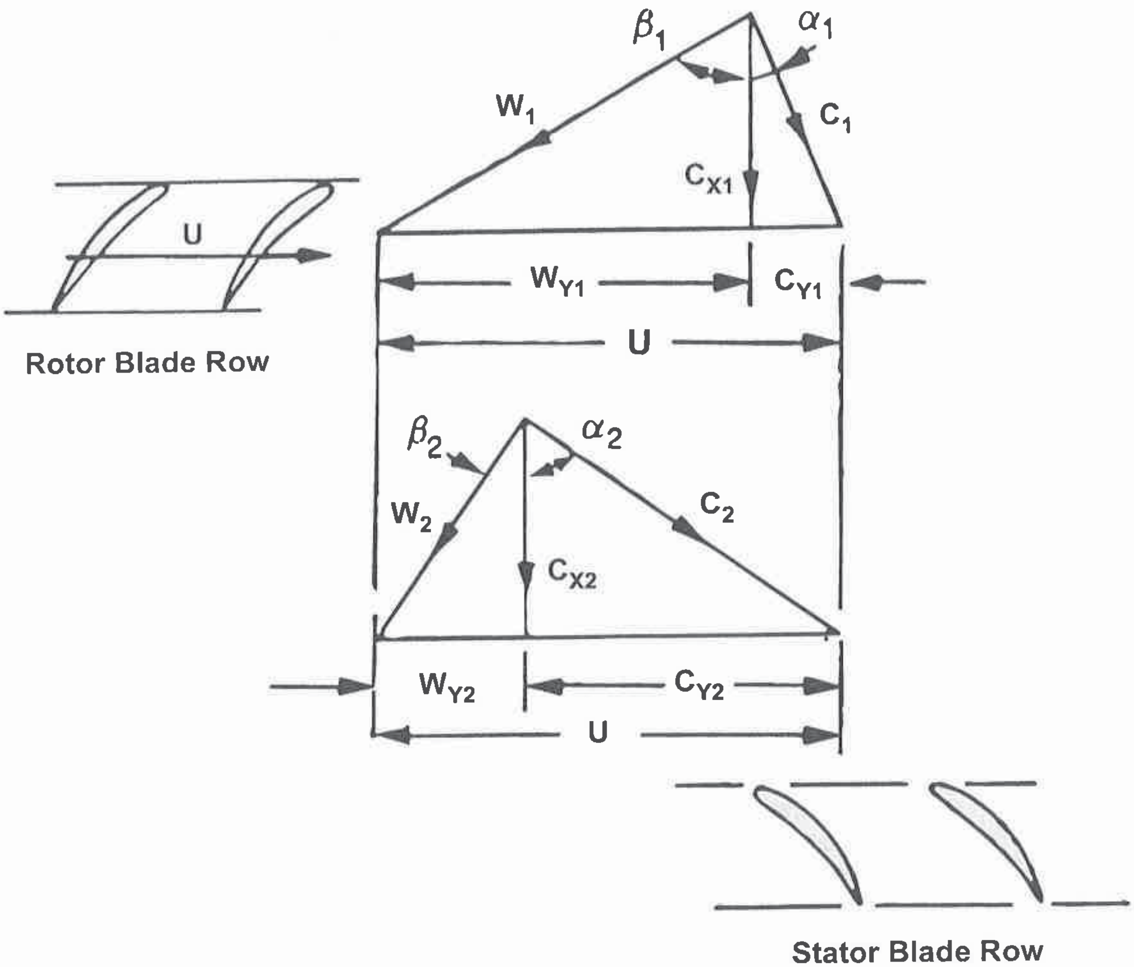
Hint: Sketches of velocity diagrams may be useful in the explanation for (ii).

(5 marks)

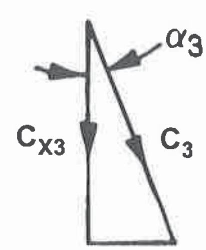
[10 marks]

EXAMINATION PAPER ATTACHMENTS

QUESTION 2 COMPRESSOR VELOCITY DIAGRAM



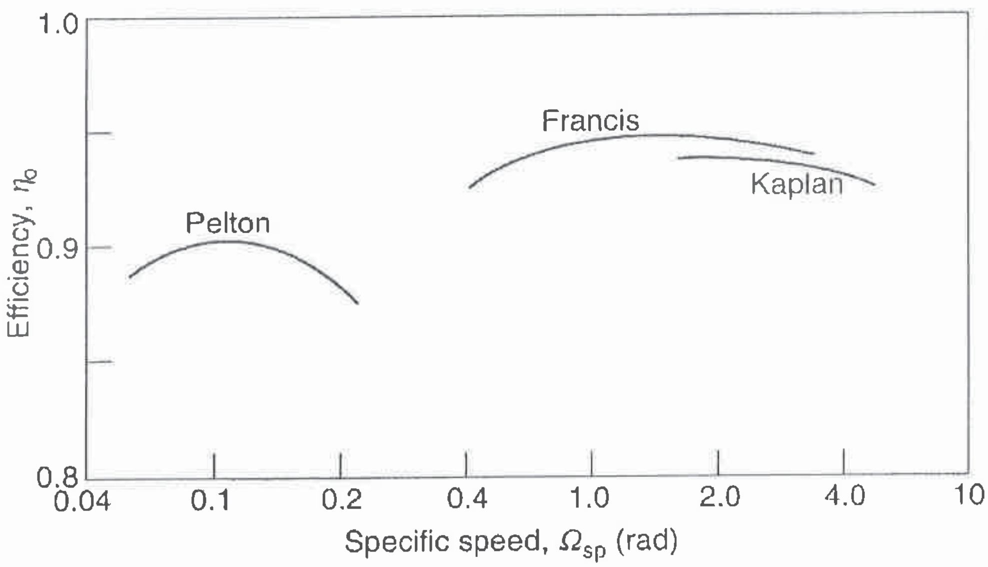
U Blade velocity
C_1 Rotor blade absolute inlet velocity
W_1 Rotor blade relative inlet velocity
C_2 Rotor blade absolute outlet velocity
W_2 Rotor blade relative outlet velocity
C_3 Stator blade absolute outlet velocity



EXAMINATION PAPER ATACHMENTS

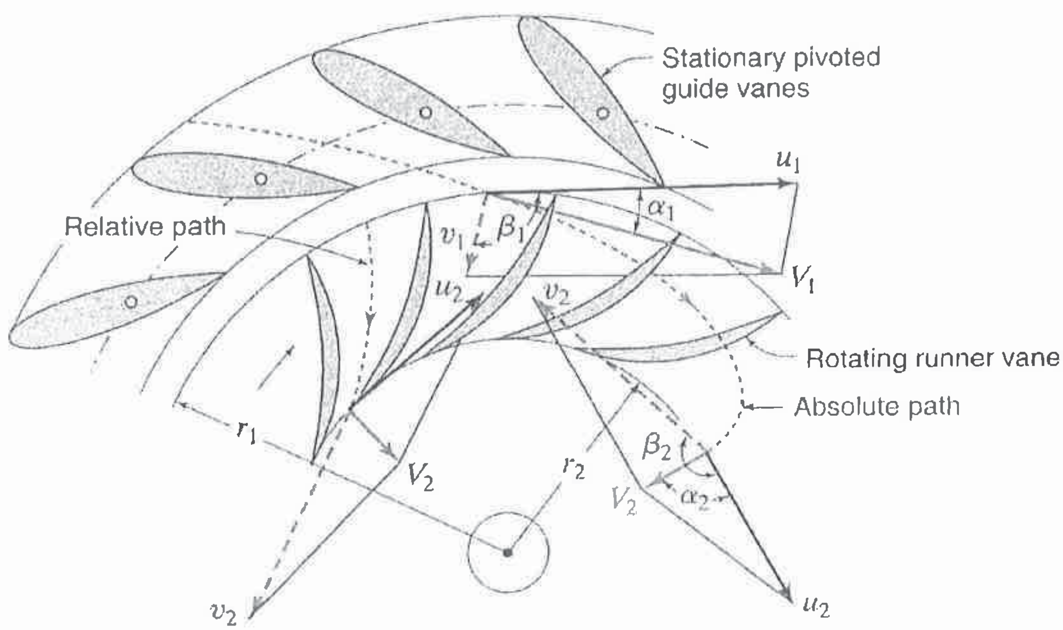
QUESTION 3 HYDRO TURBINE PARAMETERS

Turbine Efficiencies



Typical design point efficiencies for Pelton, Francis and Kaplan turbines

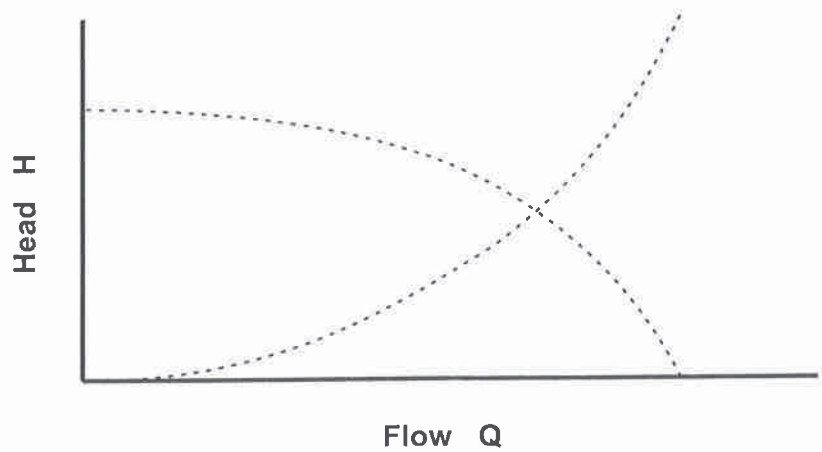
Velocity Diagram



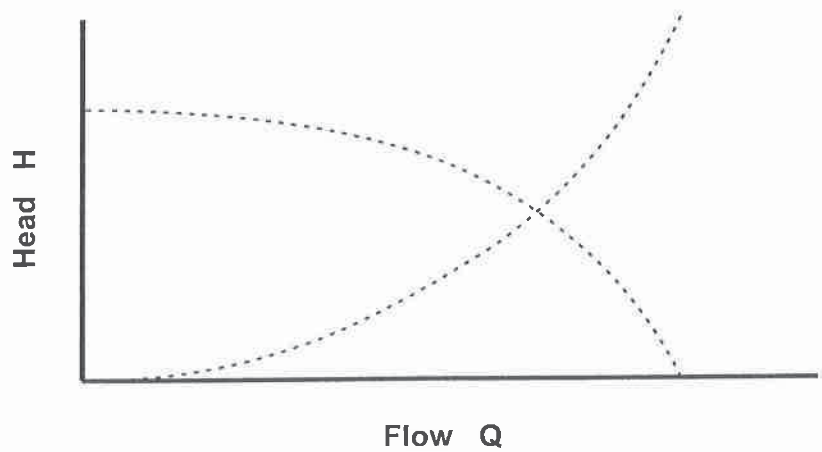
Velocity vectors for radial inward flow hydraulic turbine (Francis type)

QUESTION 8 FAN CONTROL METHODS **NAME ....**

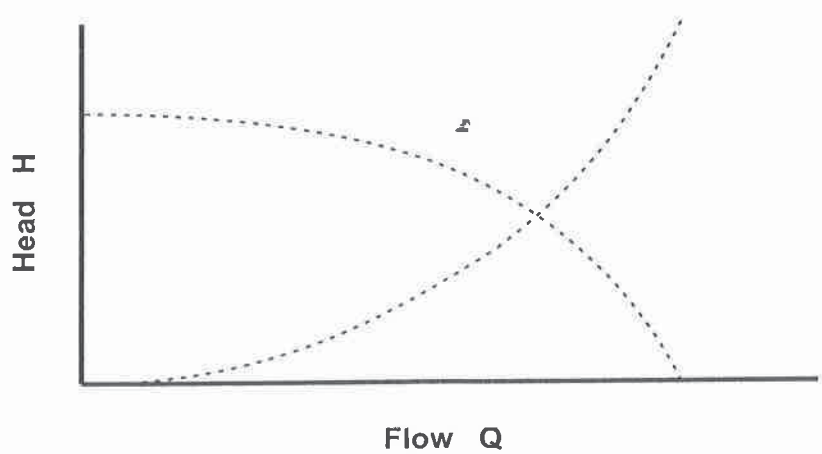
(i) Control by duct dampers



(ii) Control by inlet vanes



(iii) Control by fan speed



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	
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/kgEC	
Specific heat of air:	$c_v = 0.718$ kJ/kgEC	
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:	$w = [(V_1^2{}_{absolute} - V_2^2{}_{absolute}) + (V_2^2{}_{relative} - V_1^2{}_{relative})] / 2$
Work:	$w = (V_{S1}\cos\theta - V_{S2}\cos\delta)\, V_{blade}$
Power:	$P = wM$
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	$h_1 + \frac{1}{2}W_1^2 = h_2 + \frac{1}{2}W_2^2$
Stator Enthalpy Change	$h_2 + \frac{1}{2}C_2^2 = h_3 + \frac{1}{2}C_3^2$
Isentropic Equation	$(T_3/T_1) = (p_3/p_1)^{(k-1)/k}$

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: $\tau = \rho Q\,(r_2 V_{2T} - r_1 V_{1T})$
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: $(1 - \eta_P)/(1 - \eta_M) \approx (D_M/D_P)^{1/5}$

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