NATIONAL EXAMINATIONS

December 2014

07-MEC-B3 ENERGY CONVERSION AND POWER GENERATION

Three hours duration

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Notes to Candidates

1. This is a Closed Book examination.

2. Examination paper consists of two Sections. Section A is Calculative with four (4) questions and Section B is Descriptive with two (2) questions.

3. Note that Question 2 is on two pages.

3. Do three (3) questions (including all parts of each question) from Section A (Calculative) and one (1) question from Section B (Descriptive).

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

5. All questions are of equal value. (Each 15 marks).

6. If doubt exists as to the interpretation of any question or in the event of missing data, the candidate is urged to submit, with the answer paper, a clear statement of any assumptions made.

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

8. Reference data for particular questions are given on pages 9 to 13. All pages used are to be returned with the answer booklet showing where data has been obtained.

9. Reference formulae and constants are given on pages 14 to 17.

10. Steam Tables from "Thermodynamics and Heat Power" are provided.
SECTION A  CALCULATIVE QUESTIONS

QUESTION 1  GAS TURBINE MODULAR HELIUM REACTOR

Refer to the Examination Paper Attachments Page 9 Gas Turbine Modular Helium Reactor. Refer to General Constants on Page 15 for specific heats.

The diagram shows a schematic of the gas circuit of a high temperature nuclear reactor of the Gas Turbine Modular type. The following terminal conditions apply:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium pressure at compressor inlet</td>
<td>2 MPa</td>
</tr>
<tr>
<td>Helium pressure at intercooler</td>
<td>4 MPa</td>
</tr>
<tr>
<td>Helium pressure at compressor outlet</td>
<td>7 MPa</td>
</tr>
<tr>
<td>Helium temperature at compressor inlet</td>
<td>30°C</td>
</tr>
<tr>
<td>Helium temperature after intercooler</td>
<td>30°C</td>
</tr>
<tr>
<td>Helium temperature at turbine inlet</td>
<td>850°C</td>
</tr>
<tr>
<td>Terminal temperature differences in recuperating heat exchanger</td>
<td>20°C</td>
</tr>
<tr>
<td>Terminal temperature differences in heat rejection heat exchangers</td>
<td>15°C</td>
</tr>
<tr>
<td>Compressor efficiency</td>
<td>90%</td>
</tr>
<tr>
<td>Turbine efficiency</td>
<td>85%</td>
</tr>
<tr>
<td>Electrical power output</td>
<td>250 MW</td>
</tr>
</tbody>
</table>

The differences in the terminal temperatures are the same at each end of the respective heat exchangers.

Assume negligible pressure loss in the gas circuit and no mechanical nor electrical losses.

(a) Sketch a temperature-entropy diagram for the gas circuit in the space provided on Page 9. Identify key points by number to correspond with the flow diagram. Show terminal temperature differences. (3)

(b) Calculate the temperatures at all key points in the circuit as identified in the diagram on Page 9. (7)

(c) Calculate the thermodynamic cycle efficiency. (2)

(d) Calculate the required flow rate of helium to give the specified power output. (1)

(e) Calculate the required flow rate of cooling water to give the necessary rate of heat rejection. (2)

[ 15 marks ]
QUESTION 2  STEAM CYCLE AND COAL FIRED PLANT

PART I  STEAM CYCLE EFFICIENCY

Refer to the Examination Paper Attachments Page 10 Regenerative Feedwater Heating.

An ideal Rankine Cycle operates between a pressure of 6 MPa and 0.004 MPa with superheating to 400°C. Steam is extracted from the turbine at 0.6 MPa for feedwater heating in a direct contact feedwater heater which operates at this pressure. Complete mixing of the steam and water occurs. A condensate extraction pump is required to pump from the condenser pressure of 0.004 MPa to 0.6 MPa and a boiler feedwater pump to pump from 0.6 MPa to the boiler pressure of 6 MPa. Isentropic conditions prevail in the pumps and turbine. Use the enthalpies given in the table in the attachments.

(a) Sketch the process on the T-s diagram provided in the attachments. Label all key points by number to correspond with the flow diagram.

(b) Determine the fractional mass flow of steam required for feedwater heating.

(c) Calculate the cycle efficiency with the feedwater heater in operation.

This question is continued on the next page
Question 2  Continued

PART II COAL FIRED PLANT

A coal fired power plant with an electrical output of 600 MW has the following operating parameters:

- Steam cycle efficiency: 41%
- Boiler thermal efficiency: 94%
- Electrical generation efficiency: 96%
- Coal calorific value (as received): 35 000 kJ/kg
- Coal ash content: 6%
- Cooling water inlet temperature: 13°C
- Cooling water temperature rise: 11°C (maximum)
- Cooling water specific heat: 4.19 kJ/kg°C
- Cooling water density: 1025 kg/m³

Under full load conditions determine the following:

(a) Required mass flow rate and volume flow rate of cooling water so as not to exceed the maximum permitted cooling water temperature rise.

   (2)

(b) Required mass flow rate of coal and amount of ash produced per day.

   (3)

   (5 marks)

   [15 marks]
QUESTION 3 FEEDWATER HEATERS AND CONDENSERS

PART I BELLEDUNE FEEDWATER HEATER

In a boiler plant the feedwater entering the boiler is progressively preheated in a series of feedwater heaters which draw heating steam from the steam turbine. At Belledune Generating Station in the last stage of feedwater heating the feedwater temperature is increased from 230°C to 280°C while the pressure remains constant at 20 MPa. The heating steam enters at 400°C (superheated), is condensed and leaves as water at 240°C (subcooled) while the pressure remains constant at 5 MPa. If the feedwater flow is 350 kg/s calculate the required steam flow. Use Steam Tables as provided. The values given in this question have been rounded to facilitate the use of steam tables. Note that a sketch to properly identify the key points around the heater is required.

( 5 marks )

PART II CONDENSER PERFORMANCE

Refer to the Examination Paper Attachments Page 11 Koeberg Condenser and Page 12 Temperature Profiles. Note that 1 bar = 0.1 MPa.

Consider the condenser to be operating under the given conditions. Sketch, in dotted lines on each of the given axes, the design temperature profile, with specified temperatures for both cooling water and steam, along the condenser tubes (from inlet to outlet). Show clearly the change in cooling water temperature $\Delta T$ and the difference between the average cooling water temperature and the condensing steam temperature $\theta$.

For the following no detailed calculations are required and temperatures should be rounded to the nearest 1°C. The estimates should be based on average temperature differences (not log mean temperature differences) and in each case the new values for $\Delta T$ and $\theta$ should be stated.

If the conditions are changed as indicated below, sketch, in solid lines on the given axes, the anticipated temperature profiles, with numerical values for both cooling water and steam, across the condenser for each of the following conditions:

(a) Cooling water inlet temperature increased to 18°C.

(b) Turbine load reduced to one quarter of its original value.

(c) Cooling water flow reduced to one half of its original value which also results in the overall heat transfer coefficient being reduced to 70% of its original value.

(d) Overall heat transfer coefficient reduced by 20% due to fouling of tubes.

( 10 marks )

[ 15 marks ]
QUESTION 4  BELLEDUNE HEAT BALANCE DIAGRAM

Refer to the Examination Paper Attachments Page 13 Heat Balance Diagram for Belledune Generating Station.

At the rated electrical output of 430 MW determine the following:

(a) Steam cycle efficiency based on boiler heat input and electrical output.  
    (3)

(b) Shaft power output of high pressure turbine.  
    (4)

(c) Steam power input to boiler feed water pump turbine based on steam conditions.  
    (2)

(d) Shaft power input to boiler feedwater pump based on enthalpy rise (Δh) in the pump.  
    (2)

(e) Hydraulic power output of the boiler feedwater pump based on pressure rise \( P_0 \) in the pump. The density of water at the pump is 912 kg/m³.  
    (3)

(f) Feedwater pump efficiency.  
    (1)

[ 15 marks ]
SECTION B DESCRIPTIVE QUESTIONS

Descriptive questions should be answered in essay form with sketches, if appropriate, and taking approximately one full page for every 5 marks. A full page means approximately 250 words unless diagrams take the place of some words.

While Question 5 lists several aspects, more emphasis may be put on some aspects and less on others provided an overall comprehensive answer is given as required by the above.

QUESTION 5 NUCLEAR AND WIND POWER

Generation of electric power without the emission of carbon dioxide is possible by the use of nuclear energy or wind energy both of which are proven technologies. Suppose a large power utility has to increase its generation capacity by installing approximately 2000 MW to meet the anticipated electricity demand in 2024. Both nuclear power and wind power are options in this particular circumstance. Discuss the suitability of each for this application by addressing the following aspects:

- Number of generating units required
- Land and space requirements
- Impact on the environment
- Reliability of power supply
- Likely capacity factor
- Ability to meet varying daily load demand
- Flexibility of operation (load variation)
- Effluents and emissions
- Construction benefits and constraints
- Connections with grid system
- Maintenance requirements

As a conclusion make an appropriate recommendation. Relative costs do not have to be considered.

This question should be answered in essay form in approximately 800 words.

[15 marks]
QUESTION 6  CYCLE PERFORMANCE ENHANCEMENT

Basic thermodynamic cycles such as the Rankine, Brayton and Otto do not convert heat into work at the optimum level and their performance can be improved by certain enhancements, either to the cycle itself or to the output from the cycle, which ultimately result in better fuel economy. For each of the following explain in detail the fundamental principles which enhance the performance of the cycle or engine.

Where appropriate cycle diagrams or flow diagrams should be included to illustrate the enhancement.

(a)  Feedwater heating in a steam cycle as used in a large scale electric power generating plant.  
     ( 5 marks )

(b)  Recuperative heating in a gas turbine where exhaust gas is used to preheat combustion air.  
     ( 5 marks )

(c)  Turbocharging in a gasoline powered spark ignition automotive engine or a large diesel powered compression ignition engine (compared with a conventional or naturally aspirated engine).  
     ( 5 marks )

     [ 15 marks ]
QUESTION 1  GAS TURBINE MODULAR HELIUM REACTOR

![Gas Circuit Diagram]
### QUESTION 2 PART I REGENERATIVE FEEDWATER HEATING

![Diagram of regenerative feedwater heating system]

<table>
<thead>
<tr>
<th>Point</th>
<th>Pressure (MPa)</th>
<th>Temperature (°C)</th>
<th>Enthalpy (kJ/kg)</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.004</td>
<td>29</td>
<td>121</td>
<td>saturated water</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>29</td>
<td>122</td>
<td>subcooled water</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
<td>159</td>
<td>671</td>
<td>saturated water</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>160</td>
<td>677</td>
<td>subcooled water</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>400</td>
<td>3177</td>
<td>superheated steam</td>
</tr>
<tr>
<td>6</td>
<td>0.6</td>
<td>159</td>
<td>2662</td>
<td>wet mixture</td>
</tr>
<tr>
<td>7</td>
<td>0.004</td>
<td>29</td>
<td>1970</td>
<td>wet mixture</td>
</tr>
</tbody>
</table>
Steam flow rate  2996 t/h
Water make-up flow rate  9 t/h
Cooling water flow rate  141 000 t/h
Cooling water inlet temperature  13°C
Cooling water outlet temperature  24°C
Cooling water density  1.025
Cooling water friction head loss  4.7 m
Mean steam velocity at tube bank  92 m/s
Cooling water velocity inside tubes  2 m/s
Number of tubes  76968
Number of support plates  14 (per bundle)
Tube material  titanium
Cooling surface area  57 426 m²
Tube overall length  12.84 m
Tube effective length  12.50 m
Tube diameter (OD)  19 mm
Tube wall thickness (normal tubes)  0.5 mm
Tube wall thickness (impact tubes)  0.6 mm
tube configuration  diagonal array
Tube pitch across array  26 mm
Tube pitch along array  45 mm
Tube fixing method  expanding
Tube mass  132 t
Total volume under vacuum  7500 m³
Steam inlet pressure  0.043 bar abs
Steam inlet temperature  30°C
Terminal temperature difference  6°C
Condenser hotwell capacity  700 m³ (approx.)
Number of water boxes (inlet and outlet)  12
Water box internal lining  neoprene
Condenser shell thickness  18 mm
Tube plate thickness  25 mm
Support plate thickness  12 mm
Condenser length  43 m (approx.)
Condenser width  25 m (approx.)
Condenser mass without LP Heaters  1267 t
QUESTION 3 PART II  TEMPERATURE PROFILES

Show initial conditions as dotted lines on each diagram
Show new conditions for each case as solid lines
Give temperatures on axes
Show basic calculations and new values for $\Delta T$ and $\theta$ below each diagram

(a) Increase in cooling water temperature
(b) Reduction in turbine load

(c) Reduction in cooling water flow
(d) Reduction in heat transfer coefficient
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Flow area, Surface area</td>
<td>m²</td>
</tr>
<tr>
<td>c_p</td>
<td>Specific heat at constant pressure</td>
<td>J/kg°C</td>
</tr>
<tr>
<td>c_v</td>
<td>Specific heat at constant volume</td>
<td>J/kg°C</td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
<td>m</td>
</tr>
<tr>
<td>E</td>
<td>Energy</td>
<td>J</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational acceleration</td>
<td>m/s²</td>
</tr>
<tr>
<td>h</td>
<td>Specific enthalpy</td>
<td>J/kg</td>
</tr>
<tr>
<td>k</td>
<td>Ratio of specific heats</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
<td>m</td>
</tr>
<tr>
<td>m</td>
<td>Fractional mass flow rate</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>Mass</td>
<td>kg</td>
</tr>
<tr>
<td>M</td>
<td>Mass flow rate</td>
<td>kg/s</td>
</tr>
<tr>
<td>p</td>
<td>Pressure</td>
<td>Pa (N/m²)</td>
</tr>
<tr>
<td>q</td>
<td>Heat transferred</td>
<td>J/kg</td>
</tr>
<tr>
<td>Q</td>
<td>Heat</td>
<td>J</td>
</tr>
<tr>
<td>Q</td>
<td>Volume flow rate</td>
<td>m³/s</td>
</tr>
<tr>
<td>R</td>
<td>Specific gas constant</td>
<td>J/kg K</td>
</tr>
<tr>
<td>s</td>
<td>Entropy</td>
<td>J/kg K</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>u</td>
<td>Specific internal energy</td>
<td>J/kg</td>
</tr>
<tr>
<td>U</td>
<td>Overall heat transfer coefficient</td>
<td>W/m²°C (J/sm²°C)</td>
</tr>
<tr>
<td>v</td>
<td>Specific volume</td>
<td>m³/kg</td>
</tr>
<tr>
<td>V</td>
<td>Velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>w</td>
<td>Specific work</td>
<td>J/kg</td>
</tr>
<tr>
<td>W</td>
<td>Work</td>
<td>J</td>
</tr>
<tr>
<td>x</td>
<td>Length</td>
<td>m</td>
</tr>
<tr>
<td>z</td>
<td>Elevation</td>
<td>m</td>
</tr>
<tr>
<td>η</td>
<td>Efficiency</td>
<td></td>
</tr>
<tr>
<td>θ</td>
<td>Nozzle angle</td>
<td></td>
</tr>
<tr>
<td>Δθ</td>
<td>Temperature difference between fluids</td>
<td>°C</td>
</tr>
<tr>
<td>μ</td>
<td>Dynamic viscosity</td>
<td>Ns/m²</td>
</tr>
<tr>
<td>ν</td>
<td>Kinematic viscosity</td>
<td>m²/s</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td>kg/m³</td>
</tr>
<tr>
<td>T</td>
<td>Thrust</td>
<td>N</td>
</tr>
<tr>
<td>Ω</td>
<td>Heat transfer rate</td>
<td>J/s</td>
</tr>
</tbody>
</table>
GENERAL CONSTANTS

Acceleration due to gravity: \( g = 9.81 \text{ m/s}^2 \)  
Specific heat of air: \( c_p = 1.005 \text{ kJ/kg}^\circ\text{C} \)

Atmospheric pressure: \( p_{\text{atm}} = 100 \text{ kPa} \)  
Specific heat of air: \( c_v = 0.718 \text{ kJ/kg}^\circ\text{C} \)

Density of water: \( \rho_{\text{water}} = 1000 \text{ kg/m}^3 \)  
Specific heat of helium: \( c_p = 5.193 \text{ kJ/kg}^\circ\text{C} \)

Specific heat of water: \( c_p = 4.190 \text{ kJ/kg}^\circ\text{C} \)  
Specific heat of helium: \( c_v = 3.117 \text{ kJ/kg}^\circ\text{C} \)

THERMODYNAMICS REFERENCE EQUATIONS

Basic Thermodynamics

- First Law: \( dE = \delta Q - \delta W \)
- Enthalpy: \( h = u + pv \)
- Continuity: \( \rho v A = \text{constant} \)
- Flow Work: \( w = \Delta(pv) \)
- Energy Equation: \( zg + \frac{v^2}{2} + u + pv + \Delta w + \Delta q = \text{constant} \)
- Entropy: \( \Delta s = \Sigma \delta q / T \) (reversible conditions)

Ideal Gas Relationships

- Gas Law: \( pv = RT \)
- Specific Heat at Constant Pressure: \( c_p = \Delta h / \Delta T \)
- Specific Heat at Constant Volume: \( c_v = \Delta u / \Delta T \)
- Gas Constant: \( R = c_p - c_v \)
- Specific Heat Ratio: \( k = c_p / c_v \)
- Isentropic Relations: \( \frac{p_1}{p_2} = \left(\frac{v_2}{v_1}\right)^k = \left(\frac{T_1}{T_2}\right)^{k(\gamma-1)} \)
FLUID MECHANICS REFERENCE EQUATIONS

Fluid Mechanics

Continuity Equation: \( p_1V_1A_1 = p_2V_2A_2 = M \)

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: \( F = p_1A_1 - p_2A_2 - \rho VA(V_2 - V_1) \) (one dimensional)

Steam Turbines

Nozzle Equation: \( h_1 - h_2 = (V_2^2 - V_1^2)/2 \)

Work: \( w = [(V_1^2_{\text{absolute}} - V_2^2_{\text{absolute}}) + (V_2^2_{\text{relative}} - V_1^2_{\text{relative}})]/2 \)

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: \( F = M(V_{\text{jet}} - V_{\text{aircraft}}) \)

Thrust Power: \( FV_{\text{aircraft}} = M(V_{\text{jet}} - V_{\text{aircraft}})V_{\text{aircraft}} \)

Jet Power: \( P = M(V_{\text{jet}}^2 - V_{\text{aircraft}}^2)/2 \)

Propulsion Efficiency: \( \eta_p = 2V_{\text{aircraft}}/(V_{\text{jet}} + V_{\text{aircraft}}) \)

Wind Turbine

Maximum Ideal Power: \( P_{\text{max}} = 8 \rho AV_1^3/27 \)
HEAT EXCHANGER REFERENCE EQUATIONS

Heat transferred between fluids
\[ \dot{\Omega} = UA \theta \]

Heat gained or lost by fluids
\[ \dot{\Omega} = M \Delta h \]
\[ \dot{\Omega} = M c_p \Delta T \]
\[ \dot{\Omega} = \rho Q \Delta T \]

NUCLEAR REFERENCE EQUATIONS

Number of nuclei per gram of material
\[ N = \frac{N_A}{M} \]

Number of fissile nuclei per cm\(^3\) of material
\[ N_f = \gamma \left( \frac{N_A}{M} \right) \rho \]

Heat release rate in nuclear fuel
\[ q^* = \phi N_f \sigma_f E_f \]

Nomenclature

\begin{align*}
N & : \text{number of nuclei (number/g)} \\
N_A & : \text{Avogadro's Number} \\
M & : \text{molecular weight} \\
\gamma & : \text{fuel enrichment} \\
\rho & : \text{density (g/cm}^3) \\
q^* & : \text{heat release rate (J/cm}^3) \\
\phi & : \text{neutron flux (neutrons/cm}^2\text{s)} \\
N_f & : \text{number of fissile nuclei (number/cm}^3) \\
\sigma_f & : \text{cross section (barn) (1 barn = 10}^{-24}\text{ cm}^2) \\
E_f & : \text{energy release per fission of one atom} \\
\end{align*}

Avogadro's Number
\[ N_A = 0.602 \times 10^{24} \text{ atoms/mole} \]