

PRACTICE PAPER — NATIONAL CERTIFICATION EXAMINATION FOR ENERGY MANAGERS & ENERGY AUDITORS

PAPER – 4: ENERGY PERFORMANCE ASSESSMENT FOR EQUIPMENT AND UTILITY SYSTEMS

(For Energy Auditors only — Open book: only the official BEE Guidebook Book 4 is permitted)

Question code: 5P4CEA001 – 5P4CEA016 | SOLUTIONS & MODEL ANSWERS

Duration: 2½ HRS Max. Marks: 100 Pass: 50% marks in the paper

General instructions:

- Please check that this question paper contains 16 questions
- The question paper is divided into three sections
- All questions in all three sections are compulsory (N-4: answer any ONE alternative)
- All parts of a question should be answered at one place
- Time management guidance: Section - I & II: 10 minutes each, Section - III: 130 minutes
- Use of a non-programmable scientific calculator is permitted; show Given, Formula, Substitution with units and Result for every numerical

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Section - I: BRIEF QUESTIONS

Marks: 10 x 1 = 10

- (i) Answer all Ten questions
- (ii) Each question carries One mark
- (iii) State whether each statement is True or False

1. A 10 TPH oil-fired boiler in a Ludhiana dyeing unit has a radiation and convection loss of 1.2 % of fuel input at full load (fuel input 7.5×10^6 kcal/h). The shell temperature, and so this loss in kcal/h, hardly changes with load. When the boiler runs at 40 % load (fuel input 3.0×10^6 kcal/h), this loss rises to about 3 % of input.

[5P4CEA001 | Chapter 1: Boilers | Boiler radiation and convection loss at part load]

Answer: TRUE (1 mark)

Given: Loss at full load = 1.2 % of 7.5×10^6 kcal/h ($\approx 8,721$ kW); loss in kcal/h constant; part-load input = 3.0×10^6 kcal/h ($\approx 3,488$ kW).

Formula: Loss (kcal/h) = 0.012 $\times$ full-load input; part-load loss % = loss/part-load input $\times$ 100.

Substitution: Loss = $0.012 \times 7.5 \times 10^6 = 90,000$ kcal/h (≈ 105 kW); part-load % = $90,000 / (3.0 \times 10^6) \times 100$.

Result: Loss = 3.0 % of input at 40 % load, i.e. 1.8 points more than at full load – true. Fixed losses are why an oversized or lightly loaded boiler is inefficient; running fewer boilers at higher load is the usual remedy.

Ref: BEE Guidebook Book 4, Ch. 1 (Boilers).

2. A shell-and-tube heater in a Pune pharmaceutical plant heats process water from 30 °C to 80 °C with steam condensing at 120 °C. Water-side scale has cut the overall coefficient U to 75 % of its clean value. To keep the same water flow and outlet temperature without cleaning, the steam condensing temperature must be raised to about 130 °C.

[5P4CEA002 | Chapter 4: Heat Exchangers | Fouled steam heater – steam temperature needed to hold the duty]

Answer: FALSE (1 mark)

Given: Water 30 → 80 °C (duty unchanged); clean steam temperature 120 °C; $U_{\text{fouled}} = 0.75 U_{\text{clean}}$; same area.

Formula: $Q = U A \Delta T_{\text{lm}}$, so $\Delta T_{\text{lm,new}} = \Delta T_{\text{lm,clean}}/0.75$; with condensing steam, $\Delta T_{\text{lm}} = (t_{\text{out}} - t_{\text{in}})/\ln[(T_{\text{s}} - t_{\text{in}})/(T_{\text{s}} - t_{\text{out}})]$.

Substitution: $\Delta T_{\text{lm,clean}} = 50/\ln(90/40) = 61.66$ °C; needed = $61.66/0.75 = 82.21$ °C; solve $50/\ln[(T_{\text{s}} - 30)/(T_{\text{s}} - 80)] = 82.21 \rightarrow (T_{\text{s}} - 30)/(T_{\text{s}} - 80) = 1.8371$.

Result: $T_{\text{s}} = 139.7$ °C – false (about 140 °C, not 130 °C). Raising steam pressure to compensate for fouling also raises trap and flash losses, so cleaning is normally cheaper.

Ref: BEE Guidebook Book 4, Ch. 4 (Heat Exchangers).

3. A 75 kW motor in a Rajkot foundry drives a sand-plant blower that absorbs a steady 22 kW, so the motor runs at about 29 % load where its efficiency is 86.0 %. A 30 kW IE3 motor would run at 73 % load with an efficiency of 92.5 %. For 6,000 h/year of operation, the replacement saves more than 15,000 kWh a year.

[5P4CEA003 | Chapter 5: Electric Motors and Variable Speed Drives | Right-sizing an oversized motor – part-load efficiency gain]

Answer: FALSE (1 mark)

Given: Shaft load = 22 kW; $\eta(75 \text{ kW at } 29 \% \text{ load}) = 86.0 \%$; $\eta(30 \text{ kW at } 73 \% \text{ load}) = 92.5 \%$; 6,000 h/year.

Formula: Input = shaft load/ η ; saving = (input_old – input_new) × hours.

Substitution: Input_old = $22/0.860 = 25.58$ kW; input_new = $22/0.925 = 23.78$ kW; saving = $1.80 \times 6,000$.

Result: Saving = 1.80 kW, i.e. 10,786 kWh a year – below 15,000 kWh, so the statement is false. Right-sizing is still worthwhile when the old motor fails or needs rewinding, and the smaller motor also draws far less magnetising kVAr, improving the power factor.

Ref: BEE Guidebook Book 4, Ch. 5 (Electric Motors and Variable Speed Drives).

4. A Muzaffarnagar paper mill's back-pressure cogeneration plant burns 10,000 kg/h of coal (GCV 4,000 kcal/kg), generates 6,000 kW and supplies 22×10^6 kcal/h of process heat as exhaust steam. A separate process boiler would make the same heat at 80 % efficiency. The fuel chargeable to power is about 2,080 kcal/kWh, well below the 2,450 kcal/kWh of a coal-fired utility station.

[5P4CEA004 | Chapter 3: Cogeneration Systems | Fuel chargeable to power in a back-pressure cogeneration plant]

Answer: TRUE (1 mark)

Given: Coal = 10,000 kg/h × 4,000 kcal/kg ($\approx 16,747$ kJ/kg); power = 6,000 kW; process heat = 22×10^6 kcal/h (≈ 25.6 MW); separate boiler $\eta = 80 \%$.

Formula: FCP = (total fuel heat – process heat/ η_{boiler})/power.

Substitution: Fuel heat = 4,00,00,000 kcal/h (≈ 46.5 MW); fuel the process heat would need alone = $22 \times 10^6/0.80 = 2,75,00,000$ kcal/h (≈ 32.0 MW); FCP = $(4,00,00,000 - 2,75,00,000)/6,000$.

Result: FCP = 2,083 kcal/kWh ($\approx 8,721$ kJ/kWh) – true. Only the extra fuel burnt above what the process would need anyway is charged to power, which is why cogeneration power is far cheaper in fuel than condensing utility power.

Ref: BEE Guidebook Book 4, Ch. 3 (Cogeneration Systems).

5. In a 210 MW unit in Chhattisgarh, the air preheater exit gas temperature has risen by 20 °C because of fouling. Dry flue gas is 6.2 kg/kg coal, its specific heat 0.23 kcal/kg °C and the coal GCV 3,600 kcal/kg. The boiler efficiency was 86.0 % and the unit heat rate 2,450 kcal/kWh. The heat rate rises by roughly 23 kcal/kWh.

[5P4CEA005 | Chapter 11: Thermal Power Station | Rise in APH exit gas temperature – effect on unit heat rate]

Answer: TRUE (1 mark)

Given: $m_{\text{dfg}} = 6.2$ kg/kg coal; $C_p = 0.23$ kcal/kg °C (≈ 0.963 kJ/kg·K); $\Delta T = 20$ °C; GCV = 3,600 kcal/kg ($\approx 15,072$ kJ/kg); $\eta_{\text{b}} = 86.0 \%$; HR = 2,450 kcal/kWh ($\approx 10,258$ kJ/kWh).

Formula: Extra dry flue gas loss = $m \times C_p \times \Delta T / GCV \times 100$; new HR = $HR \times \eta_{old} / \eta_{new}$.

Substitution: Extra loss = $6.2 \times 0.23 \times 20 / 3,600 \times 100 = 0.792\%$; $\eta_{new} = 86.0 - 0.792 = 85.21\%$; $HR_{new} = 2,450 \times 86.0 / 85.21$.

Result: $HR_{new} = 2,472.8 \text{ kcal/kWh} (\approx 10,353 \text{ kJ/kWh})$, a rise of $22.8 \text{ kcal/kWh} (\approx 95.5 \text{ kJ/kWh})$ – true. Exit gas temperature is a key controllable parameter: soot blowing and APH basket cleaning repay quickly.

Ref: BEE Guidebook Book 4, Ch. 11 (Thermal Power Station).

6. In a Jamshedpur blast furnace, the hot stoves heat $3,00,000 \text{ Nm}^3/\text{h}$ of cold blast from 150°C to $1,150^\circ\text{C}$ (mean specific heat $0.335 \text{ kcal/Nm}^3^\circ\text{C}$) while burning $1,45,000 \text{ Nm}^3/\text{h}$ of BF gas with a calorific value of 850 kcal/Nm^3 . The stove efficiency exceeds 90 %.

[5P4CEA006 | Chapter 12: Steel Industry | Blast furnace hot stove – thermal efficiency]

Answer: FALSE (1 mark)

Given: Blast = $3,00,000 \text{ Nm}^3/\text{h}$; $C_p = 0.335 \text{ kcal/Nm}^3 (\approx 0.0014 \text{ MJ/Nm}^3)^\circ\text{C}$; $150 \rightarrow 1,150^\circ\text{C}$; BF gas = $1,45,000 \text{ Nm}^3/\text{h}$ at $850 \text{ kcal/Nm}^3 (\approx 3.56 \text{ MJ/Nm}^3)$.

Formula: $\eta_{stove} = \text{heat given to blast} / \text{heat in fuel gas} \times 100$.

Substitution: Heat to blast = $3,00,000 \times 0.335 \times 1,000 = 10,05,00,000 \text{ kcal/h} (\approx 117 \text{ MW})$; fuel heat = $1,45,000 \times 850 = 12,32,50,000 \text{ kcal/h} (\approx 143 \text{ MW})$.

Result: $\eta_{stove} = 81.5\%$ – false. Waste-gas heat recovery to preheat the combustion air and BF gas, and stove-dome temperature optimisation, are the usual routes to raise it.

Ref: BEE Guidebook Book 4, Ch. 12 (Steel Industry).

7. A cement grinding unit in Andhra Pradesh grinds 12 lakh t of cement a year in a closed-circuit ball mill at 34.0 kWh/t . Adding a roller press for pre-grinding would need 8.0 kWh/t in the press and cut the ball mill to 18.5 kWh/t . The hybrid circuit cuts grinding power by more than 25 %.

[5P4CEA007 | Chapter 13: Cement Industry | Roller press pre-grinding ahead of a cement ball mill]

Answer: FALSE (1 mark)

Given: Production = $12,00,000 \text{ t/year}$; ball mill alone = 34.0 kWh/t ; hybrid = $8.0 + 18.5 \text{ kWh/t}$.

Formula: Saving = $(SEC_{old} - SEC_{new}) \times \text{production}$; % saving = $\text{saving} / \text{old use} \times 100$.

Substitution: Old = $34.0 \times 12,00,000 = 4,08,00,000 \text{ kWh}$; new = $26.5 \times 12,00,000 = 3,18,00,000 \text{ kWh}$.

Result: Saving = $90,00,000 \text{ kWh a year}$, i.e. 22.1% – false (below 25 %). The roller press does the coarse size reduction far more efficiently than tumbling balls, which is why hybrid and finish-grinding circuits are a standard cement-plant upgrade.

Ref: BEE Guidebook Book 4, Ch. 13 (Cement Industry).

8. The kitchen exhaust hood fan of a Hyderabad hotel absorbs 11 kW at full flow and ran at full speed 24 hours a day. A demand-controlled kitchen ventilation system with a VFD now runs it at 50 % flow for 10 h a day when the cooking line is idle; fan power varies as the cube of flow. The fan saving alone exceeds $35,000 \text{ kWh}$ a year.

[5P4CEA008 | Chapter 14: Buildings and Commercial Establishments | Demand-controlled kitchen ventilation – exhaust fan saving]

Answer: TRUE (1 mark)

Given: Full-flow fan power = 11 kW ; 50 % flow for 10 h/day; 365 days; $P \propto Q^3$.

Formula: Saving = $P_{full} \times (1 - 0.5^3) \times \text{hours}$.

Substitution: Saving = $11 \times (1 - 0.125) \times 10 \times 365$.

Result: Fan saving = $35,131 \text{ kWh a year}$ – true. The larger benefit is usually on the conditioned make-up air that no longer has to replace the exhaust, which this figure leaves out.

Ref: BEE Guidebook Book 4, Ch. 14 (Buildings and Commercial Establishments).

9. A Bhiwandi weaving shed runs 96 air-jet looms. Each loom consumes 42 Nm³/h of compressed air for weft insertion and produces 9.6 m of fabric per hour. The compressor house supplies air at a specific energy of 0.125 kWh/Nm³. Compressed air for weft insertion costs more than 0.5 kWh per metre of fabric.

[5P4CEA009 | Chapter 15: Textile Industry | Air-jet weaving – compressed-air energy per metre of fabric]

Answer: TRUE (1 mark)

Given: 96 looms × 42 Nm³/h; 9.6 m/h per loom; 0.125 kWh/Nm³.

Formula: Compressor power = total air × specific energy; kWh/m = power/fabric output per hour.

Substitution: Air = 96 × 42 = 4,032 Nm³/h; power = 4,032 × 0.125 = 504 kW; fabric = 96 × 9.6 = 921.6 m/h.

Result: Specific energy = 0.547 kWh per metre – true. Weft insertion air is the largest energy use in air-jet weaving, so nozzle condition, main-header pressure and leak control matter most.

Ref: BEE Guidebook Book 4, Ch. 15 (Textile Industry).

10. A cooling-water pump in a Visakhapatnam refinery delivers 150 m³/h to the system. Worn wear rings now let 12 % of the impeller flow leak back from discharge to suction, so the impeller must handle 150/0.88 m³/h at the same head. When new, with negligible leakage, the pump efficiency was 74 %. The efficiency has fallen by only about 4 percentage points.

[5P4CEA010 | Chapter 7: Pumps | Worn wear rings – internal recirculation and pump efficiency]

Answer: FALSE (1 mark)

Given: Delivered flow = 150 m³/h; leakage = 12 % of impeller flow; $\eta_{\text{new}} = 74\%$; same head and other losses.

Formula: Impeller flow = delivered/(1 – leakage fraction); $\eta_{\text{worn}} = \eta_{\text{new}} \times \text{delivered/impeller flow}$; extra power = (impeller/delivered – 1) × 100.

Substitution: Impeller flow = 150/0.88 = 170.5 m³/h (leakage 20.5 m³/h); $\eta_{\text{worn}} = 74 \times 0.88$.

Result: $\eta_{\text{worn}} = 65.1\%$, a fall of 8.9 points; shaft power is 13.6 % higher – false. Restoring wear-ring clearance at overhaul is one of the cheapest pump efficiency measures.

Ref: BEE Guidebook Book 4, Ch. 7 (Pumps).

..... End of Section - I

Section - II: SHORT NUMERICAL QUESTIONS

Marks: 2 x 5 = 10

(i) Answer all the Two questions

(ii) Each question carries Five marks

[5P4CEA011] (5 marks)

Chapter 13: Cement Industry | Kiln feed transport – pneumatic air-lift versus bucket elevator: lift power, efficiency, kWh/t and payback

L-1 A 6,000 tpd clinker line in a Chittorgarh cement plant lifts 380 t/h of raw meal to the top of its preheater, 110 m above the kiln-feed silo, with a pneumatic air-lift whose blowers draw 640 kW in total. The energy auditor proposes a high-capacity belt-bucket elevator (mechanical efficiency 70 %, motor efficiency 95 %). The line runs 7,800 h/year; power costs ₹ 6.80 per kWh and the elevator installed costs ₹ 9.5 crore. Take $g = 9.81 \text{ m/s}^2$.

Determine (a) the useful lifting power, the overall efficiency of the air-lift and its specific power (kWh/t), (b) the input power and specific power of the bucket elevator, and (c) the annual energy and cost saving and the simple payback.

MODEL ANSWER

a) Useful lift power, air-lift efficiency and specific power (2 marks)

Given: $\dot{m} = 380 \text{ t/h}$; lift = 110 m; air-lift input = 640 kW.

Formula: $P_{\text{lift}} = \dot{m} g h$; $\eta_{\text{air-lift}} = P_{\text{lift}}/\text{input} \times 100$; $\text{SEC} = \text{input}/\text{throughput}$.

Substitution: $\dot{m} = 3,80,000/3,600 = 105.56 \text{ kg/s}$; $P_{\text{lift}} = 105.56 \times 9.81 \times 110/1,000$

$\eta = 113.91/640 \times 100$; $\text{SEC} = 640/380$

Result: $P_{\text{lift}} = 113.91 \text{ kW}$; **air-lift efficiency = 17.8 %**; **SEC = 1.684 kWh/t**. Most of the air-lift power goes into compressing and accelerating conveying air, not into lifting the meal.

b) Bucket elevator input and specific power (2 marks)

Given: $P_{\text{lift}} = 113.91 \text{ kW}$; $\eta_{\text{mech}} = 0.70$; $\eta_{\text{motor}} = 0.95$.

Formula: $\text{Input} = P_{\text{lift}}/(\eta_{\text{mech}} \times \eta_{\text{motor}})$; $\text{SEC} = \text{input}/\text{throughput}$.

Substitution: $\text{Input} = 113.91/(0.70 \times 0.95) = 113.91/0.665$

$\text{SEC} = 171.29/380$

Result: **Elevator input = 171.29 kW**; **SEC = 0.451 kWh/t**, about a quarter of the air-lift figure.

c) Annual saving and payback (1 mark)

Given: Saving in kW $\times 7,800 \text{ h}$; ₹ 6.80/kWh; investment ₹ 9.5 crore.

Formula: $\text{Saving} = (640 - \text{input}_{\text{elevator}}) \times \text{hours} \times \text{tariff}$; $\text{payback} = \text{investment}/\text{annual saving}$.

Substitution: $\text{Saving} = (640 - 171.29) \times 7,800 = 468.71 \times 7,800 = 36,55,971 \text{ kWh}$

₹ = $36,55,971 \times 6.80$; $\text{payback} = 9,50,00,000/2,48,60,606$

Result: **Saving = 36,55,971 kWh/year worth ₹ 2,48,60,606 (₹ 2.49 crore)**; **simple payback = 3.82 years**. Mechanical conveying is one of the main electrical saving options listed for cement plants.

[5P4CEA012] (5 marks)

Chapter 4: Heat Exchangers | Air-cooled (fin-fan) heat exchanger – duty, air flow at low ambient and VFD fan savings

L-2 In a Jamnagar refinery, an air-cooled (fin-fan) heat exchanger cools 60,000 kg/h of gas oil (specific heat 0.55 kcal/kg °C) from 95 °C to 55 °C. Four fans draw 120 kW in total at full speed. At the design ambient of 40 °C the air leaves at 70 °C. In the 3,500 cooler hours of the year the ambient averages 20 °C; the fans still run at full speed and the outlet louvres are throttled to avoid over-cooling. With VFDs (efficiency 97 %) controlling the gas-oil outlet temperature, the air could leave at 62 °C in that period. Air specific heat = 0.24 kcal/kg °C; fan power varies as the cube of air flow. Power costs ₹ 7.50 per kWh; the VFDs cost ₹ 18 lakh.

Determine (a) the cooler duty and the design air flow, (b) the air flow needed in the cool period and its ratio to the design flow, and (c) the fan power with VFDs in the cool period, the annual saving and the simple payback.

MODEL ANSWER

a) Cooler duty and design air flow (2 marks)

Given: Gas oil 60,000 kg/h; C_p 0.55 kcal/kg °C ($\approx 2.30 \text{ kJ/kg}\cdot\text{K}$); $95 \rightarrow 55 \text{ °C}$; air $40 \rightarrow 70 \text{ °C}$; C_p air 0.24 kcal/kg °C ($\approx 1.00 \text{ kJ/kg}\cdot\text{K}$).

Formula: $Q = m \times C_p \times \Delta T$ (process side); $m_{\text{air}} = Q/(C_{p_{\text{air}}} \times \Delta T_{\text{air}})$.

Substitution: $Q = 60,000 \times 0.55 \times 40 = 13,20,000 \text{ kcal/h}$ ($\approx 1,535 \text{ kW}$)

$m_{\text{air}} = 13,20,000/(0.24 \times 30)$

Result: **Duty = 13,20,000 kcal/h ($\approx 1,535 \text{ kW}$)**; **design air flow = 1,83,333 kg/h**.

b) Air flow in the cool period (1 mark)

Given: $Q = 13,20,000 \text{ kcal/h}$ ($\approx 1,535 \text{ kW}$); air $20 \rightarrow 62 \text{ °C}$.

Formula: $m_{\text{air}} = Q/(C_{p_{\text{air}}} \times \Delta T_{\text{air}})$; $\text{flow ratio} = m_{\text{cool}}/m_{\text{design}}$.

Substitution: $m_{\text{air}} = 13,20,000/(0.24 \times 42)$; $\text{ratio} = 1,30,952/1,83,333$

Result: Cool-period air flow = 1,30,952 kg/h, i.e. 0.7143 of design.

c) Fan power with VFD, saving and payback (2 marks)

Given: Full-speed fan input = 120 kW; ratio = 0.7143; $\eta_{\text{VFD}} = 0.97$; 3,500 h; ₹ 7.50/kWh; cost ₹ 18 lakh.

Formula: $P_{\text{VFD}} = P_{\text{full}} \times \text{ratio}^3 / \eta_{\text{VFD}}$; saving = $(P_{\text{full}} - P_{\text{VFD}}) \times \text{hours}$; payback = cost/₹ saving.

Substitution: $P_{\text{VFD}} = 120 \times 0.3644 / 0.97 = 45.08 \text{ kW}$; saving = $(120 - 45.08) \times 3,500 = 2,62,205 \text{ kWh}$

₹ = $2,62,205 \times 7.50$; payback = $18,00,000 / 19,66,537$

Result: Fan input falls to 45.08 kW; saving = 2,62,205 kWh/year worth ₹ 19,66,537 (₹ 19.67 lakh); simple payback = 0.92 year. Louvre throttling wastes fan power; speed control lets the cooler use the cold ambient instead.

..... End of Section - II

Section - III: LONG NUMERICAL QUESTIONS

Marks: 4 x 20 = 80

- (i) Answer all the Four questions
- (ii) Each question carries Twenty marks
- (iii) In N-4, answer any ONE of the four alternatives (a) to (d)

[5P4CEA013] (20 marks)

Chapter 1: Boilers | Petcoke-fired CFBC boiler with limestone – air, sorbent demand, flue gas, calcination and sulphation in the indirect-method efficiency

N-1 A refinery in Gujarat fires petroleum coke in a circulating fluidised bed (CFBC) boiler. Limestone is fed to the bed to capture SO_2 as CaSO_4 . The energy auditor collected the following data during a steady 8-hour test:

Parameter	Value
Petcoke ultimate analysis (as fired, % by mass)	C 84.0, H 3.6, S 6.0, N 1.4, O 1.0, moisture 3.5, ash 0.5
GCV of petcoke / firing rate	8,200 kcal/kg / 11.5 t/h
O_2 in dry flue gas at boiler exit	4.0 %
Flue gas exit / ambient temperature	145 °C / 30 °C
Humidity of air / specific heat of flue gas	0.020 kg/kg dry air / 0.23 kcal/kg °C
Limestone purity (CaCO_3) / Ca/S molar ratio	90 % / 2.2
Sulphur capture	92 %
Heat absorbed in calcination ($\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$)	425 kcal/kg CaCO_3
Heat released in sulphation ($\text{CaO} + \text{SO}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{CaSO}_4$)	3,750 kcal/kg S captured
Unburnt carbon loss (from fly-ash and bed-ash analysis)	1.8 %
Sensible heat in bed ash and fly ash (incl. spent sorbent) / radiation and unaccounted	0.6 % / 1.0 %
Operating hours; petcoke / limestone price	8,000 h/year; ₹ 11,000 / ₹ 1,600 per t

Take the dry flue gas as the combustion products of the fuel plus the CO_2 released by calcination; neglect the O_2 used in sulphation and the effect of unburnt carbon on gas quantity. Latent heat of water vapour 584 kcal/kg; specific heat of superheated vapour 0.45 kcal/kg °C.

- a) Determine the theoretical air, the excess air and the actual air supplied per kg of petcoke. **[4 Marks]**
- b) Determine the CaCO_3 and limestone needed per kg of petcoke, the limestone feed rate (t/h) and the CO_2 released by calcination. **[4 Marks]**
- c) Determine the mass of dry flue gas per kg of petcoke. **[3 Marks]**
- d) Determine every loss, the sulphation credit and the boiler efficiency by the indirect method. **[6 Marks]**
- e) Finer limestone sizing allows the Ca/S ratio to fall to 1.8 with the same capture. Estimate the new efficiency and the annual petcoke and limestone savings (₹). **[3 Marks]**

MODEL ANSWER

a) Theoretical, excess and actual air (4 marks)

Given: C = 84.0 %, H = 3.6 %, O = 1.0 %, S = 6.0 %; O₂ in flue gas = 4.0 %.

Formula: TA = $[11.6 C + 34.8 (H - O/8) + 4.35 S]/100$; EA = $O_2/(21 - O_2) \times 100$; AAS = $TA \times (1 + EA/100)$.

Substitution: TA = $[11.6 \times 84.0 + 34.8 \times (3.6 - 0.125) + 4.35 \times 6.0]/100 = (974.4 + 120.93 + 26.1)/100$

EA = $4.0/(21 - 4.0) \times 100$; AAS = 11.214×1.2353

Result: TA = 11.214 kg/kg petcoke; EA = 23.53 %; AAS = 13.853 kg/kg petcoke.

b) Sorbent requirement and calcination CO₂ (4 marks)

Given: S = 6.0 % (32 kg/kmol); Ca/S = 2.2; CaCO₃ = 100 kg/kmol; purity 90 %; firing 11.5 t/h.

Formula: CaCO₃ = (Ca/S) $\times$ S/32 $\times$ 100 kg per kg fuel; limestone = CaCO₃/purity; CO₂ = CaCO₃ $\times$ 44/100.

Substitution: CaCO₃ = $2.2 \times 0.060/32 \times 100 = 0.4125$ kg/kg; limestone = $0.4125/0.90 = 0.4583$ kg/kg

Feed = 0.4583×11.5 ; CO₂ = 0.4125×0.44

Result: CaCO₃ = 0.4125 kg and limestone = 0.4583 kg per kg petcoke; limestone feed = 5.27 t/h; calcination CO₂ = 0.1815 kg/kg petcoke.

c) Dry flue gas (3 marks)

Given: C = 0.84; uncaptured S = 8 % of 0.060; N = 0.014; AAS = 13.853; TA = 11.214 kg/kg.

Formula: m_{dfg} = $C \times 44/12 + S_{\text{free}} \times 64/32 + N + 0.77 \times \text{AAS} + 0.23 \times (\text{AAS} - \text{TA}) + \text{CO}_2(\text{calcination})$.

Substitution: CO₂ = 3.080; SO₂ = 0.0096; N₂ = $0.014 + 0.77 \times 13.853 = 10.681$; O₂ = $0.23 \times (13.853 - 11.214) = 0.607$; CO₂(calc) = 0.1815

Result: Dry flue gas = 14.559 kg/kg petcoke.

d) Losses and efficiency (indirect method) (6 marks)

Given: m_{dfg} = 14.559 kg/kg; $\Delta T = 115$ °C; GCV = 8,200 kcal/kg ($\approx 34,332$ kJ/kg); H = 0.036; moisture = 0.035; AAS = 13.853; humidity 0.020.

Formula: L1 = m_{dfg} Cp ΔT /GCV; L2 = $9H(584 + 0.45 \Delta T)/\text{GCV}$; L3 = $M(584 + 0.45 \Delta T)/\text{GCV}$; L4 = AAS $\times$ humidity $\times$ $0.45 \Delta T/\text{GCV}$; calcination = CaCO₃ $\times$ 425/GCV; sulphation credit = $0.92 S \times 3,750/\text{GCV}$ (all $\times 100$).

Substitution: $584 + 0.45 \times 115 = 635.75$ kcal/kg ($\approx 2,662$ kJ/kg); L1 = $14.559 \times 0.23 \times 115/8,200 \times 100 = 4.696$ %

L2 = $9 \times 0.036 \times 635.75/8,200 \times 100 = 2.512$ %; L3 = $0.035 \times 635.75/8,200 \times 100 = 0.271$ %; L4 = $13.853 \times 0.020 \times 0.45 \times 115/8,200 \times 100 = 0.175$ %

Calcination = $0.4125 \times 425/8,200 \times 100 = 2.138$ %; sulphation credit = $0.92 \times 0.060 \times 3,750/8,200 \times 100 = 2.524$ %

Net loss = $4.696 + 2.512 + 0.271 + 0.175 + 1.8 + 0.6 + 1.0 + 2.138 - 2.524$

Result: Net losses = 10.67 %; boiler efficiency = 89.33 %. In an FBC boiler with sorbent, calcination is a real loss and sulphation a real gain; both must enter the balance, and the gain is fixed by the sulphur captured while the loss grows with every extra kg of limestone.

e) Lower Ca/S ratio – efficiency and savings (3 marks)

Given: Ca/S = 1.8; firing 11.5 t/h; $\eta = 89.33$ %; 8,000 h; petcoke ₹ 11,000/t; limestone ₹ 1,600/t.

Formula: Recompute CaCO₃, calcination CO₂, m_{dfg}, L1 and calcination loss; new fuel = old fuel $\times \eta_{\text{old}}/\eta_{\text{new}}$.

Substitution: CaCO₃ = 0.3375 kg/kg (limestone 0.3750); m_{dfg} = 14.526; L1 = 4.685 %; calcination = 1.749 %; $\eta = 100 - 10.27$

Petcoke = $11.5 \times 89.33/89.73 = 11.4488$ t/h; saving = 0.0512 t/h $\times$ 8,000 = 409 t

Limestone = $0.3750 \times 11.4488 = 4.293$ t/h against 5.271 t/h; saving = 7,820 t/year

Result: Efficiency rises to 89.73 % (+0.40 points); petcoke saved = 409 t and limestone saved = 7,820 t a year, worth ₹ 1,70,16,406 (₹ 1.70 crore). Most of the money comes from limestone, but the efficiency gain also cuts ash disposal and CO₂.

[5P4CEA014] (20 marks)

Chapter 2: Furnaces | Natural-gas galvanizing kettle furnace – flue gas losses, heat balance, efficiency, burner tuning, bath hood and flue heat recovery

N-2 A hot-dip galvanizing plant near Chennai coats transmission-tower steel in a 450 °C molten zinc kettle heated by natural-gas burners. Treat the gas as methane: GCV 9,500 kcal/Sm³, theoretical air 9.52 Sm³/Sm³, wet combustion products 10.52 Sm³/Sm³ (1 CO₂ + 2 H₂O + 7.52 N₂). Audit data:

Parameter	Value
Steel dipped / specific heat	4,000 kg/h, from 30 °C to 450 °C / 0.12 kcal/kg °C
Zinc added to the bath (make-up)	240 kg/h from 30 °C; melts at 420 °C
Zinc: specific heat solid / liquid; latent heat	0.094 / 0.12 kcal/kg °C; 24 kcal/kg
Open bath surface / surface loss (radiation + convection + fume extraction)	9 m ² / 13,000 kcal/h per m ²
Kettle and furnace casing loss	45,000 kcal/h
O ₂ in dry flue gas / flue gas exit temperature / ambient	9.0 % / 560 °C / 30 °C
Mean specific heat of flue gas	0.34 kcal/Sm ³ °C
Water vapour: density / latent heat	0.804 kg/Sm ³ / 584 kcal/kg
Operating hours; gas price; electricity	6,000 h/year; ₹ 48 per Sm ³ ; ₹ 8.00 per kWh

- Determine the excess air, the flue gas volume per Sm³ of gas, and the sensible and latent heat lost in the flue gas per Sm³ of gas. **[4 Marks]**
- Determine the heat demand of the kettle, the gas consumption (Sm³/h), and draw up the heat balance, showing that it closes. **[5 Marks]**
- Determine the thermal efficiency (useful heat to steel and zinc) and the specific gas consumption per tonne of steel. **[3 Marks]**
- Burner tuning brings O₂ down to 3.0 %, and an insulated hood over the bath during idle periods cuts the surface loss by 40 %. Find the new gas consumption, the annual saving (₹) and the payback on ₹ 22 lakh. **[5 Marks]**
- After (d), the flue gas is passed through a heat exchanger that cools it to 250 °C to heat the pre-flux drying oven, replacing an electric heater. Find the heat recovered (kW) and its annual value. **[3 Marks]**

MODEL ANSWER

a) Excess air and flue gas losses per Sm³ (4 marks)

Given: O₂ = 9.0 %; TA = 9.52 Sm³/Sm³; wet products 10.52 Sm³/Sm³ incl. 2 Sm³ H₂O; Cp = 0.34 kcal/Sm³ (≈ 0.0014 MJ/Sm³) °C; 560 – 30 = 530 °C.

Formula: EA = O₂/(21 – O₂) × 100; V_{fg} = 10.52 + EA × 9.52; sensible = V_{fg} × Cp × ΔT; latent = 2 × 0.804 × 584.

Substitution: EA = 9/(21 – 9) × 100 = 75.0 %; V_{fg} = 10.52 + 0.75 × 9.52 = 17.66 Sm³/Sm³

Sensible = 17.66 × 0.34 × 530; latent = 2 × 0.804 × 584

Result: EA = 75.0 %; flue gas = 17.66 Sm³ per Sm³ gas; sensible loss = 3,182.3 kcal/Sm³ (≈ 13.3 MJ/Sm³); latent loss = 939.1 kcal/Sm³ (≈ 3.93 MJ/Sm³); heat available to the kettle = 9,500 – 3,182.3 – 939.1 = 5,378.6 kcal/Sm³ (≈ 22.5 MJ/Sm³).

b) Heat demand, gas consumption and heat balance (5 marks)

Given: Steel 4,000 kg/h; zinc 240 kg/h; surface 9 m² × 13,000; casing 45,000 kcal/h (≈ 52.3 kW); available heat 5,378.6 kcal/Sm³ (≈ 22.5 MJ/Sm³).

Formula: Demand = steel + zinc + surface + casing; gas = demand/available heat per Sm^3 .

Substitution: Steel = $4,000 \times 0.12 \times 420 = 2,01,600 \text{ kcal/h}$ ($\approx 234 \text{ kW}$); zinc = $240 \times [0.094 \times 390 + 24 + 0.12 \times 30] = 240 \times 64.26 = 15,422.4 \text{ kcal/h}$ ($\approx 17.9 \text{ kW}$)

Surface = $1,17,000 \text{ kcal/h}$ ($\approx 136 \text{ kW}$); demand = $3,79,022.4 \text{ kcal/h}$ ($\approx 441 \text{ kW}$); gas = $3,79,022.4/5,378.6$

Balance: input $70.469 \times 9,500 = 6,69,452 \text{ kcal/h}$ ($\approx 778 \text{ kW}$) = steel $2,01,600$ + zinc $15,422$ + surface $1,17,000$ + casing $45,000$ + flue sensible $2,24,255$ + flue latent $66,175$

Result: Heat demand = $3,79,022 \text{ kcal/h}$ ($\approx 441 \text{ kW}$); gas = $70.47 \text{ Sm}^3/\text{h}$; the balance closes at $6,69,452 \text{ kcal/h}$ ($\approx 778 \text{ kW}$). Flue gas (43.4 %) and the open bath (17.5 %) are the two largest losses.

c) Thermal efficiency and specific consumption (3 marks)

Given: Useful = $2,01,600 + 15,422 \text{ kcal/h}$ ($\approx 17.9 \text{ kW}$); input = $6,69,452 \text{ kcal/h}$ ($\approx 778 \text{ kW}$); 4 t/h steel.

Formula: $\eta = \text{useful}/\text{input} \times 100$; specific gas = $\text{Sm}^3/\text{h} \div \text{t/h}$.

Substitution: $\eta = 2,17,022/6,69,452 \times 100$; specific gas = $70.47/4$

Result: Thermal efficiency = 32.4 %; specific consumption = 17.62 Sm^3 per t of steel ($1,67,363 \text{ kcal/t}$).

d) Burner tuning and bath hood (5 marks)

Given: $\text{O}_2 = 3.0 \%$; surface loss $\times 0.60$; 6,000 h; ₹ 48/ Sm^3 ; investment ₹ 22 lakh.

Formula: Recompute EA, V_{fg} , available heat and demand; saving = $\Delta\text{gas} \times \text{hours} \times \text{price}$; payback = cost/saving.

Substitution: EA = $3/18 \times 100 = 16.67 \%$; $V_{fg} = 10.52 + 0.1667 \times 9.52 = 12.107 \text{ Sm}^3/\text{Sm}^3$; sensible = $12.107 \times 0.34 \times 530 = 2,181.6 \text{ kcal}/\text{Sm}^3$ ($\approx 9.13 \text{ MJ}/\text{Sm}^3$); available = $6,379.3 \text{ kcal}/\text{Sm}^3$ ($\approx 26.7 \text{ MJ}/\text{Sm}^3$)

Surface = $70,200 \text{ kcal/h}$ ($\approx 81.6 \text{ kW}$); demand = $3,32,222.4 \text{ kcal/h}$ ($\approx 386 \text{ kW}$); gas = $3,32,222.4/6,379.3 = 52.08 \text{ Sm}^3/\text{h}$

Saving = $(70.47 - 52.08) \times 6,000 = 1,10,343 \text{ Sm}^3$; ₹ = $1,10,343 \times 48$; payback = $22,00,000/52,96,468$

Result: Gas falls to $52.08 \text{ Sm}^3/\text{h}$ (efficiency 43.9 %); saving = $1,10,343 \text{ Sm}^3/\text{year}$ worth ₹ 52,96,468 (₹ 52.96 lakh); simple payback = 0.42 year.

e) Flue gas heat recovery to the drying oven (3 marks)

Given: Gas = $52.08 \text{ Sm}^3/\text{h}$; $V_{fg} = 12.107 \text{ Sm}^3/\text{Sm}^3$; $560 \rightarrow 250^\circ\text{C}$; $860 \text{ kcal} = 1 \text{ kWh}$; 6,000 h; ₹ 8.00/kWh.

Formula: $Q = \text{gas} \times V_{fg} \times C_p \times \Delta T$; $\text{kW} = Q/860$; value = $\text{kW} \times \text{hours} \times \text{tariff}$.

Substitution: $Q = 52.08 \times 12.107 \times 0.34 \times 310 = 66,454 \text{ kcal/h}$ ($\approx 77.3 \text{ kW}$); $\text{kW} = 66,454/860$

Value = $77.27 \times 6,000 \times 8.00$

Result: Heat recovered = 77.27 kW, worth ₹ 37,09,056 (₹ 37.09 lakh) a year by switching off the electric oven heater – the drying oven is the natural sink for kettle flue heat in a galvanizing line.

[5P4CEA015] (20 marks)

Chapter 8: Compressors | Screw compressor plant – FAD correction from normal flow, specific power, pressure reduction, leakage at lower pressure and oil-cooler heat recovery

N-3 An automobile forging and machining plant in Pithampur runs three oil-injected screw compressors (single-stage) feeding a common 7.5 bar(g) header. A thermal mass flow meter on the main header and logged power analysers gave these averages over a week:

Parameter	Value
Air delivered (flow meter, normal conditions 0°C , 1.013 bar(a))	$3,000 \text{ Nm}^3/\text{h}$
Compressor intake conditions (inside a hot compressor room)	40°C , 0.98 bar(a)
Total compressor input power	405 kW
Generation pressure now / pressure the users actually need	7.5 bar(g) / 6.5 bar(g) at the compressor (after cleaning filters)

	and resizing a header)
Leakage (from a no-production load–unload test at 7.5 bar(g))	18 % of air delivered
Recoverable heat from the oil coolers (heat-recovery kit)	72 % of compressor input
Process hot water: inlet / outlet temperature	30 °C / 70 °C, now heated in a furnace-oil boiler (η 85 %, GCV 10,200 kcal/kg, ₹ 55 per kg)
Operating hours / electricity price / heat-recovery kit cost	8,000 h/year / ₹ 8.00 per kWh / ₹ 35 lakh

Take atmospheric pressure as 1.013 bar for converting gauge pressure, an adiabatic exponent $(n - 1)/n = 0.2857$ for the compression power, leakage flow proportional to absolute header pressure, and compressor power proportional to air delivered at a given pressure.

- Convert the measured flow to free air delivery at the actual intake conditions and find the specific power in kW per m³/min. **[5 Marks]**
- Find the percentage and kW saving if the generation pressure is reduced to 6.5 bar(g). **[5 Marks]**
- Find the further saving from the lower leakage at 6.5 bar(g), and the total electrical saving per year (kWh and ₹). **[4 Marks]**
- With the new compressor input, find the hot water that the heat-recovery kit can produce, the furnace oil saved, its value and the simple payback of the kit. **[6 Marks]**

MODEL ANSWER

a) FAD at intake conditions and specific power (5 marks)

Given: $Q_N = 3,000 \text{ Nm}^3/\text{h}$ at 273 K, 1.013 bar(a); intake 313 K, 0.98 bar(a); input = 405 kW.

Formula: $\text{FAD} = Q_N \times (P_N/P_{\text{intake}}) \times (T_{\text{intake}}/T_N)$; specific power = kW/(m³/min).

Substitution: $\text{FAD} = 3,000 \times (1.013/0.98) \times (313/273) = 3,000 \times 1.0337 \times 1.1465 = 3,555.4 \text{ m}^3/\text{h}$
 $= 59.26 \text{ m}^3/\text{min}$; $\text{SP} = 405/59.26$

Result: $\text{FAD} = 59.26 \text{ m}^3/\text{min}$; **specific power = 6.83 kW per m³/min.** Quoting the 3,000 Nm³/h as if it were free air (50 m³/min) would overstate the specific power at 8.10 kW per m³/min; the basis of a flow reading must always be stated.

b) Saving from 7.5 to 6.5 bar(g) (5 marks)

Given: $P_{\text{intake}} = 0.98 \text{ bar(a)}$; $P_2 = 8.513$ and 7.513 bar(a) ; exponent 0.2857; input 405 kW.

Formula: $\text{Power} \propto [(P_2/P_1)^{0.2857} - 1]$; $\text{saving \%} = [1 - f(6.5)/f(7.5)] \times 100$.

Substitution: $P_2/P_1 = 8.513/0.98 = 8.6867 \rightarrow f = 8.6867^{0.2857} - 1 = 0.8545$

$P_2/P_1 = 7.513/0.98 = 7.6663 \rightarrow f = 0.7895$; $\text{saving} = (1 - 0.7895/0.8545) \times 100$

Result: **Saving = 7.61 %, i.e. 30.83 kW; compressor input falls to 374.17 kW.**

c) Lower leakage and total electrical saving (4 marks)

Given: Leak = 18 % at 8.513 bar(a); new pressure 7.513 bar(a); input after (b) = 374.17 kW; 8,000 h; ₹ 8.00/kWh.

Formula: $\text{Leak}_2 = \text{Leak}_1 \times P_2/P_1$ (absolute); kW saved = input $\times \Delta\text{leak}$; annual = (kW_b + kW_c) $\times$ hours.

Substitution: $\text{Leak}_2 = 18 \times 7.513/8.513 = 15.89 \%$; $\Delta = 2.114 \%$ of air

kW = $374.17 \times 0.02114 = 7.91 \text{ kW}$; total = $30.83 + 7.91 = 38.74 \text{ kW}$

Result: **Leak saving = 7.91 kW; total = 38.74 kW = 3,09,899 kWh/year worth ₹ 24,79,196 (₹ 24.79 lakh).** The new input is 366.26 kW. Repairing the leaks themselves would save far more and should follow.

d) Heat recovery to process hot water (6 marks)

Given: Input = 366.26 kW; 72 % recoverable; water 30 → 70 °C; boiler η 0.85; GCV 10,200 kcal/kg ($\approx$ 42,705 kJ/kg); ₹ 55/kg; 8,000 h; kit ₹ 35 lakh.

Formula: $Q = P \times 0.72 \times 860 \text{ kcal/h}$; water = $Q/(1 \times \Delta T)$; oil = $Q/(\eta \times \text{GCV})$; payback = cost/₹ saved.

Substitution: $Q = 366.26 \times 0.72 \times 860 = 2,26,790 \text{ kcal/h}$ ($\approx$ 264 kW); water = $2,26,790/40 = 5,670 \text{ kg/h}$

Oil = $2,26,790/(0.85 \times 10,200) = 26.16 \text{ kg/h}$; $\times 8,000 = 2,09,264 \text{ kg/year}$

₹ = $2,09,264 \times 55$; payback = $35,00,000/1,15,09,516$

Result: Hot water = 5,670 kg/h at 70 °C; furnace oil saved = 2,09,264 kg/year worth ₹ 1,15,09,516 (₹ 1.15 crore); payback = 0.30 year. Together with (b) and (c), the plant saves ₹ 1,39,88,712 (₹ 1.40 crore) a year – heat recovery is usually the largest single compressed-air opportunity because almost all the input power ends up as heat.

[5P4CEA016] (20 marks)

Chapter 11: Thermal Power Station | Answer any ONE: (a) TPS heat-rate deviation, (b) sinter plant WHR, (c) cement RDF co-processing, (d) weaving humidification plant

N-4 Answer any ONE of the following among the four questions given below (20 marks).

N-4 (a) Thermal power station – heat-rate deviation (controllable loss) analysis

A 500 MW coal-fired unit in Maharashtra has a design gross heat rate of 2,250 kcal/kWh. A performance test at full load measured a gross heat rate of 2,410 kcal/kWh. The OEM correction curves, linearised over the operating range, and the test readings are:

Parameter	Design	Actual (test)	Heat-rate correction
MS temperature (°C)	537	528	+1.2 kcal/kWh per °C below design
HRH temperature (°C)	537	522	+1.0 kcal/kWh per °C below design
MS pressure (kg/cm ²)	170	162	+1.6 kcal/kWh per kg/cm ² below design
Condenser back-pressure (kPa(a))	10.1	12.0	+18 kcal/kWh per kPa(a) above design
SH spray (t/h)	10	45	+0.12 kcal/kWh per t/h above design
RH spray (t/h)	0	18	+1.9 kcal/kWh per t/h above design
APH exit gas temperature (°C)	132	151	+1.15 kcal/kWh per °C above design
O ₂ at economiser outlet (%)	3.0	4.6	+6.5 kcal/kWh per % point above design

Plant load factor 82 %; coal GCV 3,650 kcal/kg; landed coal cost ₹ 4,300 per t; emission factor 1.55 t CO₂ per t coal; 1 toe = 10⁷ kcal.

- Determine the heat-rate deviation caused by each parameter and the total. **[8 Marks]**
- Determine the heat rate explained by these deviations, and the unaccounted part of the measured heat rate. **[3 Marks]**
- Determine the annual extra heat (toe), the extra coal (t) and its cost caused by the total deviation. **[5 Marks]**
- Identify the three largest deviations, their share of the total and the coal cost they cause; and the extra CO₂ due to the total deviation. **[4 Marks]**

OR

N-4 (b) Steel industry – sinter plant specific energy and sinter-cooler waste heat recovery

The sinter plant of an integrated steel works in Karnataka produces 560 t/h of sinter for 8,000 h a year. Its energy data and a proposal for a waste-heat recovery (WHR) boiler on the hot section of the annular sinter cooler are:

Parameter	Value
Coke breeze in the sinter mix / GCV	52 kg per t sinter / 6,600 kcal/kg
Ignition furnace fuel (mixed coke-oven and BF gas)	9,800 Nm ³ /h at 1,400 kcal/Nm ³
Electricity (main exhaust fan, cooler fans, crushing)	32 kWh per t sinter (take 860 kcal/kWh)
Hot cooler air available	5,20,000 Nm ³ /h at 380 °C, cooled to 170 °C in the WHR boiler
Mean specific heat of cooler air	0.315 kcal/Nm ³ °C
Boiler heat utilisation (casing losses 8 %) / steam enthalpy rise	92 % / 660 kcal/kg (765 – 105)
Turbine specific steam consumption / WHR auxiliary power	4.6 kg/kWh / 8 % of gross generation
Value of power / WHR project cost	₹ 6.50 per kWh / ₹ 165 crore

- Determine the specific energy consumption of the sinter plant (kcal/t sinter) and the share of each input. **[6 Marks]**
- Determine the heat recovered from the cooler air and the steam generated (t/h). **[5 Marks]**
- Determine the gross and net power generated, the net kWh per t sinter, and the share of the plant's electricity it offsets. **[4 Marks]**
- Determine the annual value, the simple payback, and the new specific energy consumption with the WHR credit. **[5 Marks]**

OR

N-4 (c) Cement industry – thermal substitution of kiln coal by refuse-derived fuel (RDF)

A 5,000 tpd clinker kiln in Madhya Pradesh runs 330 days a year at a specific heat consumption of 720 kcal/kg clinker on imported coal (NCV 5,800 kcal/kg). The plant plans to co-process RDF from nearby municipalities:

Parameter	Value
Target thermal substitution rate (TSR, by heat)	15 %
RDF net calorific value / delivered cost	3,000 kcal/kg / ₹ 1,500 per t
Heat-consumption penalty from RDF moisture and extra air	1.2 kcal/kg clinker for every 1 % TSR
Extra electricity (RDF handling, shredding, ID fan)	1.1 kWh per t clinker at ₹ 7.00 per kWh
Coal delivered cost	₹ 9,800 per t
CO ₂ factors: coal / fossil part of RDF (biogenic part excluded)	2.30 t CO ₂ per t coal / 0.55 t CO ₂ per t RDF
Investment (storage, feeding system, bypass)	₹ 32 crore

- Determine the present coal consumption (kg/kg clinker and t/day). **[3 Marks]**
- Determine the new specific heat consumption, the heat from RDF, and the RDF and coal needed (t/day). **[6 Marks]**
- Determine the annual coal saving, the RDF and extra power costs, the net saving and the simple payback. **[6 Marks]**
- Determine the net fossil CO₂ reduction per year and per t clinker. **[5 Marks]**

OR

N-4 (d) Textile industry – humidification plant of a weaving shed

A Surat weaving shed (fabric output 36 lakh m a year) is humidified by an air-washer plant that runs 8,000 h a year. The supply fans run at full speed throughout, with dampers and bypass louvres used to control conditions. Audit data and proposals:

Parameter	Value
Supply air flow / fan total pressure	5,40,000 m ³ /h / 28 mmWC
Fan efficiency / fan motor efficiency	60 % / 92 %

Washer spray pump: flow / head / pump efficiency / motor efficiency	120 m ³ /h / 32 m / 62 % / 90 %
Air flow actually needed (from shed humidity logging)	70 % for 4,000 h, 85 % for 2,500 h, 100 % for 1,500 h
Proposal 1: VFDs on supply fans (efficiency 97 %; fan power $\propto$ flow ³)	₹ 14 lakh
Proposal 2: new spray nozzles (24 m head) and an efficient pump (78 %) with IE3 motor (92 %)	₹ 6 lakh
Electricity price	₹ 7.20 per kWh

Take water density 1,000 kg/m³ and $g = 9.81 \text{ m/s}^2$.

- Determine the present input power of the supply fans and the spray pump. **[6 Marks]**
- Determine the annual fan energy now and with VFDs, and the saving. **[6 Marks]**
- Determine the new pump input and the annual pump saving. **[4 Marks]**
- Determine the total annual saving (₹), the simple payback, and the humidification energy per 1,000 m of fabric before and after. **[4 Marks]**

MODEL ANSWER

N-4 (a) Solution — heat-rate deviation analysis

a) Deviation per parameter (8 marks)

Given: Design and test values with the linear correction factors in the table.

Formula: $\Delta HR_i = |\text{actual} - \text{design}| \times \text{correction factor}$; total = $\sum \Delta HR_i$.

Substitution: MS temperature: $|528 - 537| \times 1.2 = 10.80 \text{ kcal/kWh}$ ($\approx 45.2 \text{ kJ/kWh}$); HRH temperature: $|522 - 537| \times 1.0 = 15.00 \text{ kcal/kWh}$ ($\approx 62.8 \text{ kJ/kWh}$); MS pressure: $|162 - 170| \times 1.6 = 12.80 \text{ kcal/kWh}$ ($\approx 53.6 \text{ kJ/kWh}$); Condenser back-pressure: $|12.0 - 10.1| \times 18 = 34.20 \text{ kcal/kWh}$ ($\approx 143 \text{ kJ/kWh}$)

SH spray: $|45 - 10| \times 0.12 = 4.20 \text{ kcal/kWh}$ ($\approx 17.6 \text{ kJ/kWh}$); RH spray: $|18 - 0| \times 1.9 = 34.20 \text{ kcal/kWh}$ ($\approx 143 \text{ kJ/kWh}$); APH exit gas temperature: $|151 - 132| \times 1.15 = 21.85 \text{ kcal/kWh}$ ($\approx 91.5 \text{ kJ/kWh}$); O₂ at economiser outlet: $|4.6 - 3.0| \times 6.5 = 10.40 \text{ kcal/kWh}$ ($\approx 43.5 \text{ kJ/kWh}$)

Result: Total deviation = 143.45 kcal/kWh ($\approx 601 \text{ kJ/kWh}$). Condenser back-pressure and reheat spray (34.2 kcal/kWh ($\approx 143 \text{ kJ/kWh}$) each) lead, followed by APH exit gas temperature (21.85 kcal/kWh ($\approx 91.5 \text{ kJ/kWh}$)).

b) Explained and unaccounted heat rate (3 marks)

Given: Design HR = 2,250 kcal/kWh ($\approx 9,420 \text{ kJ/kWh}$); total deviation = 143.45 kcal/kWh ($\approx 601 \text{ kJ/kWh}$); measured HR = 2,410 kcal/kWh ($\approx 10,090 \text{ kJ/kWh}$).

Formula: $HR_{\text{explained}} = HR_{\text{design}} + \sum \Delta HR$; $unaccounted = HR_{\text{measured}} - HR_{\text{explained}}$.

Substitution: $HR_{\text{explained}} = 2,250 + 143.45$; $unaccounted = 2,410 - 2,393.45$

Result: Explained heat rate = 2,393.45 kcal/kWh ($\approx 10,021 \text{ kJ/kWh}$); unaccounted = 16.55 kcal/kWh ($\approx 69.3 \text{ kJ/kWh}$) (turbine internal losses such as seal wear, valve passing and heater performance should be investigated next).

c) Annual extra heat, coal and cost (5 marks)

Given: Generation = $500 \text{ MW} \times 0.82 \times 8,760 \text{ h} = 3,591.6 \text{ MU}$; $\Delta HR = 143.45 \text{ kcal/kWh}$ ($\approx 601 \text{ kJ/kWh}$); GCV 3,650 kcal/kg ($\approx 15,282 \text{ kJ/kg}$); ₹ 4,300/t.

Formula: Extra heat = $\Delta HR \times \text{kWh}$; toe = $\text{kcal}/10^7$; coal = heat/GCV ; cost = coal $\times$ price.

Substitution: Extra heat = $143.45 \times 3,591.6 \times 10^6 = 5.1522 \times 10^{11} \text{ kcal} = 51,522 \text{ toe}$ ($\approx 2,157 \text{ TJ}$)

Coal = $5.1522 \times 10^{11} / 3,650 = 1,41,155 \text{ t}$; cost = $1,41,155 \times 4,300$

Result: Extra heat = 51,522 toe ($\approx 2,157$ TJ); extra coal = 1,41,155 t/year costing ₹ 60,69,65,640 (₹ 60.70 crore).

d) Largest deviations and extra CO₂ (4 marks)

Given: Back-pressure 34.2, RH spray 34.2, APH exit gas 21.85 kcal/kWh (≈ 91.5 kJ/kWh); coal = 1,41,155 t; 1.55 t CO₂/t coal.

Formula: Share = Σ top-three/total; coal share = coal $\times$ share; CO₂ = coal $\times$ emission factor.

Substitution: Top three = 34.2 + 34.2 + 21.85 = 90.25 kcal/kWh (≈ 378 kJ/kWh); share = 90.25/143.45 $\times$ 100

Coal = 1,41,155 $\times$ 0.6291 = 88,806 t; CO₂ = 1,41,155 $\times$ 1.55

Result: The top three give 62.9 % of the deviation, costing ₹ 38,18,65,800 (₹ 38.19 crore) a year in coal; total extra CO₂ = 2,18,790 t/year. Priorities: condenser cleaning and air-ingress tests, finding the cause of reheat spray (burner tilt, soot blowing), and APH cleaning.

N-4 (b) Solution — sinter plant energy and cooler WHR

a) Specific energy consumption (6 marks)

Given: Coke breeze 52 kg/t $\times$ 6,600 kcal/kg ($\approx 27,633$ kJ/kg); ignition gas 9,800 Nm³/h $\times$ 1,400 kcal/Nm³ (≈ 5.86 MJ/Nm³) for 560 t/h; electricity 32 kWh/t $\times$ 860.

Formula: SEC = solid fuel + ignition fuel + electricity (all per t sinter); share = each/SEC $\times$ 100.

Substitution: Solid fuel = 52 $\times$ 6,600 = 3,43,200 kcal/t; ignition = 9,800 $\times$ 1,400/560 = 24,500 kcal/t; electricity = 32 $\times$ 860 = 27,520 kcal/t

Result: SEC = 3,95,220 kcal/t sinter (0.3952 Gcal/t): coke breeze 86.8 %, ignition 6.2 %, electricity 7.0 %. Coke breeze rate, ignition intensity and main-fan power (false air through pallets) are therefore the targets besides waste heat.

b) Heat recovered and steam generated (5 marks)

Given: Cooler air 5,20,000 Nm³/h; 380 $\rightarrow$ 170 °C; Cp = 0.315 kcal/Nm³ (≈ 0.0013 MJ/Nm³) °C; utilisation 92 %; Δh = 660 kcal/kg ($\approx 2,763$ kJ/kg).

Formula: Q = V $\times$ Cp $\times$ ΔT ; steam = Q $\times$ 0.92/ Δh .

Substitution: Q = 5,20,000 $\times$ 0.315 $\times$ 210 = 3,43,98,000 kcal/h (≈ 40.0 MW)

Steam = 3,43,98,000 $\times$ 0.92/660 = 47,949 kg/h

Result: Heat recovered = 3,43,98,000 kcal/h (≈ 40.0 MW); steam = 47.95 t/h.

c) Power generated (4 marks)

Given: Steam = 47.95 t/h; 4.6 kg/kWh; auxiliaries 8 %; 560 t/h sinter; plant uses 32 kWh/t.

Formula: Gross kW = steam (kg/h)/SSC; net = gross $\times$ 0.92; kWh/t = net/production.

Substitution: Gross = 47,949/4.6 = 10,424 kW; net = 10,424 $\times$ 0.92 = 9,590 kW

kWh/t = 9,590/560; share = 17.12/32 $\times$ 100

Result: Gross = 10,424 kW; net = 9,590 kW = 17.12 kWh/t sinter, offsetting 53.5 % of the sinter plant's electricity.

d) Value, payback and new SEC (5 marks)

Given: Net = 9,590 kW $\times$ 8,000 h; ₹ 6.50/kWh; cost ₹ 165 crore; SEC = 3,95,220 kcal/t.

Formula: Value = kWh $\times$ tariff; payback = cost/value; SEC_{new} = SEC – (kWh/t $\times$ 860).

Substitution: kWh = 9,590 $\times$ 8,000 = 7,67,17,964; value = 7,67,17,964 $\times$ 6.50

Payback = 1,65,00,00,000/49,86,66,764; SEC_{new} = 3,95,220 – 17.12 $\times$ 860

Result: Annual value = ₹ 49,86,66,764 (₹ 49.87 crore); simple payback = 3.31 years; SEC falls to 3,80,493 kcal/t (– 3.73 %).

N-4 (c) Solution — RDF co-processing in a cement kiln

a) Present coal consumption (3 marks)

Given: SHC = 720 kcal/kg clinker ($\approx 3,014$ kJ/kg clinker); coal NCV = 5,800 kcal/kg ($\approx 24,283$ kJ/kg); 5,000 tpd.

Formula: Coal (kg/kg clinker) = SHC/NCV; t/day = $\times 5,000$.

Substitution: Coal = $720/5,800 = 0.1241$ kg/kg; $\times 5,000$

Result: Coal = **0.1241 kg/kg clinker = 620.7 t/day.**

b) Heat, RDF and coal with 15 % TSR (6 marks)

Given: TSR 15 %; penalty 1.2 kcal/kg clinker (≈ 5.02 kJ/kg clinker) per 1 % TSR; RDF NCV 3,000; coal NCV 5,800 kcal/kg ($\approx 24,283$ kJ/kg).

Formula: SHC_new = $720 + 1.2 \times \text{TSR}$; RDF heat = $\text{TSR} \times \text{SHC_new}$; RDF = $\text{RDF heat}/\text{NCV_RDF}$; coal = $(\text{SHC_new} - \text{RDF heat})/\text{NCV_coal}$.

Substitution: SHC_new = $720 + 1.2 \times 15 = 738.0$ kcal/kg ($\approx 3,090$ kJ/kg); RDF heat = $0.15 \times 738.0 = 110.70$ kcal/kg (≈ 463 kJ/kg); coal heat = 627.30 kcal/kg ($\approx 2,626$ kJ/kg)

RDF = $110.70/3,000 = 0.0369$ kg/kg $\rightarrow 184.5$ t/day; coal = $627.30/5,800 = 0.1082$ kg/kg $\rightarrow 540.8$ t/day

Result: SHC rises to **738.0 kcal/kg clinker ($\approx 3,090$ kJ/kg clinker); RDF = 184.5 t/day; coal falls to 540.8 t/day (saving 79.91 t/day).**

c) Net saving and payback (6 marks)

Given: 330 days; coal ₹ 9,800/t; RDF ₹ 1,500/t; extra power 1.1 kWh/t clinker at ₹ 7.00; investment ₹ 32 crore.

Formula: Net saving = coal saved $\times$ price – RDF $\times$ price – extra kWh $\times$ tariff; payback = investment/net saving.

Substitution: Coal saved = $79.91 \times 330 = 26,372$ t $\rightarrow$ ₹ 25,84,41,207

RDF = $184.5 \times 330 = 60,885$ t $\rightarrow$ ₹ 9,13,27,500; power = $1.1 \times 5,000 \times 330 = 18,15,000$ kWh $\rightarrow$ ₹ 1,27,05,000

Net = $25,84,41,207 - 9,13,27,500 - 1,27,05,000$; payback = $32,00,00,000/15,44,08,707$

Result: Net saving = **₹ 15,44,08,707 (₹ 15.44 crore) a year; simple payback = 2.07 years.** The heat penalty is real: RDF moisture and the extra air it needs raise the kiln's specific heat, so TSR projects must be judged on net coal saved, not gross RDF heat.

d) Net fossil CO₂ reduction (5 marks)

Given: Coal saved = 26,372 t/year at 2.30 t CO₂/t; RDF = 60,885 t/year at 0.55 t CO₂/t; clinker = $5,000 \times 330$ t.

Formula: Net CO₂ = coal saved $\times 2.30$ – RDF $\times 0.55$; per t clinker = net/clinker.

Substitution: Coal CO₂ avoided = $26,372 \times 2.30 = 60,655$ t; RDF fossil CO₂ = $60,885 \times 0.55 = 33,487$ t

Net = $60,655 - 33,487$; per t = $27,168 \times 1,000/16,50,000$ kg

Result: Net fossil CO₂ reduction = **27,168 t/year = 16.47 kg per t clinker.** Raising the biogenic share of the RDF raises this figure without changing the coal saving.

N-4 (d) Solution — weaving-shed humidification plant

a) Present fan and pump input (6 marks)

Given: Q = 5,40,000 m³/h; $\Delta p = 28$ mmWC (≈ 275 Pa); η_{fan} 0.60; η_{m} 0.92; pump 120 m³/h, 32 m, 0.62, 0.90.

Formula: Fan input = $Q \times \Delta p / (\eta_{\text{fan}} \times \eta_{\text{m}})$; pump input = $\rho g Q H / (\eta_{\text{p}} \times \eta_{\text{m}})$.

Substitution: $Q = 5,40,000/3,600 = 150.0 \text{ m}^3/\text{s}$; $\Delta p = 28 \times 9.80665 = 274.59 \text{ Pa}$; fan input $= 150.0 \times 274.59 / (0.60 \times 0.92) / 1,000$

Pump hydraulic $= 1,000 \times 9.81 \times 0.03333 \times 32 / 1,000 = 10.464 \text{ kW}$; input $= 10.464 / (0.62 \times 0.90)$

Result: Fan input = 74.62 kW; pump input = 18.75 kW.

b) Fan energy with VFDs (6 marks)

Given: Fan input = 74.62 kW; 8,000 h now; profile 70 %/4,000 h, 85 %/2,500 h, 100 %/1,500 h; $\eta_{\text{VFD}} 0.97$.

Formula: $E_{\text{now}} = P \times 8,000$; $E_{\text{VFD}} = (P/0.97) \times \Sigma (\text{flow ratio}^3 \times \text{hours})$.

Substitution: $E_{\text{now}} = 74.62 \times 8,000 = 5,96,927 \text{ kWh}$

$\Sigma = 0.343 \times 4,000 + 0.6141 \times 2,500 + 1 \times 1,500 = 4,407.3 \text{ h}$; $E_{\text{VFD}} = 74.62 / 0.97 \times 4,407.3$

Result: Fan energy falls from 5,96,927 to 3,39,026 kWh; saving = 2,57,901 kWh/year.

c) Pump retrofit (4 marks)

Given: $120 \text{ m}^3/\text{h}$ at 24 m; $\eta_{\text{p}} 0.78$; $\eta_{\text{m}} 0.92$; 8,000 h.

Formula: Input $= \rho g Q H / (\eta_{\text{p}} \times \eta_{\text{m}})$; saving $= (\text{old} - \text{new}) \times \text{hours}$.

Substitution: Hydraulic $= 1,000 \times 9.81 \times 0.03333 \times 24 / 1,000 = 7.848 \text{ kW}$; input $= 7.848 / (0.78 \times 0.92) = 10.94 \text{ kW}$

Saving $= (18.75 - 10.94) \times 8,000$

Result: New pump input = 10.94 kW; saving = 62,530 kWh/year.

d) Total saving, payback and kWh per 1,000 m (4 marks)

Given: ₹ 7.20/kWh; investment ₹ 14 + 6 = ₹ 20 lakh; 36,00,000 m/year.

Formula: ₹ saving $= \text{kWh} \times \text{tariff}$; payback $= \text{cost} / \text{saving}$; kWh/1,000 m $= \text{annual kWh} / \text{fabric} \times 1,000$.

Substitution: Total $= 2,57,901 + 62,530 = 3,20,430 \text{ kWh} \rightarrow ₹ 23,07,099$; payback $= 20,00,000 / 23,07,099$

Before $= 7,46,948 / 36,00,000 \times 1,000$; after $= 4,26,518 / 36,00,000 \times 1,000$

Result: Saving = ₹ 23,07,099 (₹ 23.07 lakh) a year; simple payback = 0.87 year; humidification energy falls from 207.5 to 118.5 kWh per 1,000 m of fabric.

..... End of Section - III

ANSWER KEY**Section I – Brief questions (True/False)**

Q	Code	Chapter	Answer
1	5P4CEA001	Chapter 1: Boilers	True
2	5P4CEA002	Chapter 4: Heat Exchangers	False
3	5P4CEA003	Chapter 5: Electric Motors and Variable Speed Drives	False
4	5P4CEA004	Chapter 3: Cogeneration Systems	True
5	5P4CEA005	Chapter 11: Thermal Power Station	True
6	5P4CEA006	Chapter 12: Steel Industry	False
7	5P4CEA007	Chapter 13: Cement Industry	False
8	5P4CEA008	Chapter 14: Buildings and Commercial Establishments	True
9	5P4CEA009	Chapter 15: Textile Industry	True
10	5P4CEA010	Chapter 7: Pumps	False

Sections II and III – headline results (full working in the model answers)

Q	Code	Marks	Headline result
L-1	5P4CEA011	5	Saving = 36,55,971 kWh/year worth ₹ 2,48,60,606 (₹ 2.49 crore); simple payback = 3.82 years. Mechanical conveying is one of the main electrical saving options listed for cement plants.
L-2	5P4CEA012	5	Fan input falls to 45.08 kW; saving = 2,62,205 kWh/year worth ₹ 19,66,537 (₹ 19.67 lakh); simple payback = 0.92 year. Louvre throttling wastes fan power; speed control lets the cooler use the cold ambient instead.
N-1	5P4CEA013	20	Efficiency rises to 89.73 % (+0.40 points); petcoke saved = 409 t and limestone saved = 7,820 t a year, worth ₹ 1,70,16,406 (₹ 1.70 crore). Most of the money comes from limestone, but the efficiency gain also cuts ash disposal and CO ₂ .
N-2	5P4CEA014	20	Heat recovered = 77.27 kW, worth ₹ 37,09,056 (₹ 37.09 lakh) a year by switching off the electric oven heater – the drying oven is the natural sink for kettle flue heat in a galvanizing line.
N-3	5P4CEA015	20	Hot water = 5,670 kg/h at 70 °C; furnace oil saved = 2,09,264 kg/year worth ₹ 1,15,09,516 (₹ 1.15 crore); payback = 0.30 year.

			Together with (b) and (c), the plant saves ₹ 1,39,88,712 (₹ 1.40 crore) a year – heat recovery is usually the largest single compressed-air opportunity because almost all th
N-4(a)	5P4CEA016a	20	The top three give 62.9 % of the deviation, costing ₹ 38,18,65,800 (₹ 38.19 crore) a year in coal; total extra CO ₂ = 2,18,790 t/year. Priorities: condenser cleaning and air-ingress tests, finding the cause of reheat spray (burner tilt, soot blowing), and APH cleaning.
N-4(b)	5P4CEA016b	20	Annual value = ₹ 49,86,66,764 (₹ 49.87 crore); simple payback = 3.31 years; SEC falls to 3,80,493 kcal/t (– 3.73 %).
N-4(c)	5P4CEA016c	20	Net saving = ₹ 15,44,08,707 (₹ 15.44 crore) a year; simple payback = 2.07 years. The heat penalty is real: RDF moisture and the extra air it needs raise the kiln's specific heat, so TSR projects must be judged on net coal saved, not gross RDF heat.
N-4(d)	5P4CEA016d	20	Saving = ₹ 23,07,099 (₹ 23.07 lakh) a year; simple payback = 0.87 year; humidification energy falls from 207.5 to 118.5 kWh per 1,000 m of fabric.