

PRACTICE PAPER

NATIONAL CERTIFICATION EXAMINATION FOR ENERGY MANAGERS & ENERGY AUDITORS

PAPER – 2: ENERGY EFFICIENCY IN THERMAL UTILITIES

Question Code: 1P2CEM — SOLUTIONS & MODEL ANSWERS

Duration: 3 HRS Max. Marks: 150

General instructions:

- Please check that this question paper contains 64 questions
- The question paper is divided into three sections
- All questions in all three sections are compulsory
- All parts of a question should be answered at one place
- Use of a non-programmable scientific calculator is permitted

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Section – I: OBJECTIVE TYPE

Marks: 50 x 1 = 50

(i) Answer all 50 questions

(ii) Each question carries one mark

1. A furnace oil has C 85%, H₂ 12%, O₂ 1% and S 2% by mass. The flue gas O₂ measured at the boiler outlet is 4%. The actual mass of air supplied per kg of oil is closest to: [1P2CEM001]

- a) 14.1 kg
- b) 16.8 kg
- c) 17.4 kg**
- d) 19.7 kg

Correct answer: (c) 17.4 kg.

Given: C = 85%, H₂ = 12%, O₂ = 1%, S = 2%; O₂ in flue gas = 4%.

Formula (guidebook): Theoretical air = $[11.6C + 34.8(H_2 - O_2/8) + 4.35S]/100$ kg/kg fuel; EA% = $O_2/(21 - O_2) \times 100$; AAS = $(1 + EA/100) \times \text{theoretical air}$.

Substitution: Theoretical air = $[11.6 \times 85 + 34.8 \times (12 - 0.125) + 4.35 \times 2]/100 = (986 + 413.25 + 8.7)/100 = 14.08$ kg/kg. EA = $4/(21 - 4) \times 100 = 23.5\%$. AAS = 1.235×14.08 .

Result: **AAS ≈ 17.4 kg air/kg oil.**

Why not the others: (a) 14.1 kg is only the stoichiometric air; excess air is ignored. (b) 16.8 kg uses EA = O₂/21 (19%), which is the wrong relation. (d) 19.7 kg assumes 40% excess air (a rough 10% per 1% O₂ rule), not the guidebook formula.

Ref: BEE Guidebook Paper 2, Ch. 1 (Combustion of oil) and Ch. 2 (indirect method, Steps 1–3).

Chapter 1: Fuels and Combustion | Stoichiometric and actual air from ultimate analysis

2. An Indian steam coal has GCV 4,200 kcal/kg, hydrogen 4% and total moisture 12%. Using the guidebook relation between GCV and NCV, the NCV of this coal is about: [1P2CEM002]

- a) 3,640 kcal/kg

b) 3,920 kcal/kg

c) 3,990 kcal/kg

d) 4,130 kcal/kg

Correct answer: (b) 3,920 kcal/kg.

Given: GCV = 4,200 kcal/kg ($\approx 17,585$ kJ/kg); H = 4%; M = 12%; latent heat = 584 kcal/kg ($\approx 2,445$ kJ/kg).

Formula (guidebook): $GCV = NCV + 584 \times (9H\% + M\%)/100$, so $NCV = GCV - 584 \times (9H + M)/100$.

Substitution: Water formed and present = $(9 \times 4 + 12)/100 = 0.48$ kg/kg coal. Deduction = $0.48 \times 584 = 280.3$ kcal/kg. $NCV = 4,200 - 280.3$.

Result: **NCV $\approx 3,920$ kcal/kg ($\approx 16,410$ kJ/kg).**

Why not the others: (d) 4,130 deducts only the moisture (0.12×584) and forgets water formed from hydrogen. (c) 3,990 deducts only the hydrogen water (9H) and forgets the moisture. (a) 3,640 deducts the latent heat twice.

Ref: BEE Guidebook Paper 2, Ch. 1, §1.2 (Calorific value).

Chapter 1: Fuels and Combustion | GCV–NCV conversion

3. Select the WRONG statement regarding properties of furnace oil as given in the BEE guidebook: [1P2CEM003]

a) Its viscosity rises with temperature, so it is preheated to thicken

b) Its flash point is about 66 °C, which governs safe storage

c) Its specific heat lies between about 0.22 and 0.28 kcal/kg °C

d) Its pour point indicates the lowest temperature at which it flows

Correct answer: (a) Its viscosity rises with temperature, so it is preheated to thicken.

The guidebook states that viscosity is the most important property for storage and use of fuel oil, and that viscosity decreases as temperature increases. That is exactly why furnace oil is heated (for pumping and then for atomisation at the burner). The statement that viscosity rises with temperature is therefore wrong.

Why the others are correct: (b) The guidebook gives the flash point of furnace oil as 66 °C; it decides storage and handling temperatures. (c) Specific heat varies from 0.22 to 0.28 kcal/kg °C depending on specific gravity; heavier oils have higher specific heat. (d) Pour point is the lowest temperature at which oil will pour or flow when cooled, and indicates the minimum handling temperature.

Ref: BEE Guidebook Paper 2, Ch. 1, §1.2 (Properties of liquid fuels).

Chapter 1: Fuels and Combustion | Properties of liquid fuels

4. An energy auditor must calculate the theoretical combustion air and the flue gas quantity for a stoker-fired coal boiler. Which coal data set is essential for this calculation? [1P2CEM004]

a) Proximate analysis giving fixed carbon, volatiles and ash

b) Ash fusion temperature and the Hardgrove grindability index

c) Gross calorific value together with the coal size grading

d) Ultimate analysis giving C, H, O, N and S percentages

Correct answer: (d) Ultimate analysis giving C, H, O, N and S percentages.

The theoretical air formula used in the guidebook, $[11.6C + 34.8(H_2 - O_2/8) + 4.35S]/100$, needs the elemental composition of the fuel. The mass of dry flue gas (CO_2 from carbon, SO_2 from sulphur, N_2 from fuel and air) also needs C, N and S. These values come only from the ultimate analysis.

Why not the others: (a) Proximate analysis (fixed carbon, volatile matter, ash, moisture) indicates burning behaviour and furnace design needs, but gives no elemental C, H, O, S. (b) Ash fusion temperature and grindability matter for clinkering and milling, not for an air calculation. (c) GCV and sizing affect heat input and the firing method, but you cannot derive the air requirement from them.

Ref: BEE Guidebook Paper 2, Ch. 1, §1.3 (Properties of coal) and §1.6 (Combustion).

Chapter 1: Fuels and Combustion | Proximate vs ultimate analysis

5. Which statement correctly explains why a natural gas burner can operate with far less excess air (about 5%) than a stoker-fired coal boiler? [1P2CEM005]

a) Gas mixes with air at the molecular level, so mixing is nearly perfect

b) Gas has a higher calorific value, so it needs less oxygen per kcal

c) Gas contains no hydrogen, so no water vapour is formed in combustion

d) Gas burns at a lower flame temperature, which suppresses CO formation

Correct answer: (a) Gas mixes with air at the molecular level, so mixing is nearly perfect.

Excess air is needed because mixing of fuel and air is never perfect. The guidebook explains that in a gas burner the fuel and air are well mixed (both are gases), so only a small amount of excess air, of the order of 5%, is required. Solid fuels need much more excess air because oxygen must reach the surface of each burning particle.

Why not the others: (b) Calorific value does not decide excess air; the air needed per unit heat is broadly similar for most fossil fuels. (c) Natural gas (mainly methane) is rich in hydrogen and produces a lot of water vapour. (d) Natural gas flames are not cooler in a way that removes the need for air; good mixing is the reason.

Ref: BEE Guidebook Paper 2, Ch. 1, §1.9 (Combustion of gas) and §1.7 (Optimising excess air).

Chapter 1: Fuels and Combustion | Excess air requirement for different fuels

6. On a mass basis (kg of air per kg of fuel), which of the following fuels needs the MAXIMUM air for stoichiometric combustion? [1P2CEM006]

a) Butane

b) Furnace oil

c) Bituminous coal

d) Hydrogen

Correct answer: (d) Hydrogen.

Using the guidebook relation, hydrogen needs 34.8 kg of air per kg ($8 \text{ kg O}_2 \text{ per kg H}_2 \div 0.23$), while carbon needs only 11.6 kg of air per kg. So the higher a fuel's hydrogen share, the more air it needs per kg.

Why not the others: (a) Butane (C_4H_{10}) needs about 15.4 kg/kg because it is mostly carbon by mass. (b) Furnace oil needs about 14.1 kg/kg (guidebook value). (c) Coal needs even less air per kg (about 5–8 kg/kg for Indian coals) because of its ash, moisture and oxygen.

Exam tip: $34.8 (\text{H}_2) > 11.6 (\text{C}) > 4.35 (\text{S}) \text{ kg air per kg element}$.

Ref: BEE Guidebook Paper 2, Ch. 1, §1.6 (Stoichiometric calculation).

Chapter 1: Fuels and Combustion | Theoretical air: comparison of fuels

7. A Fyrite test on an oil-fired boiler shows 11.2% CO_2 in dry flue gas. The theoretical CO_2 for this oil is 15.5%. Using the guidebook formula, the excess air is about: [1P2CEM007]

a) 25.9%

b) 27.7%

c) 35.9%

d) 38.4%

Correct answer: (c) 35.9%.

Given: $(\text{CO}_2)_t = 15.5\%$; $(\text{CO}_2)_a = 11.2\%$.

Formula (guidebook): $\text{EA}\% = 7900 \times [(\text{CO}_2)_t - (\text{CO}_2)_a] / \{(\text{CO}_2)_a \times [100 - (\text{CO}_2)_t]\}$.

Substitution: $\text{EA} = 7900 \times (15.5 - 11.2) / [11.2 \times (100 - 15.5)] = 7900 \times 4.3 / (11.2 \times 84.5) = 33,970 / 946.4$.

Result: **EA $\approx$ 35.9%**.

Why not the others: (d) 38.4% is the simple ratio $(15.5/11.2 - 1) \times 100$, which ignores the dilution of CO_2 by the extra nitrogen. (a) 25.9% puts the theoretical CO_2 (15.5) in the denominator instead of the actual CO_2 . (b) 27.7% simply takes the CO_2 drop as a fraction of theoretical CO_2 , $(15.5 - 11.2)/15.5$, which is not the guidebook relation.

Ref: BEE Guidebook Paper 2, Ch. 1, §1.7 (Calculation of constituents of flue gas with excess air).

8. A burner rated at 600 kg/h of oil can hold a stable flame at the correct excess air down to 150 kg/h. Which statement about this burner is correct? [1P2CEM008]

- a) Its turndown ratio is 4:1, the max-to-min firing range
- b) Its turndown ratio is 0.25, the min-to-max firing range
- c) Its turndown ratio is 450 kg/h, the usable firing span
- d) Its turndown ratio is 4:1, the max-to-min air flow range

Correct answer: (a) Its turndown ratio is 4:1, the max-to-min firing range.

The guidebook defines turndown ratio as the relationship between the maximum and minimum fuel input without affecting the excess air level. Here $600/150 = 4$, so the turndown ratio is 4:1. A higher turndown lets the burner follow load changes without frequent on/off cycling, which saves purge and start-up losses.

Why not the others: (b) It inverts the ratio; turndown is always expressed as maximum to minimum. (c) It gives a difference in kg/h, not a ratio. (d) It uses the right number but the wrong basis; turndown is defined on fuel input at constant excess air, not on air flow range.

Ref: BEE Guidebook Paper 2, Ch. 1, §1.7 (Oil firing burners; turndown ratio).

Chapter 1: Fuels and Combustion | Burner turndown ratio

9. A rice mill wants to fire paddy husk in an existing oil-fired package boiler. Which characteristic of husk is the MAIN reason this needs a different furnace design? [1P2CEM009]

- a) High sulphur content causes severe cold-end corrosion in the boiler
- b) High hydrogen content forms excess water vapour in the flue gas
- c) High flash point stops husk from igniting in an oil-type furnace
- d) High ash and low bulk density need larger furnaces and ash handling**

Correct answer: (d) High ash and low bulk density need larger furnaces and ash handling.

Agro residues such as paddy husk have low bulk density, a modest calorific value (about 3,570 kcal/kg in the guidebook table) and high ash (about 17%). A much larger volume of fuel must be fed and burnt, and a large quantity of ash must be removed continuously. A compact oil-fired furnace with no grate or ash handling cannot do this, so a grate, fluidised bed or dedicated biomass furnace is needed.

Why not the others: (a) Paddy husk is low in sulphur (about 0.1%); corrosion from SO₃ is a problem of high-sulphur oils and coals. (b) Husk is not rich in hydrogen compared with oil or gas. (c) Flash point is a property of liquid fuels and does not apply to a solid residue.

Ref: BEE Guidebook Paper 2, Ch. 1, §1.5 (Properties of agro residues) and §1.10; Ch. 6, §6.6.

Chapter 1: Fuels and Combustion | Agro residue and biomass properties

10. An oil-fired boiler generates 10 TPH of steam (enthalpy 660 kcal/kg) with feed water at 70 °C. It consumes 820 litres/h of furnace oil (density 0.93 kg/litre, GCV 10,200 kcal/kg). The boiler efficiency by the direct method is:

[1P2CEM010]

- a) 70.5%
- b) 75.9%**
- c) 78.9%
- d) 84.8%

Correct answer: (b) 75.9%.

Given: $Q = 10,000$ kg/h; $h_g = 660$ kcal/kg ($\approx 2,763$ kJ/kg); $h_f = 70$ kcal/kg (≈ 293 kJ/kg); fuel = $820 \text{ L/h} \times 0.93 = 762.6$ kg/h; GCV = $10,200$ kcal/kg ($\approx 42,705$ kJ/kg).

Formula (guidebook): $\eta = Q \times (h_g - h_f) / (q \times \text{GCV}) \times 100$.

Substitution: Heat output = $10,000 \times (660 - 70) = 59,00,000$ kcal/h. Heat input = $762.6 \times 10,200 = 77,78,520$ kcal/h.

Result: $\eta = 75.9\%$ (GCV basis).

Why not the others: (a) 70.5% uses 820 litres as kg (density ignored). (c) 78.9% ignores the density and also uses steam enthalpy without subtracting the feed water enthalpy. (d) 84.8% forgets to subtract the feed water enthalpy (uses 660 kcal/kg).

Ref: BEE Guidebook Paper 2, Ch. 2, §2.4 (Direct method).

Chapter 2: Boilers | Boiler efficiency by direct method

11. For an oil-fired boiler: hydrogen in fuel 11.5%, GCV 10,250 kcal/kg, flue gas exit 210 °C, ambient 30 °C. Taking latent heat 584 kcal/kg and Cp of superheated vapour 0.45 kcal/kg °C, the heat loss due to hydrogen in fuel is:

[1P2CEM011]

a) 0.75%

b) 5.90%

c) 6.71%

d) 7.71%

Correct answer: (c) 6.71%.

Given: $H_2 = 0.115$ kg/kg; $T_f = 210$ °C; $T_a = 30$ °C; GCV = 10,250 kcal/kg ($\approx 42,915$ kJ/kg).

Formula (guidebook): $L_2 = 9 \times H_2 \times [584 + C_p(T_f - T_a)] / \text{GCV} \times 100$.

Substitution: Water formed = $9 \times 0.115 = 1.035$ kg/kg fuel. Heat per kg water = $584 + 0.45 \times 180 = 665$ kcal/kg. Loss = $1.035 \times 665 / 10,250 \times 100$.

Result: $L_2 = 6.71\%$.

Why not the others: (a) 0.75% forgets the factor 9 (1 kg H_2 forms 9 kg water). (b) 5.90% leaves out the superheat term $C_p(T_f - T_a)$. (d) 7.71% uses $C_p = 1$ kcal/kg °C (liquid water) instead of 0.45 for vapour.

Note: this is the largest loss after dry flue gas loss in oil and gas boilers, and it is the reason GCV- and NCV-based efficiencies differ.

Ref: BEE Guidebook Paper 2, Ch. 2, §2.4 (Indirect method, loss L_2).

Chapter 2: Boilers | Indirect method: loss due to hydrogen in fuel

12. While computing boiler efficiency by the indirect (heat loss) method as per the guidebook, which of the following losses is NOT included in the standard loss list? [1P2CEM012]

a) Blowdown loss from the boiler water drum

b) Loss due to moisture in combustion air

c) Loss due to unburnt carbon in fly ash

d) Loss due to partial combustion of C to CO

Correct answer: (a) Blowdown loss from the boiler water drum.

The guidebook clearly states that the standards do not include blowdown loss in the efficiency determination. The indirect method deducts these from 100: dry flue gas loss, loss due to hydrogen in fuel, moisture in fuel, moisture in air, partial conversion of C to CO, radiation and convection (surface) loss, and unburnt in fly ash and bottom ash.

Why not the others: (b) Moisture in combustion air is loss L_4 ($AAS \times \text{humidity} \times 0.45 \times \Delta T / \text{GCV}$). (c) Unburnt in fly ash is loss L_7 , worked out from fly ash quantity and its GCV. (d) The CO loss L_5 uses $\%CO \times C / (\%CO + \%CO_2) \times 5654 / \text{GCV}$.

Exam tip: blowdown is still an energy loss; it is assessed separately (Section 2.6), not inside the efficiency.

Ref: BEE Guidebook Paper 2, Ch. 2, §2.4.

Chapter 2: Boilers | Indirect method: scope of losses

13. A package boiler has a maximum permissible TDS of 3,000 ppm. Feed water TDS is 250 ppm and make-up water is 40% of feed water. The required blowdown as a percentage is: [1P2CEM013]

a) 3.08%

b) 3.33%

c) 3.64%

d) 9.09%

Correct answer: (c) 3.64%.

Given: Feed water TDS = 250 ppm; make-up = 40%; maximum permissible TDS = 3,000 ppm.

Formula (guidebook): Blowdown % = (Feed water TDS × % make-up water) / (Maximum permissible TDS – Feed water TDS).

Substitution: Blowdown = $(250 \times 40) / (3,000 - 250) = 10,000 / 2,750$.

Result: **Blowdown ≈ 3.64%.**

Why not the others: (a) 3.08% adds the feed TDS in the denominator (3,000 + 250) instead of subtracting it. (b) 3.33% divides by 3,000 only and forgets to subtract the feed water TDS. (d) 9.09% takes make-up as 100%, so the benefit of condensate return is ignored.

Ref: BEE Guidebook Paper 2, Ch. 2, §2.6 (Blowdown calculations).

Chapter 2: Boilers | Blowdown calculation

14. Select the CORRECT statement about boiler feed water treatment as described in the guidebook: [1P2CEM014]

a) A base-exchange softener removes hardness but does not reduce TDS

b) Internal treatment alone is recommended for high-pressure boilers

c) Sodium sulphite dosing lowers boiler water TDS and blowdown

d) Reverse osmosis is suitable only for low-TDS raw water supplies

Correct answer: (a) A base-exchange softener removes hardness but does not reduce TDS.

In a base-exchange (ion-exchange) softener, calcium and magnesium ions are swapped for sodium ions. Sodium salts are soluble and do not form scale, but the total dissolved solids stay the same. So the softener does not reduce TDS, blowdown quantity or alkalinity.

Why not the others: (b) The guidebook says internal treatment is limited to low-pressure boilers with low-hardness feed water, and that internal treatment alone is not recommended. (c) Sodium sulphite reacts with oxygen to form sodium sulphate, which raises TDS and blowdown; hydrazine is used where low solids are needed. (d) RO is suitable for waters with very high TDS, such as sea water.

Ref: BEE Guidebook Paper 2, Ch. 2, §2.5 (Boiler water treatment).

Chapter 2: Boilers | Boiler water treatment

15. A pressure-type deaerator is preferred over a vacuum deaerator in a 40 kg/cm² boiler house. Which pair of figures matches the guidebook description of these two types? [1P2CEM015]

a) Pressure type: about 82 °C, O₂ to 0.02 mg/L; vacuum type: min. 105 °C, below 0.005 mg/L

b) Pressure type: min. 105 °C, O₂ to 0.5 mg/L; vacuum type: about 82 °C, below 2.0 mg/L

c) Pressure type: min. 120 °C, O₂ to zero mg/L; vacuum type: about 60 °C, below 0.05 mg/L

d) Pressure type: min. 105 °C, O₂ to 0.005 mg/L; vacuum type: about 82 °C, below 0.02 mg/L

Correct answer: (d) Pressure type: min. 105 °C, O₂ to 0.005 mg/L; vacuum type: about 82 °C, below 0.02 mg/L.

The guidebook explains that mechanical deaeration works on Charles' and Henry's laws: heating the feed water drives out dissolved O₂ and CO₂. The vacuum type works below atmospheric pressure at about 82 °C and can reduce oxygen to less than 0.02 mg/litre. The pressure type admits steam to hold a minimum of 105 °C and can reduce oxygen to 0.005 mg/litre. It can also use surplus low-pressure steam, which improves fuel economy.

Why not the others: (a) It swaps the two types. (b) The temperatures are right but the oxygen levels are 100 times too high to protect a boiler. (c) It invents 120 °C and 'zero' oxygen; residual oxygen is removed by chemical scavengers.

Ref: BEE Guidebook Paper 2, Ch. 2, §2.5 (De-aeration).

Chapter 2: Boilers | Deaeration

16. A boiler fires 1,200 kg/h of furnace oil for 7,200 h/year. A new economiser raises feed water temperature by 36 °C. Using the guidebook thumb rule, the annual fuel oil saving is about: [1P2CEM016]

a) 156 tonnes

b) 311 tonnes

c) 518 tonnes

d) 622 tonnes

Correct answer: (c) 518 tonnes.

Given: Fuel = 1,200 kg/h; operation = 7,200 h/year; feed water rise = 36 °C.

Formula (guidebook thumb rule): 1% fuel saving for every 6 °C rise in feed water temperature through an economiser.

Substitution: Saving = $36/6 = 6\%$. Fuel saved = $0.06 \times 1,200 \times 7,200 / 1,000$.

Result: **≈ 518 tonnes/year.**

Why not the others: (a) 156 t applies the air-preheater rule (1% per 20 °C rise in combustion air temperature) to feed water. (b) 311 t assumes 1% per 10 °C, which is not a guidebook rule. (d) 622 t assumes 1% per 5 °C and overstates the benefit.

Related rule: 1% saving per 22 °C reduction in flue gas temperature.

Ref: BEE Guidebook Paper 2, Ch. 2, §2.9, and Ch. 8 (Economiser).

Chapter 2: Boilers | Economiser thumb rule

17. A 60 TPH high-pressure boiler uses manual intermittent blowdown 'once a shift for 2 minutes'. What is the main energy advantage of converting to continuous blowdown? [1P2CEM017]

a) It eliminates blowdown completely because TDS stays below the limit

b) It allows a smaller deaerator because less feed water is needed

c) It raises the boiler steam pressure as boiler water density falls

d) Steady TDS, and blowdown heat is recoverable in a flash tank

Correct answer: (d) Steady TDS, and blowdown heat is recoverable in a flash tank.

In continuous blowdown, a small, steady stream of concentrated boiler water is removed and replaced by feed water. This keeps TDS and steam purity constant without operator action. Because the flow is steady, it can be piped to a flash tank to make flash steam (for example for the deaerator), and the residual hot water can preheat make-up water. The guidebook notes this is common in high-pressure boilers.

Why not the others: (a) Blowdown is still needed; continuous operation only removes it steadily. (b) Intermittent blowdown needs large short-term increases in feed water, but deaerator size is not the energy benefit. (c) Blowdown method does not change boiler operating pressure.

Ref: BEE Guidebook Paper 2, Ch. 2, §2.6 (Intermittent and continuous blowdown).

Chapter 2: Boilers | Blowdown methods and heat recovery

18. A plant needs steam with an enthalpy rise of 600 kcal/kg from coal (GCV 4,000 kcal/kg, ₹ 8,000 per tonne) in a boiler of 80% efficiency. The fuel cost of generating one tonne of steam is: [1P2CEM018]

a) ₹ 960

b) ₹ 1,200

c) ₹ 1,500

d) ₹ 1,875

Correct answer: (c) ₹ 1,500.

Given: Heat to steam = $1,000 \text{ kg} \times 600 \text{ kcal/kg} = 6,00,000 \text{ kcal}$ ($\approx 2,512 \text{ MJ}$); GCV = 4,000 kcal/kg ($\approx 16,747 \text{ kJ/kg}$); $\eta = 80\%$; coal = ₹ 8/kg.

Formula: Coal per tonne of steam = Heat to steam / (GCV $\times \eta$); Fuel cost = coal kg $\times$ ₹/kg.

Substitution: Coal = $6,00,000 / (4,000 \times 0.80) = 187.5 \text{ kg}$. Cost = 187.5×8 .

Result: **₹ 1,500 per tonne of steam** (evaporation ratio 5.33).

Why not the others: (a) ₹ 960 multiplies by the efficiency instead of dividing. (b) ₹ 1,200 ignores boiler efficiency altogether (150 kg coal). (d) ₹ 1,875 divides by efficiency twice.

Exam tip: always compare fuels on cost per unit of useful heat (₹ per lakh kcal delivered), not on ₹ per tonne of fuel.

Ref: BEE Guidebook Paper 2, Ch. 2, §2.4 and Ch. 1.

19. Condensate at 4,000 kg/h from a 12 kg/cm²(g) process is flashed to 3 kg/cm²(g). Sensible heat at 12 kg/cm² = 195.0 kcal/kg; at 3 kg/cm² sensible heat = 133.4 kcal/kg and latent heat = 517.0 kcal/kg. The flash steam generated is about: [1P2CEM019]

- a) 379 kg/h
- b) 477 kg/h**
- c) 523 kg/h
- d) 642 kg/h

Correct answer: (b) 477 kg/h.

Given: $S_1 = 195.0$ kcal/kg (≈ 816 kJ/kg); $S_2 = 133.4$ kcal/kg (≈ 559 kJ/kg); $L_2 = 517.0$ kcal/kg ($\approx 2,165$ kJ/kg); condensate = 4,000 kg/h.

Formula (guidebook): Flash steam fraction = $(S_1 - S_2)/L_2$.

Substitution: $(195.0 - 133.4)/517.0 = 61.6/517.0 = 0.1191$ (11.9%). Flash steam = $0.1191 \times 4,000$.

Result: **≈ 477 kg/h** of 3 kg/cm² steam (≈ 2.94 bar); balance $\approx 3,523$ kg/h of condensate.

Why not the others: (a) 379 kg/h divides by the total heat ($S_2 + L_2 = 650.4$) instead of the latent heat. (c) 523 kg/h uses the latent heat at the high pressure (471 kcal/kg). (d) 642 kg/h divides by $(L_2 - S_2)$, which is not a valid term.

Ref: BEE Guidebook Paper 2, Ch. 3, §3.7 (Flash steam recovery).

Chapter 3: Steam System | Flash steam recovery

20. A heater receives steam at 8 kg/cm²(g) that is only 92% dry. Which statement correctly describes the effect compared with dry saturated steam? [1P2CEM020]

- a) More steam is needed per kcal, and the water film on surfaces cuts heat transfer**
- b) Steam needed per kcal is unchanged, since only latent heat is used by the heater
- c) Less steam is needed per kcal, since the water droplets add extra sensible heat
- d) Heat transfer improves because the water film on the tubes raises the surface coefficient

Correct answer: (a) More steam is needed per kcal, and the water film on surfaces cuts heat transfer.

Wet steam carries only $x \times L$ of latent heat per kg (here $0.92 \times L$). For the same process heat, the steam flow must rise by about $1/0.92 = 8.7\%$. The guidebook also points out that the water in wet steam forms a film on heat transfer surfaces, which acts as a barrier and reduces the heat transfer rate. Dry saturated steam is therefore preferred for process heating, and separators and correct trap drainage are used to keep steam dry.

Why not the others: (b) Heaters do use latent heat, which is exactly why reduced dryness raises steam use. (c) Water droplets carry no extra latent heat; their sensible heat is already counted in h_f . (d) A water film adds resistance; it does not improve the coefficient.

Ref: BEE Guidebook Paper 2, Ch. 3, §3.2 (Dryness fraction) and §3.4.

Chapter 3: Steam System | Effect of wetness of steam

21. For a temperature-controlled heat exchanger whose steam pressure varies widely with load and which must drain condensate immediately as it forms, the guidebook regards which trap as closest to the ideal? [1P2CEM021]

- a) Float trap fitted with a thermostatic air vent**
- b) Thermodynamic (disc) trap fitted with a strainer
- c) Bimetallic thermostatic trap with sub-cooled discharge
- d) Inverted bucket trap fitted without any air vent

Correct answer: (a) Float trap fitted with a thermostatic air vent.

The guidebook states that, in many ways, the float-thermostatic trap is the closest to an ideal steam trap. It discharges condensate continuously at steam temperature as soon as it forms, whatever the load or pressure, while the thermostatic element vents air at start-up. This makes it suitable for heat exchangers with modulating control.

Why not the others: (b) Thermodynamic traps need a minimum pressure difference and do not work well with modulating control or low back pressure. (c) A bimetallic thermostatic trap holds condensate back until it sub-cools, so condensate waterlogs the exchanger. (d) An inverted bucket trap discharges intermittently and has poor air handling, which slows start-up.

Ref: BEE Guidebook Paper 2, Ch. 3, §3.5 (Selection, operation and maintenance of steam traps).

Chapter 3: Steam System / Steam trap selection

22. A pressure gauge on a jacketed vessel reads 3 kg/cm²(g), yet the measured steam space temperature is clearly below the saturation temperature at that pressure. The most likely cause is: [1P2CEM022]

- a) Superheat in the supply steam, raising the specific volume
- b) High dryness fraction of steam entering the vessel jacket
- c) Flash steam formation at the outlet of the jacket steam trap
- d) Air mixed with steam, lowering the steam's partial pressure**

Correct answer: (d) Air mixed with steam, lowering the steam's partial pressure.

In a steam–air mixture, the total pressure is shared between steam and air (Dalton's law). The steam's own partial pressure is lower than the gauge reading, so its temperature is lower than the saturation temperature for that gauge pressure. Air also forms an insulating film on the heating surface, so it reduces the heat transfer rate too. This is why air vents are fitted at the far end of steam spaces and why traps with good air venting are preferred.

Why not the others: (a) Superheat would raise the temperature, not lower it. (b) A high dryness fraction is desirable and has no effect on saturation temperature. (c) Flash steam at the trap outlet occurs on the low-pressure side and does not lower the jacket temperature.

Ref: BEE Guidebook Paper 2, Ch. 3, §3.3 and §3.4 (Air venting).

Chapter 3: Steam System / Air and non-condensables in steam

23. A 5,000 kg/h saturated steam line at 7 kg/cm²(g) (specific volume 0.24 m³/kg) is to be sized at 35 m/s, within the guidebook velocity band for saturated steam. The required internal diameter is about: [1P2CEM023]

- a) 55 mm
- b) 92 mm
- c) 110 mm**
- d) 130 mm

Correct answer: (c) 110 mm.

Given: $m = 5,000 \text{ kg/h}$; $v = 0.24 \text{ m}^3/\text{kg}$; velocity $u = 35 \text{ m/s}$ (guidebook band for saturated steam: 30–40 m/s).

Formula: Volume flow = $m \times v / 3,600$; Area = Volume flow / u ; $d = \sqrt{4A/\pi}$.

Substitution: Volume flow = $5,000 \times 0.24 / 3,600 = 0.333 \text{ m}^3/\text{s}$. $A = 0.333/35 = 0.00952 \text{ m}^2$. $d = \sqrt{4 \times 0.00952/\pi}$.

Result: **$d \approx 0.110 \text{ m} = 110 \text{ mm}$** (select the next standard size).

Why not the others: (a) 55 mm is the radius, not the diameter. (b) 92 mm uses 50 m/s, a velocity meant for superheated steam (50–70 m/s). (d) 130 mm uses 25 m/s, which is the band for wet or exhaust steam (20–30 m/s).

Ref: BEE Guidebook Paper 2, Ch. 3, §3.3 (Pipe sizing and velocities).

Chapter 3: Steam System / Steam pipe sizing

24. A dyeing unit reduces process steam pressure from 10 kg/cm²(g) to 4 kg/cm²(g) with a PRV, since the 4 kg/cm² saturation temperature still meets its needs. Why does this generally reduce steam consumption? [1P2CEM024]

- a) Latent heat per kg is higher at the lower pressure, so fewer kg are needed**
- b) Enthalpy rises across the PRV, so each kg of steam carries more total heat
- c) Sensible heat is higher at the lower pressure, so condensate holds more heat
- d) Steam becomes wetter after the PRV, which improves the film heat transfer

Correct answer: (a) Latent heat per kg is higher at the lower pressure, so fewer kg are needed.

As steam pressure falls, the sensible heat (hf) falls and the latent heat (hfg) rises, while total enthalpy changes only a little. Process heaters use the latent heat, so steam at the lowest pressure that still gives the required temperature delivers more usable heat per kg. Throttling across a PRV is also an isenthalpic process, so the steam becomes slightly drier (it does not become wetter). Lower pressure also reduces flash and distribution losses.

Why not the others: (b) Enthalpy stays constant across a PRV; it does not rise. (c) Sensible heat falls at lower pressure. (d) Throttling dries the steam, and wetness would reduce heat transfer anyway.

Ref: BEE Guidebook Paper 2, Ch. 3, §3.2 (Properties of steam) and §3.4 (Steam at lowest acceptable pressure).

Chapter 3: Steam System / Steam pressure and latent heat

25. A plant starts returning 6 TPH of condensate at 85 °C instead of using make-up water at 30 °C. The boiler fires furnace oil (GCV 10,200 kcal/kg) at 85% efficiency. The fuel oil saved is about: [1P2CEM025]

a) 27.5 kg/h

b) 32.4 kg/h

c) 38.1 kg/h

d) 58.8 kg/h

Correct answer: (c) 38.1 kg/h.

Given: Condensate = 6,000 kg/h; $\Delta T = 85 - 30 = 55$ °C; $C_p = 1$ kcal/kg °C (≈ 4.19 kJ/kg·K); GCV = 10,200 kcal/kg ($\approx 42,705$ kJ/kg); $\eta = 0.85$.

Formula: Heat recovered = $m \times C_p \times \Delta T$; Fuel saved = Heat recovered / (GCV $\times \eta$).

Substitution: Heat = $6,000 \times 1 \times 55 = 3,30,000$ kcal/h. Fuel = $3,30,000 / (10,200 \times 0.85) = 3,30,000 / 8,670$.

Result: ≈ 38.1 kg/h of furnace oil (≈ 2.74 tonnes/day at 24 h/day).

Why not the others: (a) 27.5 kg/h multiplies by efficiency instead of dividing. (b) 32.4 kg/h ignores boiler efficiency. (d) 58.8 kg/h uses 85 °C as the temperature rise, forgetting the 30 °C make-up water base.

Note: water and treatment chemical savings come on top of this. Ref: BEE Guidebook Paper 2, Ch. 3, §3.7 (Condensate recovery).

Chapter 3: Steam System / Condensate recovery: energy balance

26. Select the WRONG statement about the use of steam in indirect process heating: [1P2CEM026]

a) Dry saturated steam gives up latent heat at a constant, controllable temperature

b) Steam should be supplied at the lowest pressure that meets the process temperature

c) Wet steam lowers heat transfer and raises steam consumption per kg of product

d) Superheated steam is preferred, as it gives up heat faster than saturated steam

Correct answer: (d) Superheated steam is preferred, as it gives up heat faster than saturated steam.

This statement is wrong. Superheated steam must first cool to saturation temperature by giving up sensible heat as a gas, and its heat transfer coefficient is much lower than that of condensing steam. Its temperature also varies along the surface, which makes control harder. For indirect heating, dry saturated steam is preferred. Superheat is useful for power generation in turbines and for long distribution lines to prevent condensation.

Why the others are correct: (a) Condensing steam releases latent heat at the saturation temperature fixed by pressure, which gives precise control. (b) Lower pressure means more latent heat per kg and lower distribution losses. (c) Wet steam carries less latent heat and forms a water film.

Ref: BEE Guidebook Paper 2, Ch. 3, §3.2 and §3.4.

Chapter 3: Steam System / Superheated vs saturated steam for process

27. A rerolling mill furnace heats 6 t/h of billets from 35 °C to 1,180 °C (mean C_p 0.12 kcal/kg °C) using 300 litres/h of furnace oil (density 0.92 kg/litre, GCV 10,000 kcal/kg). The furnace efficiency by the direct method is: [1P2CEM027]

a) 27.5%

b) 29.9%

c) 30.8%

d) 52.6%

Correct answer: (b) 29.9%.

Given: $m = 6,000 \text{ kg/h}$; $C_p = 0.12 \text{ kcal/kg } ^\circ\text{C}$ ($\approx 0.502 \text{ kJ/kg}\cdot\text{K}$); $t_2 - t_1 = 1,180 - 35 = 1,145 \text{ } ^\circ\text{C}$; fuel = $300 \times 0.92 = 276 \text{ kg/h}$; GCV = $10,000 \text{ kcal/kg}$ ($\approx 41,868 \text{ kJ/kg}$).

Formula (guidebook): $\eta = \text{Heat in stock} / \text{Heat in fuel} \times 100$, where heat in stock = $m \times C_p \times (t_2 - t_1)$.

Substitution: Heat in stock = $6,000 \times 0.12 \times 1,145 = 8,24,400 \text{ kcal/h}$. Heat in fuel = $276 \times 10,000 = 27,60,000 \text{ kcal/h}$.

Result: $\eta \approx 29.9\%$ (heat lost $\approx 19.4 \text{ lakh kcal/h} \approx 2,251 \text{ kW}$).

Why not the others: (a) 27.5% treats 300 litres as 300 kg. (c) 30.8% uses the final temperature $1,180 \text{ } ^\circ\text{C}$ without subtracting the $35 \text{ } ^\circ\text{C}$ charge temperature. (d) 52.6 is the specific fuel consumption in litres per tonne of finished product at 95% yield, not an efficiency.

Ref: BEE Guidebook Paper 2, Ch. 4, §4.2 (Direct method).

Chapter 4: Furnaces | Furnace efficiency by direct method

28. A reheating furnace side wall of 45 m^2 has an average skin temperature of $95 \text{ } ^\circ\text{C}$, ambient $35 \text{ } ^\circ\text{C}$ and emissivity 0.8. Using $Q = a(t_1 - t_2)^{1.25} + 4.88E[(t_1+273)/100]^4 - [(t_2+273)/100]^4]$ with the guidebook factor for side walls, the total heat loss is about: [1P2CEM028]

a) 16,500 kcal/h

b) 22,300 kcal/h

c) 32,900 kcal/h

d) 37,500 kcal/h

Correct answer: (c) 32,900 kcal/h.

Given: $A = 45 \text{ m}^2$; $t_1 = 95 \text{ } ^\circ\text{C}$; $t_2 = 35 \text{ } ^\circ\text{C}$; $E = 0.8$; $a = 2.2$ for side walls (ceiling 2.8, hearth 1.5).

Formula (guidebook): $Q = a(t_1 - t_2)^{1.25} + 4.88E[(t_1+273)/100]^4 - [(t_2+273)/100]^4]$ kcal/h·m².

Substitution: Convection = $2.2 \times 60^{1.25} = 2.2 \times 167.0 = 367.4$. Radiation = $4.88 \times 0.8 \times (3.68^4 - 3.08^4) = 3.904 \times (183.40 - 89.99) = 364.7$. $Q = 732.0 \text{ kcal/h}\cdot\text{m}^2$. Total = 732.0×45 .

Result: $\approx 32,940 \text{ kcal/h}$ ($\approx 38.3 \text{ kW}$).

Why not the others: (a) 16,500 kcal/h counts convection only and ignores radiation. (b) 22,300 kcal/h uses an exponent of 1.0 instead of 1.25. (d) 37,500 kcal/h uses the ceiling factor 2.8 for a side wall.

Ref: BEE Guidebook Paper 2, Ch. 4, §4.3 (Minimising wall losses).

Chapter 4: Furnaces | Heat loss from furnace walls

29. A pusher-type reheating furnace runs at a slight negative pressure because the stack damper is kept fully open. What is the main consequence, and the guidebook remedy? [1P2CEM029]

a) Flames stretch out of the doors; keep a strong negative pressure

b) Cold air infiltrates through openings; keep a slight positive pressure

c) Flue gas escapes into the shop; open the stack damper even further

d) Billet scale rises sharply; switch to a fully reducing atmosphere

Correct answer: (b) Cold air infiltrates through openings; keep a slight positive pressure.

Because of the draft effect of hot stacks, negative furnace pressure is common. Cold ambient air then leaks in through doors, peep holes, cracks and the charging and discharge openings. This air must be heated to flue gas temperature and leaves through the stack, which adds a large loss on top of the excess air at the burners. The guidebook recommends keeping the hearth pressure slightly positive (just above atmospheric) by damper control, so infiltration is avoided without large flame or gas leakage.

Why not the others: (a) Flames leaking out are a sign of high positive pressure, and stronger suction worsens infiltration.

(c) Gas escaping happens at positive pressure, and opening the damper increases suction. (d) A reducing atmosphere wastes fuel through CO and does not fix infiltration.

Ref: BEE Guidebook Paper 2, Ch. 4, §4.2 (Air infiltration) and §4.3 (Furnace draft).

30. An induction furnace foundry melts MS scrap at 720 kWh per tonne. Which statement is consistent with the guidebook data on induction furnaces? [1P2CEM030]

- a) Theory needs about 385–400 kWh/t, and crucible losses are the largest single loss
- b) Theory needs about 720 kWh/t, so this furnace is already operating at 100% efficiency
- c) Theory needs about 385–400 kWh/t, and the radiation loss is the largest single loss
- d) Theory needs about 550–950 kWh/t, so the capacitor bank causes most of the losses

Correct answer: (a) Theory needs about 385–400 kWh/t, and crucible losses are the largest single loss.

The guidebook gives the theoretical energy to melt one tonne of steel as 385 to 400 kWh/t, while actual specific energy consumption is much higher, 550 to 950 kWh/t. At 720 kWh/t the efficiency is only about 55%. In the guidebook's loss distribution, the crucible loss is the largest (18–25%). Radiation loss is 7–9%, generator/panel loss 2–4%, and capacitor bank loss is small.

Why not the others: (b) 720 kWh/t is an actual figure, far above the theoretical requirement. (c) It has the right theoretical figure, but radiation (7–9%) is smaller than the crucible loss. (d) 550–950 kWh/t is the actual range, not the theoretical one, and the capacitor bank loss is minor.

Ref: BEE Guidebook Paper 2, Ch. 4, §4.1 (Induction furnaces; losses).

Chapter 4: Furnaces | Induction furnace energy performance

31. In an oil-fired furnace (theoretical air 14 kg/kg oil), the O₂ in flue gas is reduced from 10% to 4% while the flue gas leaves at 750 °C (ambient 35 °C, Cp 0.24 kcal/kg °C). Taking flue gas mass = actual air + 1 kg, the reduction in flue gas loss per kg of oil is about: [1P2CEM031]

- a) 686 kcal/kg
- b) 1,349 kcal/kg
- c) **1,619 kcal/kg**
- d) 1,698 kcal/kg

Correct answer: (c) 1,619 kcal/kg.

Given: Theoretical air = 14 kg/kg; O₂ falls from 10% to 4%; $\Delta T = 750 - 35 = 715$ °C; Cp = 0.24.

Formula: $EA = O_2 / (21 - O_2)$; $AAS = 14 \times (1 + EA)$; flue gas loss = $(AAS + 1) \times Cp \times \Delta T$.

Substitution: At 10% O₂: EA = 90.9%, AAS = 26.73, loss = $27.73 \times 0.24 \times 715 = 4,758$ kcal/kg. At 4% O₂: EA = 23.5%, AAS = 17.29, loss = $18.29 \times 0.24 \times 715 = 3,139$ kcal/kg.

Result: **Reduction $\approx 1,619$ kcal/kg of oil** (about 15.9% of a 10,200 kcal/kg ($\approx 42,705$ kJ/kg) GCV).

Why not the others: (a) 686 kcal/kg uses $EA = O_2 / 21$. (b) 1,349 kcal/kg uses Cp = 0.20. (d) 1,698 kcal/kg uses 750 °C without subtracting ambient.

Ref: BEE Guidebook Paper 2, Ch. 4, §4.3 (Complete combustion with minimum excess air).

Chapter 4: Furnaces | Excess air control in furnaces

32. A 120 m steam line has an outer diameter over insulation of 250 mm. The cladding surface is at 72 °C and ambient 32 °C. Using $S = [10 + (T_s - T_a)/20] \times (T_s - T_a)$ kcal/h·m², the total heat loss is about: [1P2CEM032]

- a) 27,140 kcal/h
- b) 37,700 kcal/h
- c) **45,240 kcal/h**
- d) 92,290 kcal/h

Correct answer: (c) 45,240 kcal/h.

Given: L = 120 m; D (outer, over insulation) = 0.25 m; T_s = 72 °C; T_a = 32 °C.

Formula (guidebook): $S = [10 + (T_s - T_a)/20] \times (T_s - T_a)$; Area = $\pi \times D \times L$; Q = S $\times$ A.

Substitution: $S = (10 + 40/20) \times 40 = 12 \times 40 = 480$ kcal/h·m². A = $\pi \times 0.25 \times 120 = 94.25$ m². Q = 480×94.25 .

Result: $Q \approx 45,240 \text{ kcal/h}$ ($\approx 52.6 \text{ kW}$).

Why not the others: (a) 27,140 kcal/h uses a 150 mm bare pipe diameter instead of the insulation outer diameter. (b) 37,700 kcal/h drops the $(T_s - T_a)/20$ term and uses $S = 10 \times \Delta T$. (d) 92,290 kcal/h uses the surface temperature (72) as ΔT and forgets ambient.

Ref: BEE Guidebook Paper 2, Ch. 5, §5.5 (Simplified formula for heat loss).

Chapter 5: Insulation and Refractories | Heat loss from insulated pipe – simplified formula

33. An electric arc furnace hearth is in contact with highly basic (CaO-rich) slag at about 1,650 °C. Which refractory is the correct choice per the guidebook classification? [1P2CEM033]

- a) Silica brick, an acid refractory with at least 93% SiO_2
- b) Fireclay brick, a semi-acid refractory made mostly of alumina and silica
- c) Insulating brick, a light porous refractory of low density
- d) Magnesite brick, a basic refractory with at least 85% MgO**

Correct answer: (d) Magnesite brick, a basic refractory with at least 85% MgO.

Refractories are classified as acid, basic or neutral. Acid refractories (silica, semi-silica) combine readily with bases; basic refractories (magnesite, chrome-magnesite, dolomite) resist basic slags. The guidebook describes magnesite refractories as chemically basic, containing at least 85% MgO, and suited to contact with the most basic slags used in steel melting.

Matching chemistry prevents slag attack.

Why not the others: (a) Silica is acidic and would be rapidly attacked by CaO-rich slag. (b) Fireclay is alumina–silica based, has lower refractoriness and also reacts with basic slag. (c) Insulating bricks have high porosity and low strength; they are back-up insulation, not a slag-contact hot face.

Ref: BEE Guidebook Paper 2, Ch. 5, §5.9 (Classification) and §5.10 (Typical refractories).

Chapter 5: Insulation and Refractories | Selection of refractories

34. A refractory supplier quotes a high PCE value for a brick that will carry a heavy roof load at high temperature. Why does the guidebook advise checking another property as well? [1P2CEM034]

- a) PCE shows only the porosity; cold crushing strength shows load
- b) PCE shows only the expansion; creep shows the softening point
- c) PCE shows only the density; thermal conductivity shows the load
- d) PCE shows only the softening point; RUL shows collapse under load**

Correct answer: (d) PCE shows only the softening point; RUL shows collapse under load.

The pyrometric cone equivalent (PCE) indicates only the softening temperature, where the refractory deforms under its own weight. In service, a refractory carries loads that can deform it at a much lower temperature than the PCE shows. The refractoriness under load (RUL) test indicates the temperature at which bricks will collapse under service-like load. For a loaded roof, RUL (and creep, a time-dependent deformation under stress) must be checked.

Why not the others: (a) Cold crushing strength mainly reveals the ability to withstand transport and handling, not hot load behaviour. (b) PCE is not an expansion test, and creep is deformation over time, not softening. (c) PCE is not a density test, and conductivity has nothing to do with load-bearing.

Ref: BEE Guidebook Paper 2, Ch. 5, §5.8 (Properties of refractories).

Chapter 5: Insulation and Refractories | Refractory properties

35. A forge shop runs a batch furnace for one shift a day and a chilled-water line at 7 °C. Which pairing of insulating material is the most energy-appropriate as per the guidebook? [1P2CEM035]

- a) Ceramic fibre lining for the furnace; PUF for the chilled line**
- b) Dense firebrick lining for the furnace; mineral wool for chilled line
- c) Calcium silicate for the furnace hot face; magnesia for chilled line
- d) Insulating brick for the furnace; ceramic fibre for the chilled line

Correct answer: (a) Ceramic fibre lining for the furnace; PUF for the chilled line.

Ceramic fibre is a low-thermal-mass refractory. In an intermittent furnace, much of the heat stored in a heavy lining is lost every cooling cycle; the guidebook notes that energy saving from ceramic fibre is possible mainly in intermittent furnaces, with faster heat-up. For cold lines (low temperature insulation, up to 90 °C), cold insulation such as thermocol (expanded polystyrene) or polyurethane foam (PUF) is used, with a vapour barrier.

Why not the others: (b) Dense firebrick has high heat storage, which is wasted in one-shift operation; mineral wool absorbs moisture on cold lines. (c) Calcium silicate is a medium- to high-temperature pipe insulation, not a forge-furnace hot face.

(d) Ceramic fibre is a high-temperature material and is not used for chilled water.

Ref: BEE Guidebook Paper 2, Ch. 4, §4.3 and Ch. 5, §5.2, §5.6.

Chapter 5: Insulation and Refractories | Ceramic fibre and insulation classes

36. An AFBC boiler operator wants to raise the bed temperature from 830 °C to 1,000 °C to 'improve combustion'.

Why does the guidebook advise against this? [1P2CEM036]

a) NO_x falls sharply above 950 °C, so stack limestone use rises sharply

b) Clinker forms above 950 °C, and sulphur capture is best at 800–850 °C

c) Bed material melts above 900 °C, so the fluidising air must be stopped

d) Combustion efficiency falls above 850 °C, because volatiles escape the bed unburnt

Correct answer: (b) Clinker forms above 950 °C, and sulphur capture is best at 800–850 °C.

FBC takes place at about 840 °C to 950 °C, which is well below the ash fusion temperature, so ash does not melt or form clinker. The guidebook warns of clinker formation in the bed if temperature exceeds 950 °C, and loss of combustion efficiency if it falls below 800 °C. For efficient sulphur retention by limestone, the bed should be kept in the range 800–850 °C. Low combustion temperature also suppresses NO_x formation.

Why not the others: (a) NO_x rises, not falls, with higher combustion temperature. (c) The bed material does not melt at 900 °C; the risk is ash fusion and clinkering above 950 °C. (d) Combustion efficiency drops when the bed is too cold (below 800 °C), not at 850 °C.

Ref: BEE Guidebook Paper 2, Ch. 6, §6.2 and §6.5.

Chapter 6: FBC Boilers | FBC bed temperature

37. An AFBC boiler burns 12 t/h of coal containing 0.6% sulphur. Using the guidebook rule for limestone addition, the limestone feed required is about: [1P2CEM037]

a) 72 kg/h

b) 216 kg/h

c) 360 kg/h

d) 432 kg/h

Correct answer: (b) 216 kg/h.

Given: Coal = 12,000 kg/h; sulphur = 0.6%.

Formula (guidebook): 3% limestone (of coal feed) is required for every 1% sulphur in the coal.

Substitution: Limestone % = $3 \times 0.6 = 1.8\%$ of coal. Limestone = $0.018 \times 12,000$.

Result: **≈ 216 kg/h (≈ 5.2 t/day).**

Why not the others: (a) 72 kg/h is the sulphur flow itself ($0.006 \times 12,000$), not the limestone. (c) 360 kg/h applies 3% of coal regardless of the sulphur content. (d) 432 kg/h doubles the rule (6% per 1% S).

Note: limestone or dolomite captures SO₂ as calcium sulphate in the bed, best at 800–850 °C, so no separate flue gas desulphurisation is needed for small FBC boilers.

Ref: BEE Guidebook Paper 2, Ch. 6, §6.5 (Pollution control).

Chapter 6: FBC Boilers | Limestone requirement for SO₂ control

38. Select the CORRECT comparison of bubbling (AFBC) and circulating (CFBC) fluidised bed boilers as given in the guidebook: [1P2CEM038]

a) AFBC air velocity is 1.2–3.7 m/s; CFBC is 3.7–9 m/s with cyclone recycle

b) AFBC air velocity is 3.7–9 m/s; CFBC is 1.2–3.7 m/s with cyclone recycle

c) AFBC air velocity is 1.2–3.7 m/s; CFBC is 3.7–9 m/s with no solids recycle

d) AFBC air velocity is 0.1–0.5 m/s; CFBC is 10–20 m/s with cyclone recycle

Correct answer: (a) AFBC air velocity is 1.2–3.7 m/s; CFBC is 3.7–9 m/s with cyclone recycle.

In AFBC (bubbling bed) boilers, the fluidising air velocity is 1.2 to 3.7 m/s, and the bed stays in the furnace with bubbles passing through it. In CFBC, the fluidising velocity ranges from 3.7 to 9 m/s. Fine particles are carried out of the furnace, captured by large mechanical cyclones and circulated back, which gives long residence time, high combustion efficiency and good sulphur retention. The guidebook notes CFBC is generally more economical for larger capacities.

Why not the others: (b) It swaps the two velocity ranges. (c) It omits the defining feature of CFBC, the separation and recycling of solids. (d) Its velocities are outside the guidebook ranges; 0.1–0.5 m/s would not fluidise the bed properly.

Ref: BEE Guidebook Paper 2, Ch. 6, §6.3 (Types of FBC boilers).

Chapter 6: FBC Boilers / AFBC vs CFBC

39. A paper mill needs 25 TPH of process steam (useful heat 560 kcal/kg) and 4 MW of electricity simultaneously. Which option correctly gives its heat-to-power ratio (kW basis) and the best-matching cogeneration system?

[1P2CEM039]

a) 4.07, matching a combined cycle plant

b) 4.07, matching a back-pressure steam turbine

c) 0.25, matching a reciprocating engine system

d) 3,500, matching an extraction-condensing turbine

Correct answer: (b) 4.07, matching a back-pressure steam turbine.

Given: Steam = 25,000 kg/h; useful heat = 560 kcal/kg ($\approx 2,345$ kJ/kg); power = 4,000 kW.

Formula: Heat-to-power ratio = thermal energy (kW) / electrical energy (kW), with 1 kW = 860 kcal/h.

Substitution: Thermal = $25,000 \times 560 / 860 = 16,279$ kW. Ratio = $16,279 / 4,000$.

Result: **H:P $\approx$ 4.07.**

Guidebook Table 7.2: back-pressure steam turbine 4.0–14.3; extraction-condensing 2.0–10.0; combined cycle 1.0–1.7; reciprocating engine 1.1–2.5. A ratio of about 4 with steady steam demand suits a back-pressure turbine.

Why not the others: (a) Right ratio, but combined cycle suits only 1.0–1.7. (c) 0.25 inverts the ratio (power/heat). (d) 3,500 mixes kcal/h with kW.

Ref: BEE Guidebook Paper 2, Ch. 7, §7.6.1.

Chapter 7: Cogeneration / Heat-to-power ratio and prime mover selection

40. A condensing steam turbine generator receives 30 TPH of steam at 3,300 kJ/kg; feed water returns at 420 kJ/kg; output is 7,200 kW. Its heat rate and thermal efficiency are: [1P2CEM040]

a) 13,750 kJ/kWh and 26.2%

b) 12,000 kJ/kWh and 33.3%

c) 10,800 kJ/kWh and 33.3%

d) 12,000 kJ/kWh and 30.0%

Correct answer: (d) 12,000 kJ/kWh and 30.0%.

Given: $m = 30,000$ kg/h; $h_1 = 3,300$ kJ/kg; $h_{fw} = 420$ kJ/kg; $P = 7,200$ kW.

Formula: Heat rate = $m \times (h_1 - h_{fw}) / P$ (kJ/kWh); $\eta = 3,600 / \text{Heat rate}$ (1 kWh = 3,600 kJ = 860 kcal).

Substitution: Heat input = $30,000 \times (3,300 - 420) = 8,640,000$ kJ/h. Heat rate = $8,640,000 / 7,200 = 12,000$ kJ/kWh ($\approx 2,866$ kcal/kWh). $\eta = 3,600 / 12,000$.

Result: **12,000 kJ/kWh and 30.0%.**

Why not the others: (a) It does not subtract the feed water enthalpy. (b) It uses the correct heat rate but a wrong conversion (4,000 kJ/kWh). (c) It back-calculates the heat rate from a guessed efficiency.

Note: as the guidebook explains, the inverse relation between heat rate and efficiency holds only for pure power generation, not for cogeneration.

Ref: BEE Guidebook Paper 2, Ch. 7, §7.10.

Chapter 7: Cogeneration | Turbine heat rate and efficiency

41. Why does the guidebook state that an extraction-condensing cogeneration turbine has a higher heat rate than a back-pressure turbine? [1P2CEM041]

- a) Extraction steam leaves at a higher pressure than back-pressure steam
- b) The condenser vacuum lowers exhaust enthalpy and raises turbine output
- c) Extraction turbines cannot use coal or biomass as boiler fuel at all

d) Steam sent to the condenser loses its latent heat to cooling water

Correct answer: (d) Steam sent to the condenser loses its latent heat to cooling water.

In a back-pressure turbine, all the exhaust steam goes to the process as useful heat, so system efficiency can reach about 85%. In an extraction-condensing turbine, the steam that passes to the condenser gives up its latent heat to cooling water and the cooling tower. The guidebook notes that as the steam quantity through the condenser increases, the heat rate becomes higher, so extraction-condensing systems need more heat input and are less efficient. They are chosen for flexibility when steam and power demands vary.

Why not the others: (a) Extraction pressure is set by process needs; it is not why the heat rate rises. (b) Vacuum does raise output per kg, but the condenser loss outweighs it. (c) Steam turbines can use almost any boiler fuel.

Ref: BEE Guidebook Paper 2, Ch. 7, §7.10 (Notes on cogeneration efficiency).

Chapter 7: Cogeneration | Back-pressure vs extraction-condensing operation

42. Steam enters a turbine at 790 kcal/kg and leaves at an actual enthalpy of 690 kcal/kg. The isentropic exit enthalpy for the same pressure ratio is 655 kcal/kg. The turbine cylinder efficiency is: [1P2CEM042]

- a) 25.9%
- b) 74.1%**
- c) 87.3%
- d) 94.9%

Correct answer: (b) 74.1%.

Given: $H_1 = 790$ kcal/kg ($\approx 3,308$ kJ/kg); actual exit $H_2 = 690$ kcal/kg ($\approx 2,889$ kJ/kg); isentropic exit $H_{2s} = 655$ kcal/kg ($\approx 2,742$ kJ/kg).

Formula (guidebook): Cylinder efficiency = actual enthalpy drop (A) / isentropic enthalpy drop (B) $\times 100$.

Substitution: $A = 790 - 690 = 100$ kcal/kg. $B = 790 - 655 = 135$ kcal/kg. Efficiency = $100/135 \times 100$.

Result: $\approx 74.1\%$.

Why not the others: (a) 25.9% is the shortfall ($100 - 74.1$), not the efficiency. (c) 87.3% is the ratio of exit to inlet enthalpy ($690/790$), which has no meaning as an efficiency. (d) 94.9% compares the two exit enthalpies ($655/690$).

Note: a falling cylinder efficiency, confirmed by a pressure survey across the stages, points to blade deposits, erosion or seal leakage.

Ref: BEE Guidebook Paper 2, Ch. 7, §7.10 (Steam turbine efficiency).

Chapter 7: Cogeneration | Steam turbine cylinder efficiency

43. Which of the following applications is best served by a BOTTOMING cycle cogeneration system? [1P2CEM043]

- a) A cement kiln needing heat at about 1,450 °C**
- b) A sugar mill needing process heat at about 120 °C
- c) A textile unit needing steam at about 160 °C

d) A dairy needing hot water and chilled water

Correct answer: (a) A cement kiln needing heat at about 1,450 °C.

In a bottoming cycle, fuel is first used to meet a high-temperature process need, and the waste heat rejected from that process is then used to generate power. The guidebook gives the example of a cement plant requiring thermal energy at about 1,450 °C, where a bottoming cycle meets both the high-quality heat demand and the electricity demand. In a topping cycle, power is produced first and the exhaust heat meets a lower-temperature process.

Why not the others: (b) The guidebook cites the sugar mill at about 120 °C as a topping cycle case. (c) Medium-pressure process steam at 160 °C is also met by a topping cycle such as a back-pressure turbine. (d) Combined hot and chilled water needs trigeneration (topping cycle with an absorption chiller).

Ref: BEE Guidebook Paper 2, Ch. 7, §7.4 and §7.6.2.

Chapter 7: Cogeneration / Topping and bottoming cycles

44. A gas turbine generator's gross turbine output is much higher than its net electrical output. As per the guidebook, which item accounts for the largest share of this difference? [1P2CEM044]

a) The fuel gas booster, using about 30–35% of turbine work

b) The air compressor, using about 50–60% of turbine work

c) The HRSG feed pump, using about 20–25% of turbine work

d) The generator cooling fans, using about 10–15% of turbine work

Correct answer: (b) The air compressor, using about 50–60% of turbine work.

The guidebook explains that stand-alone gas turbine efficiency (35–40%) does not include energy consumed by the air compressor, fuel pump and other auxiliaries. The air compressor alone consumes about 50 to 60% of the energy generated by the turbine, so net turbine efficiency is less than the gross value. This is also why GT output falls on hot days (lower air density means more compressor work per kg). Recovering the high exhaust heat in an HRSG is what makes GT cogeneration attractive.

Why not the others: (a) A gas booster is a small auxiliary load, nowhere near 30%. (c) The HRSG feed pump is a small load and sits outside the turbine. (d) Generator cooling uses a fraction of a percent.

Ref: BEE Guidebook Paper 2, Ch. 7, §7.7.2 (Gas turbine efficiency; net turbine efficiency).

Chapter 7: Cogeneration / Gas turbine performance

45. A heat treatment furnace exhausts 9,000 m³/h of flue gas (density 1.19 kg/m³, Cp 0.24 kcal/kg °C) at 650 °C. If a recuperator cools it to 200 °C, the heat recoverable is about: [1P2CEM045]

a) 9.7 lakh kcal/h

b) 11.6 lakh kcal/h

c) 13.0 lakh kcal/h

d) 16.7 lakh kcal/h

Correct answer: (b) 11.6 lakh kcal/h.

Given: $V = 9,000 \text{ m}^3/\text{h}$; $\rho = 1.19 \text{ kg/m}^3$; $C_p = 0.24 \text{ kcal/kg } ^\circ\text{C}$ ($\approx 1.00 \text{ kJ/kg}\cdot\text{K}$); $\Delta T = 650 - 200 = 450 \text{ } ^\circ\text{C}$.

Formula (guidebook): $Q = V \times \rho \times C_p \times \Delta T$.

Substitution: $Q = 9,000 \times 1.19 \times 0.24 \times 450 = 11,56,680 \text{ kcal/h}$.

Result: **$Q \approx 11.6 \text{ lakh kcal/h}$ ($\approx 1,345 \text{ kW}$)**. By the guidebook thumb rule (1% fuel saving per 22 °C drop in flue gas temperature), the indicative fuel saving is $450/22 \approx 20\%$.

Why not the others: (a) 9.7 lakh kcal/h leaves out the density (treats m³ as kg). (c) 13.0 lakh kcal/h uses $C_p = 0.27$. (d) 16.7 lakh kcal/h cools the gas to 0 °C ($\Delta T = 650$).

Ref: BEE Guidebook Paper 2, Ch. 8, §8.1 (Heat losses – quantity).

Chapter 8: Waste Heat Recovery / Quantifying waste heat

46. A pharmaceutical plant wants to recover heat from 60 °C dryer exhaust air to preheat fresh make-up air. Cross-contamination must be minimal and no moving parts are preferred. Which device fits best? [1P2CEM046]

a) Heat pipe exchanger, sealed and with no moving parts

b) Rotary heat wheel, with a porous rotating matrix

c) Ceramic recuperator, for gas up to about 1,550 °C

d) Waste heat boiler, raising low-pressure process steam

Correct answer: (a) Heat pipe exchanger, sealed and with no moving parts.

A heat pipe heat exchanger is a lightweight, compact system with a sealed container, wick and working fluid. It has no moving parts, needs no input power and virtually no mechanical maintenance. Each pipe passes through a partition, so exhaust and fresh air stay separate, which keeps cross-contamination low. The guidebook lists process-to-process and make-up air preheating as typical uses, with 60–80% heat recovery at up to about 315 °C.

Why not the others: (b) A heat wheel suits large air flows with small temperature differences, but its rotating matrix carries some exhaust into the supply air and has moving parts. (c) Ceramic recuperators are for very high-temperature furnace gases. (d) A waste heat boiler cannot raise steam from 60 °C air.

Ref: BEE Guidebook Paper 2, Ch. 8, §8.5 (Heat pipe; heat wheel).

Chapter 8: Waste Heat Recovery | Selection of waste heat recovery devices

47. Which statement about industrial heat pumps is consistent with the guidebook? [1P2CEM047]

a) They convert high-grade waste heat directly into electricity at the site

b) They work best when the source and sink temperatures are very far apart

c) They operate without any compressor work when the source is above 30 °C

d) They upgrade low-grade heat, delivering over twice the energy they consume

Correct answer: (d) They upgrade low-grade heat, delivering over twice the energy they consume.

A heat pump (usually working on the vapour compression cycle) absorbs heat from a low-temperature source in the evaporator, raises its temperature with compressor work, and rejects it at a higher temperature in the condenser. The guidebook states that heat pumps can upgrade heat to more than twice the energy consumed by the device (COP above 2). Applications are most promising when both heating and cooling can be used, for example cooling injection-moulding machines while heating a factory.

Why not the others: (a) That describes power generation from waste heat, not a heat pump. (b) A large temperature lift lowers the COP sharply; heat pumps are best with a small lift. (c) A vapour compression heat pump always needs compressor (or other) work input.

Ref: BEE Guidebook Paper 2, Ch. 8, §8.5 (Heat pumps).

Chapter 8: Waste Heat Recovery | Heat pumps

48. A hot stream is cooled from 140 °C to 90 °C by water heated from 30 °C to 70 °C. For the same duty and overall U, how does the area needed in parallel flow compare with counter flow? [1P2CEM048]

a) About 18.6% more area

b) About 22.9% more area

c) About 22.9% less area

d) No change in the area

Correct answer: (b) About 22.9% more area.

Given: $T_h: 140 \rightarrow 90$ °C; $T_c: 30 \rightarrow 70$ °C; same Q and U.

Formula: $LMTD = (\Delta T_1 - \Delta T_2) / \ln(\Delta T_1 / \Delta T_2)$; $A = Q / (U \times LMTD)$, so $A \propto 1 / LMTD$.

Substitution: Counter flow: $\Delta T_1 = 140 - 70 = 70$, $\Delta T_2 = 90 - 30 = 60$, $LMTD = 10 / \ln(70/60) = 64.9$ °C. Parallel flow: $\Delta T_1 = 140 - 30 = 110$, $\Delta T_2 = 90 - 70 = 20$, $LMTD = 90 / \ln(5.5) = 52.8$ °C. Area ratio = $64.9 / 52.8 = 1.229$.

Result: **Parallel flow needs $\approx 22.9\%$ more area.**

Why not the others: (a) 18.6% is $(1 - 52.8/64.9)$, which compares the wrong way round. (c) It reverses the direction; counter flow always has the larger LMTD. (d) 'No change' comes from using the arithmetic mean (65 °C in both).

Ref: BEE Guidebook Paper 2, Ch. 9, §9.3.

Chapter 9: Heat Exchangers | LMTD: counter flow vs parallel flow

49. During a pinch study, the design team increases the minimum approach temperature $\Delta T_{\min}$ from 10 °C to 30 °C. As per the guidebook, what is the effect? [1P2CEM049]

- a) Hot and cold utility needs fall, while heat exchanger area rises
- b) Both the utility needs and the heat exchanger area fall together
- c) Hot and cold utility needs rise, while heat exchanger area falls**
- d) Utility needs are unchanged, but the pinch moves to a hotter level

Correct answer: (c) Hot and cold utility needs rise, while heat exchanger area falls.

The pinch is the point where the hot and cold composite curves come closest, separated by $\Delta T_{\min}$. The guidebook states that increasing the $\Delta T_{\min}$ value leads to higher utility requirements and lower area requirements. A larger approach means less heat can be exchanged within the process, so more external steam and cooling water are needed, but the exchangers have larger temperature differences and need less area. Choosing $\Delta T_{\min}$ is therefore a trade-off between energy cost and capital cost.

Why not the others: (a) This describes the effect of reducing $\Delta T_{\min}$. (b) Energy and area move in opposite directions; both cannot fall. (d) Utility targets depend directly on $\Delta T_{\min}$, so they cannot stay the same.

Ref: BEE Guidebook Paper 2, Ch. 9, §9.6 (Pinch analysis).

Chapter 9: Heat Exchangers | Pinch analysis – $\Delta T_{\min}$

50. In a counter-flow cooler, oil (2.0 kg/s, C_p 2.1 kJ/kg K) enters at 160 °C. Water (1.5 kg/s, C_p 4.18 kJ/kg K) is heated from 20 °C to 50 °C. The effectiveness of the exchanger is about: [1P2CEM050]

- a) 0.21
- b) 0.32**
- c) 0.47
- d) 0.68

Correct answer: (b) 0.32.

Given: $C_{\text{oil}} = 2.0 \times 2.1 = 4.20$ kW/K ($C_{\min}$); $C_{\text{water}} = 1.5 \times 4.18 = 6.27$ kW/K ($C_{\max}$); $T_{h,\text{in}} = 160$ °C; $T_{c,\text{in}} = 20$ °C.

Formula (guidebook): $\epsilon = Q_{\text{actual}} / [C_{\min} \times (T_{h,\text{in}} - T_{c,\text{in}})]$.

Substitution: $Q_{\text{actual}} = 6.27 \times (50 - 20) = 188.1$ kW. $Q_{\text{max}} = 4.20 \times (160 - 20) = 588$ kW. $\epsilon = 188.1/588$.

Result: $\epsilon \approx \mathbf{0.32}$ (oil leaves at $160 - 188.1/4.2 \approx 115.2$ °C).

Why not the others: (a) 0.21 uses $C_{\max}$ instead of $C_{\min}$ in Q_{max} . (c) 0.47 uses the oil outlet temperature (115.2 °C) instead of its inlet temperature when working out Q_{max} . (d) 0.68 is $1 - \epsilon$, which has no meaning here.

Ref: BEE Guidebook Paper 2, Ch. 9, §9.3 (Effectiveness).

Chapter 9: Heat Exchangers | Heat exchanger effectiveness

..... End of Section I

Section – II: SHORT DESCRIPTIVE QUESTIONS**Marks: 8 x 5 = 40**

- (i) Answer all Eight questions
- (ii) Each question carries Five marks

S-1 [1P2CEM051 | Chapter 1: Fuels and Combustion | Combustion air and NCV from ultimate analysis of coal]

A 15 t/h coal-fired stoker boiler burns coal with the following ultimate analysis (as fired, % by mass) and GCV of 3,900 kcal/kg:

C	H ₂	O ₂	S	N ₂	Moisture	Ash
42.0	2.8	7.2	0.5	0.9	12.0	34.6

The oxygen in flue gas measured at the boiler outlet is 6%.

- a) Calculate the theoretical air required per kg of coal. (2 Marks)
- b) Calculate the excess air and the actual combustion air flow in kg/h. (2 Marks)
- c) Estimate the NCV of the coal using the guidebook relation (latent heat 584 kcal/kg). (1 Mark)

S-1 Ans (model answer with marking scheme)

Given: C = 42.0%, H₂ = 2.8%, O₂ = 7.2%, S = 0.5%, M = 12.0%; GCV = 3,900 kcal/kg ($\approx$ 16,329 kJ/kg); O₂ in flue gas = 6%; coal firing = 15,000 kg/h.

a) Theoretical air (2 marks)

Formula: Theoretical air = $[11.6 \times C + 34.8 \times (H_2 - O_2/8) + 4.35 \times S] / 100$ kg/kg coal [1 mark]

Substitution: $= [11.6 \times 42.0 + 34.8 \times (2.8 - 7.2/8) + 4.35 \times 0.5] / 100 = [487.2 + 34.8 \times 1.9 + 2.175] / 100 = [487.2 + 66.12 + 2.175] / 100$

Result: **Theoretical air = 5.55 kg air/kg coal** [1 mark]

b) Excess air and actual air (2 marks)

Formula: EA % = $O_2 / (21 - O_2) \times 100$; AAS = $(1 + EA/100) \times$ theoretical air

Substitution: EA = $6 / (21 - 6) \times 100 = 40\%$ [1 mark]; AAS = $1.40 \times 5.555 = 7.78$ kg/kg coal

Actual air flow = $7.777 \times 15,000 = 1,16,654$ kg/h

Result: **Excess air = 40%; actual air $\approx$ 7.78 kg/kg coal $\approx$ 1,16,650 kg/h ($\approx$ 116.7 t/h)** [1 mark]

c) NCV (1 mark)

Formula: NCV = GCV – $584 \times (9H + M)/100$

Substitution: $= 3,900 - 584 \times (9 \times 2.8 + 12.0)/100 = 3,900 - 584 \times 0.372 = 3,900 - 217.2$

Result: **NCV $\approx$ 3,683 kcal/kg ($\approx$ 15,420 kJ/kg)** [1 mark]

Marking note: full marks for answers within $\pm 1\%$ of the values shown; deduct $\frac{1}{2}$ mark where the O₂/8 correction for fuel oxygen is omitted.

S-2 [1P2CEM052 | Chapter 2: Boilers | Blowdown quantity and flash steam recovery]

A 20 TPH water tube boiler operates at 10.5 kg/cm²(g). Make-up water is 30% of the feed water. Feed water TDS is 180 ppm and the maximum permissible boiler water TDS is 3,000 ppm. The continuous blowdown is led to a flash vessel at 0.5 kg/cm²(g) and the flash steam is used in the deaerator.

Data	Value
Sensible heat of boiler water at 10.5 kg/cm ² (g)	186 kcal/kg
Sensible heat at 0.5 kg/cm ² (g)	111 kcal/kg

Latent heat at 0.5 kg/cm ² (g)	532 kcal/kg
Boiler efficiency / GCV of furnace oil	82% / 10,200 kcal/kg

- a) Calculate the blowdown percentage and the blowdown quantity in kg/h. (2 Marks)
b) Calculate the flash steam recoverable in kg/h. (2 Marks)
c) Estimate the furnace oil saved per hour if the latent heat of the flash steam displaces boiler steam. (1 Mark)

S-2 Ans (model answer with marking scheme)

Given: Steam = 20,000 kg/h; make-up = 30%; feed TDS = 180 ppm; permissible TDS = 3,000 ppm; $S_1 = 186$ kcal/kg (≈ 779 kJ/kg), $S_2 = 111$ kcal/kg (≈ 465 kJ/kg), $L_2 = 532$ kcal/kg ($\approx 2,227$ kJ/kg); $\eta = 0.82$; GCV = 10,200 kcal/kg ($\approx 42,705$ kJ/kg).

a) Blowdown (2 marks)

Formula: Blowdown % = (Feed water TDS $\times$ % make-up water) / (Max. permissible TDS – Feed water TDS)

Substitution: = $(180 \times 30) / (3,000 - 180) = 5,400 / 2,820 = 1.915\%$ [1 mark]

Blowdown quantity = $1.915/100 \times 20,000$

Result: **Blowdown $\approx 1.91\%$, ≈ 383 kg/h** [1 mark]

b) Flash steam (2 marks)

Formula: Flash fraction = $(S_1 - S_2) / L_2$

Substitution: = $(186 - 111) / 532 = 75/532 = 0.141$ (14.1%) [1 mark]; flash steam = 0.141×383

Result: **Flash steam ≈ 54 kg/h** at 0.5 kg/cm²(g) (≈ 0.490 bar(g) = 49.0 kPa(g)); about 329 kg/h of residual hot water remains for make-up preheating [1 mark]

c) Fuel saving (1 mark)

Heat recovered = $54.0 \times 532 = 28,724$ kcal/h (≈ 33.4 kW); Fuel saved = $28,724 / (10,200 \times 0.82)$

Result: **≈ 3.43 kg/h of furnace oil** (≈ 27.5 t/year at 8,000 h) [1 mark]

Marking note: accept blowdown 1.9–1.92% and flash steam 53–55 kg/h.

S-3 [1P2CEM053 | Chapter 3: Steam System | Condensate recovery and feed water temperature]

A 12 TPH oil-fired boiler presently uses 100% make-up water at 28 °C. The plant proposes to return 60% of the steam as condensate at 90 °C, mixing it with make-up water at 28 °C in the feed tank. Steam enthalpy is 665 kcal/kg, boiler efficiency 84%, GCV of furnace oil 10,200 kcal/kg, and the boiler runs 8,000 h/year.

- a) Calculate the new feed water temperature. (1 Mark)
b) Estimate the % fuel saving using the guidebook thumb rule. (1 Mark)
c) Calculate the actual fuel saving (kg/h and t/year) by energy balance and the % saving, and comment on the thumb rule estimate. (3 Marks)

S-3 Ans (model answer with marking scheme)

Given: Steam = 12,000 kg/h; condensate return = 60% at 90 °C; make-up = 40% at 28 °C; $h_g = 665$ kcal/kg ($\approx 2,784$ kJ/kg); $\eta = 0.84$; GCV = 10,200 kcal/kg ($\approx 42,705$ kJ/kg); 8,000 h/year.

Formula: $T_{fw} = (m_c \times T_c + m_{mu} \times T_{mu}) / (m_c + m_{mu})$; heat saved = $m \times C_p \times \Delta T$; fuel saved = heat saved / (GCV $\times \eta$); thumb rule: 1% fuel per 6 °C feed water rise

a) Feed water temperature (1 mark)

Mixing: $T_{fw} = 0.60 \times 90 + 0.40 \times 28 = 54.0 + 11.2$

Result: **$T_{fw} = 65.2$ °C** [1 mark]

b) Thumb rule (1 mark)

Rule (guidebook): about 1% fuel saving for every 6 °C rise in feed water temperature. Rise = 65.2 – 28 = 37.2 °C

Result: **Saving $\approx 37.2/6 = 6.2\%$** [1 mark]

c) Energy balance (3 marks)

Heat saved = $m \times C_p \times \Delta T = 12,000 \times 1 \times 37.2 = 4,46,400 \text{ kcal/h}$ ($\approx 519 \text{ kW}$) [1 mark]

Fuel saved = $4,46,400 / (10,200 \times 0.84) = \mathbf{52.1 \text{ kg/h} \approx 417 \text{ t/year}}$ [1 mark]

Present fuel = $12,000 \times (665 - 28) / (10,200 \times 0.84) = 892.2 \text{ kg/h}$; % saving = $52.1 / 892.2 \times 100 = \mathbf{5.84\%}$

Comment: the thumb rule (6.2%) is close to the exact energy balance (5.84%) and is fine for quick screening; the energy balance should be used for the investment decision. Water and treatment chemical savings are additional. [1 mark]

S-4 [1P2CEM054 | Chapter 4: Furnaces | Furnace skin (wall and roof) heat loss]

A continuous reheating furnace has a roof area of 30 m² with an average skin temperature of 90 °C and side walls of 60 m² at 75 °C. Ambient is 35 °C and the surface emissivity is 0.85. Use $Q = a(t_1 - t_2)^{1.25} + 4.88E[(t_1+273)/100]^4 - [(t_2+273)/100]^4]$ kcal/h·m², with $a = 2.8$ for the ceiling and 2.2 for side walls.

a) Calculate the heat loss from the roof and from the side walls. (3 Marks)

b) Express the total skin loss as furnace oil equivalent in litres/h (GCV 10,000 kcal/kg, specific gravity 0.92) and as annual cost for 6,000 h/year at ₹ 52,000 per tonne. (2 Marks)

S-4 Ans (model answer with marking scheme)

Given: Roof: $A = 30 \text{ m}^2$, $t_1 = 90 \text{ °C}$, $a = 2.8$; side walls: $A = 60 \text{ m}^2$, $t_1 = 75 \text{ °C}$, $a = 2.2$; $t_2 = 35 \text{ °C}$; $E = 0.85$; GCV = 10,000 kcal/kg ($\approx 41,868 \text{ kJ/kg}$); SG = 0.92; 6,000 h/year; oil = ₹ 52,000/t.

Formula: $Q = a(t_1 - t_2)^{1.25} + 4.88E[(t_1+273)/100]^4 - [(t_2+273)/100]^4]$ kcal/h·m²; skin loss = $Q \times A$; fuel equivalent = loss/GCV

a) Heat loss (3 marks)

Roof: convection = $2.8 \times (55)^{1.25} = 2.8 \times 149.8 = 419.4$; radiation = $4.88 \times 0.85 \times (3.63^4 - 3.08^4) = 4.148 \times (173.63 - 89.99) = 346.9$

Result: $Q_{\text{roof}} = 766.3 \text{ kcal/h} \cdot \text{m}^2$ ($\approx 891 \text{ W/m}^2$) $\times 30 \text{ m}^2 = \mathbf{22,990 \text{ kcal/h} (\approx 26.7 \text{ kW})}$ [1½ marks]

Side walls: convection = $2.2 \times (40)^{1.25} = 2.2 \times 100.6 = 221.3$; radiation = $4.148 \times (3.48^4 - 3.08^4) = 4.148 \times (146.66 - 89.99) = 235.1$

Result: $Q_{\text{walls}} = 456.4 \text{ kcal/h} \cdot \text{m}^2$ ($\approx 531 \text{ W/m}^2$) $\times 60 \text{ m}^2 = \mathbf{27,383 \text{ kcal/h} (\approx 31.8 \text{ kW})}$ [1½ marks]

b) Fuel equivalent and cost (2 marks)

Total = $22,990 + 27,383 = 50,372 \text{ kcal/h}$ ($\approx 58.6 \text{ kW}$)

Result: Fuel equivalent = $50,372 / 10,000 = 5.04 \text{ kg/h} = 5.04/0.92 = \mathbf{5.48 \text{ litres/h}}$ [1 mark]

Result: Annual = $5.04 \times 6,000 / 1,000 = 30.2 \text{ t}$; cost = $30.2 \times 52,000 = \mathbf{₹ 15.7 \text{ lakh/year}}$ [1 mark]

Marking note: full marks for $\pm 2\%$ values; ½ mark deducted if the same factor 'a' is used for roof and walls.

S-5 [1P2CEM055 | Chapter 5: Insulation and Refractories | Refractory properties and their significance]

Match each refractory property in Column A with its correct significance in Column B (write the pair and one line of justification).

Column A – Property	Column B – Significance
1. Bulk density	a. Temperature at which bricks collapse under service-like load
2. Apparent porosity	b. Softening temperature, found by the cone fusion method

3. Pyrometric cone equivalent (PCE)	c. Higher value raises volume stability, heat capacity and slag resistance
4. Refractoriness under load (RUL)	d. Time-dependent deformation at a given temperature under stress
5. Creep at high temperature	e. Low value prevents easy penetration of molten charge and slag

S-5 Ans (model answer with marking scheme)

Answer (1 mark each):

1 – c: Bulk density is the material present in a given volume; higher bulk density increases volume stability, heat capacity and resistance to slag penetration.

2 – e: Apparent porosity is the volume of open pores as a % of total volume; a low value is desirable where the refractory contacts molten charge and slag.

3 – b: PCE indicates the softening temperature (refractoriness), assessed by the standard cone that melts to the same extent as the test cone. It does not reflect behaviour under load.

4 – a: RUL gives the temperature at which bricks collapse under service-like load; it is lower than the PCE and is critical for roofs and load-bearing walls.

5 – d: Creep is a time-dependent property that gives the deformation in a given time at a given temperature under stress.

Marking note: award ½ mark for the correct pair and ½ mark for the justification.

S-6 [1P2CEM056 | Chapter 6: FBC Boilers | FBC boiler operation – true or false with reasons]

State whether each statement is TRUE or FALSE and give a one-line reason for each (1 mark each).

1. An FBC boiler can fire coal with ash content as high as 62% and calorific value as low as 2,500 kcal/kg.
2. Raising the bed temperature above 950 °C improves sulphur retention by limestone.
3. Limestone required is about 3% of the coal feed for every 1% sulphur in the coal.
4. In a CFBC boiler, the fluidising velocity is lower than in an AFBC boiler.
5. Corrosion and erosion are lower in FBC boilers because of low combustion temperature, soft ash and low particle velocity.

S-6 Ans (model answer with marking scheme)

1. **TRUE:** the guidebook states FBC boilers can fire coals with ash up to 62% and CV as low as 2,500 kcal/kg ($\approx 10,467$ kJ/kg), and even 1% carbon can sustain combustion.

2. **FALSE:** above 950 °C clinker forms in the bed; efficient sulphur retention needs 800–850 °C.

3. **TRUE:** the guidebook rule is 3% limestone per 1% sulphur in the coal feed (with limestone or dolomite capturing SO_2 in the bed).

4. **FALSE:** CFBC fluidising velocity is 3.7–9 m/s, higher than the 1.2–3.7 m/s of AFBC; particles are carried over and recycled through cyclones.

5. **TRUE:** lower combustion temperature, softness of ash and low particle velocity (about 1 m/s) reduce corrosion and erosion.

Marking note: ½ mark for True/False and ½ mark for the reason.

S-7 [1P2CEM057 | Chapter 7: Cogeneration | Gas turbine cogeneration – fuel, efficiency, H:P ratio and EUF]

A 5 MW natural-gas-fired gas turbine generator operates at full load with a heat rate of 3,100 kcal/kWh (GCV basis). Its exhaust passes through an unfired HRS that generates 10 TPH of steam with enthalpy 660 kcal/kg from feed water at 105 °C. GCV of natural gas is 8,500 kcal/sm³.

- Calculate the natural gas consumption in sm³/h and the electrical efficiency of the GT. (2 Marks)
- Calculate the heat-to-power ratio of the cogeneration plant. (1 Mark)
- Calculate the Energy Utilisation Factor (EUF). (2 Marks)

S-7 Ans (model answer with marking scheme)

Given: P = 5,000 kW; HR = 3,100 kcal/kWh ($\approx 12,979$ kJ/kWh); steam = 10,000 kg/h; hg = 660 kcal/kg ($\approx 2,763$ kJ/kg); hfw = 105 kcal/kg (≈ 440 kJ/kg); GCV = 8,500 kcal/sm³ (≈ 35.6 MJ/sm³).

a) Fuel and efficiency (2 marks)

Fuel heat input = $5,000 \times 3,100 = 1,55,00,000$ kcal/h (≈ 18.0 MW); gas = $1,55,00,000 / 8,500 = \mathbf{1,824}$ sm³/h [1 mark]

$\eta_{el} = 860 / 3,100 \times 100 = \mathbf{27.7\%}$ [1 mark]

b) Heat-to-power ratio (1 mark)

Thermal output = $10,000 \times (660 - 105) = 55,50,000$ kcal/h = $55,50,000/860 = 6,453$ kW

H:P = $6,453 / 5,000 = \mathbf{1.29}$ (within the guidebook range for gas-turbine/combined systems, far below back-pressure steam turbines) [1 mark]

c) EUF (2 marks)

Formula: EUF = (Electrical output + Thermal output) / Fuel heat input

Substitution: = $(5,000 \times 860 + 55,50,000) / 1,55,00,000 = (43,00,000 + 55,50,000) / 1,55,00,000$

Result: **EUF $\approx 63.5\%$** [2 marks]

S-8 [1P2CEM058 | Chapter 9: Heat Exchangers | Heat exchanger – outlet temperature, LMTD, area and effectiveness]

In a counter-flow shell-and-tube exchanger, hot condensate (3 kg/s, Cp 4.18 kJ/kg K) entering at 95 °C heats boiler make-up water (4 kg/s, Cp 4.18 kJ/kg K) from 25 °C to 45 °C. The overall heat transfer coefficient is 1.2 kW/m² K. Heat losses are negligible.

- Calculate the heat duty and the condensate outlet temperature. (2 Marks)
- Calculate the LMTD and the heat transfer area required. (2 Marks)
- Calculate the effectiveness of the exchanger. (1 Mark)

S-8 Ans (model answer with marking scheme)

Given: m_h = 3 kg/s; m_c = 4 kg/s; Cp = 4.18 kJ/kg K; Th,in = 95 °C; Tc: 25 → 45 °C; U = 1.2 kW/m² K.

Formula: Q = m × Cp × ΔT; LMTD = $(\Delta T_1 - \Delta T_2) / \ln(\Delta T_1 / \Delta T_2)$; A = Q / (U × LMTD); $\epsilon = Q / [C_{min} \times (Th,in - Tc,in)]$

a) Duty and outlet (2 marks)

Result: Q = m_c × Cp × ΔT_c = $4 \times 4.18 \times 20 = \mathbf{334.4}$ kW ($\approx 2,87,600$ kcal/h) [1 mark]

Result: Th,out = $95 - 334.4 / (3 \times 4.18) = 95 - 26.67 = \mathbf{68.3}$ °C [1 mark]

b) LMTD and area (2 marks)

Result: ΔT₁ = 95 – 45 = 50 °C; ΔT₂ = 68.3 – 25 = 43.3 °C; LMTD = $(50 - 43.3) / \ln(50/43.3) = \mathbf{46.6}$ °C [1 mark]

Result: A = Q / (U × LMTD) = $334.4 / (1.2 \times 46.6) = \mathbf{5.98}$ m² [1 mark]

c) Effectiveness (1 mark)

Result: C_{min} = $3 \times 4.18 = 12.54$ kW/K (hot side); Q_{max} = $12.54 \times (95 - 25) = 877.8$ kW; $\epsilon = 334.4 / 877.8 = \mathbf{0.38}$ [1 mark]

Marking note: area between 5.9 and 6.1 m² gets full marks.

..... End of Section II

Section – III: LONG DESCRIPTIVE QUESTIONS

Marks: 6 x 10 = 60

(i) Answer all Six questions

(ii) Each question carries Ten marks

L-1 [1P2CEM059 | Chapter 2: Boilers | Boiler efficiency by indirect method (coal-fired)]

An energy auditor tests a 25 TPH coal-fired travelling-grate boiler. Data collected:

Parameter	Value
Ultimate analysis of coal (%)	C 40.5, H ₂ 2.6, O ₂ 6.8, N ₂ 0.8, S 0.45, Moisture 13.0, Ash 35.85
GCV of coal	3,750 kcal/kg
Flue gas at APH outlet	O ₂ 6.5%, CO ₂ 13.0%, CO 400 ppm, temperature 175 °C
Ambient air	32 °C; humidity 0.0204 kg/kg dry air
Ash split	Fly ash 80%, bottom ash 20% of total ash
GCV of fly ash / bottom ash	180 kcal/kg / 600 kcal/kg
Radiation and unaccounted loss	1.2%
Steam enthalpy / feed water temperature	665 kcal/kg / 105 °C

Take Cp of flue gas = 0.24 kcal/kg °C, Cp of superheated vapour = 0.45 kcal/kg °C and latent heat = 584 kcal/kg.

- Calculate the theoretical air, excess air and actual air supplied per kg of coal. (2 Marks)
- Calculate the mass of dry flue gas per kg of coal. (1 Mark)
- Calculate all the heat losses and the boiler efficiency by the indirect method. (5 Marks)
- Calculate the evaporation ratio and the coal consumption at 25 TPH steam. (2 Marks)

L-1 Ans (model answer with marking scheme)

Given: Coal: C = 40.5%, H₂ = 2.6%, O₂ = 6.8%, N₂ = 0.8%, S = 0.45%, M = 13.0%, ash = 35.85%; GCV = 3,750 kcal/kg ($\approx 15,700$ kJ/kg); flue gas: O₂ = 6.5%, CO₂ = 13.0%, CO = 400 ppm (0.04%), Tf = 175 °C; Ta = 32 °C; humidity = 0.0204 kg/kg dry air; GCV of fly ash = 180 kcal/kg (≈ 754 kJ/kg), bottom ash = 600 kcal/kg ($\approx 2,512$ kJ/kg); L₆ = 1.2%; hg = 665 kcal/kg ($\approx 2,784$ kJ/kg); feed water 105 °C (hf = 105 kcal/kg (≈ 440 kJ/kg)); Cp of flue gas = 0.24 kcal/kg °C (≈ 1.00 kJ/kg·K); Cp of vapour = 0.45 kcal/kg °C (≈ 1.88 kJ/kg·K); latent heat = 584 kcal/kg ($\approx 2,445$ kJ/kg); steam = 25,000 kg/h.

a) Air (2 marks)

Formula: Theoretical air = $[11.6C + 34.8(H_2 - O_2/8) + 4.35S]/100$; EA = $O_2/(21 - O_2) \times 100$; AAS = $(1 + EA/100) \times$ theoretical air

Theoretical air = $[11.6 \times 40.5 + 34.8 \times (2.6 - 6.8/8) + 4.35 \times 0.45]/100 = [469.8 + 60.9 + 1.96]/100 = \mathbf{5.33 \text{ kg/kg coal}}$ [1 mark]

EA = $6.5/(21 - 6.5) \times 100 = \mathbf{44.8\%}$; AAS = $1.448 \times 5.327 = \mathbf{7.71 \text{ kg/kg coal}}$ [1 mark]

b) Dry flue gas (1 mark)

Formula: m = CO₂ + N₂ (fuel) + N₂ (air) + excess O₂ + SO₂, all in kg/kg coal

m = CO₂ ($0.405 \times 44/12 = 1.485$) + N₂ from fuel (0.008) + N₂ in air ($7.714 \times 0.77 = 5.940$) + excess O₂ ($((7.714 - 5.327) \times 0.23 = 0.549)$) + SO₂ ($0.0045 \times 64/32 = 0.009$) = $\mathbf{7.99 \text{ kg/kg coal}}$ [1 mark]

c) Losses (5 marks; ½–1 mark each)

Formula: L₁ = $m \times C_p \times (T_f - T_a)/GCV \times 100$; L₂ = $9H_2 \times [584 + C_p(T_f - T_a)]/GCV \times 100$; L₃ = $M \times [584 + C_p(T_f - T_a)]/GCV \times 100$; L₄ = AAS $\times$ humidity $\times C_p \times (T_f - T_a)/GCV \times 100$; L₅ = $[\%CO \times C/(\%CO + \%CO_2)] \times 5,654/GCV \times 100$; L₇, L₈ = ash fraction $\times$ GCV of ash/GCV $\times 100$

Loss	Formula and substitution	%
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L ₁ Dry flue gas	$7.99 \times 0.24 \times (175 - 32)/3,750 \times 100$	7.31
L ₂ H ₂ in fuel	$9 \times 0.026 \times [584 + 0.45 \times 143]/3,750 \times 100 = 0.234 \times 648.35/3,750 \times 100$	4.05
L ₃ Moisture in fuel	$0.13 \times 648.35/3,750 \times 100$	2.25
L ₄ Moisture in air	$7.714 \times 0.0204 \times 0.45 \times 143/3,750 \times 100$	0.27
L ₅ CO	$[0.04 \times 0.405/(0.04 + 13.0)] \times 5,654/3,750 \times 100$	0.19
L ₆ Radiation and unaccounted	given	1.20
L ₇ Unburnt in fly ash	$0.80 \times 0.3585 \times 180/3,750 \times 100$ (0.2868 kg $\times$ 180 = 51.6 kcal/kg)	1.38
L ₈ Unburnt in bottom ash	$0.20 \times 0.3585 \times 600/3,750 \times 100$ (0.0717 kg $\times$ 600 = 43.0 kcal/kg)	1.15
Total losses		17.79

Result: Boiler efficiency = $100 - 17.79 = 82.2\%$ (**GCV basis**), i.e. useful heat $\approx 0.822 \times 3,750 = 3,083$ kcal/kg coal ($\approx 12,908$ kJ/kg coal) [1 mark for the final result]

d) Evaporation ratio and coal (2 marks)

Formula: $ER = \eta \times GCV / (h_g - h_f)$; coal = steam/ER

$ER = \eta \times GCV / (h_g - h_f) = 0.822 \times 3,750 / (665 - 105) = 5.51$ **kg steam/kg coal** [1 mark]

Coal = $25,000 / 5.505 = 4,541$ **kg/h $\approx$ 4.54 t/h** [1 mark]

Insight: dry flue gas loss (7.3%) is the largest controllable loss; cutting O₂ from 6.5% to about 4.5% and cleaning heat transfer surfaces are the first actions. Blowdown loss is not part of this test as per the standards.

L-2 [1P2CEM060 | Chapter 3: Steam System | Steam line insulation economics and pipe sizing]

A 200 m long steam main (pipe OD 168 mm) carries 8 TPH of saturated steam at 10 kg/cm²(g). The existing 50 mm insulation is damaged and its surface temperature averages 85 °C. The auditor proposes new 75 mm mineral wool insulation with aluminium cladding, expected surface temperature 45 °C. Ambient is 30 °C.

Data	Value
Operating hours	8,000 h/year
Boiler efficiency	82%
GCV of furnace oil	10,200 kcal/kg
Cost of furnace oil	₹ 52,000 per tonne
Cost of new insulation (installed)	₹ 1,800 per metre
Specific volume of steam at 10 kg/cm ² (g)	0.177 m ³ /kg
Internal diameter of existing pipe	154 mm

Use $S = [10 + (T_s - T_a)/20] \times (T_s - T_a)$ kcal/h·m².

- Calculate the heat loss with existing and proposed insulation. (3 Marks)
- Calculate annual fuel savings (tonnes and ₹) and the simple payback period. (3 Marks)
- Check the steam velocity in the existing line against the guidebook range for saturated steam and find the internal diameter needed for 35 m/s. Comment. (4 Marks)

L-2 Ans (model answer with marking scheme)

Given: L = 200 m; pipe OD = 168 mm, ID = 154 mm; steam = 8,000 kg/h at 10 kg/cm²(g) (≈ 9.81 bar(g)), $v = 0.177$ m³/kg; T_s = 85 °C existing (50 mm), 45 °C proposed (75 mm); T_a = 30 °C; 8,000 h/year; $\eta = 82\%$; GCV = 10,200 kcal/kg ($\approx 42,705$ kJ/kg); oil = ₹ 52,000/t; insulation = ₹ 1,800/m.

a) Heat loss (3 marks)

Formula: $S = [10 + (T_s - T_a)/20] \times (T_s - T_a)$ kcal/h·m²; $A = \pi \times D \times L$; $Q = S \times A$

Result (Existing): outer dia = $0.168 + 2 \times 0.050 = 0.268$ m; $A_1 = \pi \times 0.268 \times 200 = 168.4$ m²; $S_1 = [10 + (85 - 30)/20] \times 55 = 12.75 \times 55 = 701.25$ kcal/h·m² (≈ 816 W/m²); $Q_1 = 701.25 \times 168.4 = \mathbf{1,18,083}$ kcal/h ($\approx \mathbf{137}$ kW) [1½ marks]

Result (Proposed): outer dia = $0.168 + 2 \times 0.075 = 0.318$ m; $A_2 = \pi \times 0.318 \times 200 = 199.8$ m²; $S_2 = [10 + 15/20] \times 15 = 10.75 \times 15 = 161.25$ kcal/h·m² (≈ 188 W/m²); $Q_2 = 161.25 \times 199.8 = \mathbf{32,219}$ kcal/h ($\approx \mathbf{37.5}$ kW) [1½ marks]

b) Savings and payback (3 marks)

Formula: Fuel saved = $\Delta Q \times \text{hours} / (\text{GCV} \times \eta)$; payback = investment/annual saving

Reduction = $1,18,083 - 32,219 = 85,864$ kcal/h (≈ 99.8 kW) [1 mark]

Result: Fuel saved = $85,864 \times 8,000 / (10,200 \times 0.82) / 1,000 = \mathbf{82.1}$ t/year; value = $82.1 \times 52,000 = \mathbf{₹ 42.7}$ lakh/year [1 mark]

Result: Investment = $200 \times 1,800 = ₹ 3,60,000$; payback = $3.6 / 42.7 \times 12 = \approx \mathbf{1.0}$ month [1 mark]

c) Velocity check (4 marks)

Formula: Volume flow = $m \times v$; velocity = volume flow/ $(\pi/4 \times d^2)$; $d = \sqrt{4 \times \text{volume flow} / (\pi \times \text{velocity})}$

Volume flow = $8,000 \times 0.177 / 3,600 = 0.3933$ m³/s [1 mark]

Result: Area = $\pi/4 \times 0.154^2 = 0.01863$ m²; velocity = $0.3933/0.01863 = \mathbf{21.1}$ m/s [1 mark]

Guidebook velocity for saturated steam = 30–40 m/s, so the line is oversized (21.1 m/s is in the wet/exhaust steam band of 20–30 m/s) [1 mark]

Result: ID for 35 m/s = $\sqrt{4 \times 0.3933 / (\pi \times 35)} = 0.120$ m $\rightarrow \approx \mathbf{120}$ mm (**125 NB**). Comment: an oversized main has more surface area, higher heat loss and more condensate; when the line is replaced, use the smaller size.

Meanwhile, the insulation upgrade is essential. Lay the main with a falling slope (at least 125 mm per 30 m) and drain points every 30–50 m. [1 mark]

L-3 [1P2CEM061 | Chapter 4: Furnaces | Reheating furnace – efficiency, excess air and combustion air preheat]

A continuous pusher-type reheating furnace heats 40 t/h of billets from 30 °C to 1,180 °C (mean C_p 0.12 kcal/kg °C) and fires 1,850 kg/h of furnace oil (GCV 10,000 kcal/kg, specific gravity 0.93, theoretical air 14 kg/kg). Flue gas leaves the recuperator at 650 °C with 9% O₂; combustion air is now preheated to 250 °C. Ambient is 35 °C, and C_p of air and flue gas is 0.24 kcal/kg °C. Proposed improvements: (i) reduce O₂ to 3% through burner tuning and furnace pressure control, and (ii) upgrade the recuperator to preheat air to 350 °C (flue gas exit temperature stays at 650 °C). The furnace runs 6,000 h/year and oil costs ₹ 48,000 per tonne.

a) Calculate the present furnace efficiency (direct method) and SEC in kg/t and litres/t. (3 Marks)

b) Calculate the present flue gas loss as % of fuel input (take flue gas = actual air + 1 kg per kg fuel). (2 Marks)

c) Calculate the % fuel saving from O₂ reduction. (2 Marks)

d) Calculate the additional % fuel saving from higher air preheat (heat added to air per kg fuel ÷ GCV, with air quantity after O₂ correction). (2 Marks)

e) Calculate the new SEC and the annual savings in ₹ lakh (add the two savings, as in the guidebook approach). (1 Mark)

L-3 Ans (model answer with marking scheme)

Given: Stock = 40,000 kg/h, 30 $\rightarrow$ 1,180 °C, $C_p = 0.12$ kcal/kg °C (≈ 0.502 kJ/kg·K); oil = 1,850 kg/h, GCV = 10,000 kcal/kg ($\approx 41,868$ kJ/kg), SG = 0.93, theoretical air = 14 kg/kg; flue gas 650 °C, O₂ 9% $\rightarrow$ 3%; air preheat 250 $\rightarrow$ 350 °C; $T_a = 35$ °C; C_p of air and flue gas = 0.24 kcal/kg °C (≈ 1.00 kJ/kg·K); 6,000 h/year; oil = ₹ 48,000/t.

a) Direct efficiency and SEC (3 marks)

Formula: $\eta = m \times C_p \times (t_2 - t_1) / (\text{fuel} \times \text{GCV}) \times 100$; SEC = fuel/production

Heat to stock = $40,000 \times 0.12 \times (1,180 - 30) = 55,20,000 \text{ kcal/h}$ ($\approx 6,419 \text{ kW}$); heat in fuel = $1,850 \times 10,000 = 1,85,00,000 \text{ kcal/h}$ ($\approx 21.5 \text{ MW}$)

Result: $\eta = 55,20,000 / 1,85,00,000 \times 100 = \mathbf{29.8\%}$ [1½ marks]

Result: $\text{SEC} = 1,850/40 = \mathbf{46.25 \text{ kg/t}}$; $= 46.25/0.93 = \mathbf{49.7 \text{ litres/t}}$ [1½ marks]

b) Present flue gas loss (2 marks)

Formula: $\text{EA} = \text{O}_2/(21 - \text{O}_2)$; flue gas loss = $(\text{AAS} + 1) \times \text{Cp} \times (\text{Tf} - \text{Ta})/\text{GCV} \times 100$

$\text{EA} = 9/(21 - 9) = 75\%$; $\text{AAS} = 14 \times 1.75 = 24.5 \text{ kg/kg}$; flue gas = 25.5 kg/kg

Result: $\text{Loss} = 25.5 \times 0.24 \times (650 - 35) = \mathbf{3,764 \text{ kcal/kg}}$ ($\approx \mathbf{15,759 \text{ kJ/kg}}$) = **37.6% of GCV** [2 marks]

c) O₂ reduction (2 marks)

$\text{EA} = 3/(21 - 3) = 16.7\%$; $\text{AAS} = 14 \times 1.167 = 16.33 \text{ kg/kg}$; loss = $17.33 \times 0.24 \times 615 = 2,558 \text{ kcal/kg}$ ($\approx 10,710 \text{ kJ/kg}$) = **25.6% of GCV**

Result: $\text{Saving} = (3,764 - 2,558)/10,000 \times 100 = \mathbf{12.05\%}$ [2 marks]

d) Higher air preheat (2 marks)

Formula: $\text{saving} = \text{AAS} \times \text{Cp} \times (\text{t}_{\text{air,new}} - \text{t}_{\text{air,old}})/\text{GCV} \times 100$

Result: Extra heat to air = $16.33 \times 0.24 \times (350 - 250) = 392 \text{ kcal/kg fuel}$ ($\approx 1,641 \text{ kJ/kg fuel}$); saving = $392/10,000 \times 100 = \mathbf{3.92\%}$ [2 marks]

e) New SEC and savings (1 mark)

Result: Total saving = $12.05 + 3.92 = 15.97\%$; new fuel = $1,850 \times (1 - 0.1597) = 1,554.5 \text{ kg/h}$; new SEC = **38.9 kg/t** ($\approx 41.8 \text{ litres/t}$)

Result: Fuel saved = $295.5 \text{ kg/h} \times 6,000 = 1,773 \text{ t/year} \times ₹ 48,000 = \mathbf{₹ 851 \text{ lakh/year}}$ ($\approx \mathbf{₹ 8.5 \text{ crore}}$) [1 mark]

Insight: excess air control alone gives three-quarters of the benefit at almost no capital cost, so it should be done before the recuperator upgrade.

L-4 [1P2CEM062 | Chapter 7: Cogeneration | Back-pressure steam turbine cogeneration – techno-economics]

A chemical plant buys 6 MW from the grid at ₹ 8.50/kWh and produces 40 TPH of process steam at $4 \text{ kg/cm}^2(\text{g})$ in a low-pressure coal-fired boiler (efficiency 82%, steam enthalpy $2,740 \text{ kJ/kg}$). It proposes a new 65 kg/cm^2 , 480°C boiler (efficiency 85%) with a back-pressure turbine exhausting the full 40 TPH to process at $4 \text{ kg/cm}^2(\text{g})$.

Data	Value
Turbine inlet enthalpy	3,350 kJ/kg
Turbine exhaust enthalpy (actual)	2,800 kJ/kg
Feed water enthalpy (both cases)	440 kJ/kg
Turbine mechanical $\times$ gearbox $\times$ alternator efficiency	$0.96 \times 0.98 \times 0.97$
GCV of coal / cost	$4,200 \text{ kcal/kg}$ ($1 \text{ kcal} = 4.187 \text{ kJ}$) / ₹ 6,500 per tonne
Operating hours	8,000 h/year
Investment	₹ 42 crore

a) Calculate the electrical power generated. (3 Marks)

b) Calculate the heat-to-power ratio and the Energy Utilisation Factor of the new scheme. (3 Marks)

c) Calculate the incremental coal cost, the net annual benefit and the simple payback period. (4 Marks)

L-4 Ans (model answer with marking scheme)

Given: Steam = $40,000 \text{ kg/h}$; $h_1 = 3,350 \text{ kJ/kg}$, $h_2 = 2,800 \text{ kJ/kg}$, $h_{\text{fw}} = 440 \text{ kJ/kg}$; old LP boiler: $h_g = 2,740 \text{ kJ/kg}$, $\eta = 0.82$; new boiler at 65 kg/cm^2 ($\approx 63.7 \text{ bar}$), 480°C , $\eta = 0.85$; process steam at $4 \text{ kg/cm}^2(\text{g})$ ($\approx 3.92 \text{ bar(g)}$); $\eta_m \times \eta_g \times \eta_a = 0.96 \times 0.98 \times 0.97$; coal GCV = $4,200 \text{ kcal/kg}$ ($\approx 17,585 \text{ kJ/kg}$), ₹ 6,500/t; grid ₹ 8.50/kWh; 8,000 h/year; investment ₹ 42 crore.

a) Power (3 marks)

Formula: $P = m \times (h_1 - h_2)/3,600 \times \eta_m \times \eta_g \times \eta_a$ (kW)

Enthalpy drop = $3,350 - 2,800 = 550$ kJ/kg; turbine shaft input = $40,000 \times 550/3,600 = 6,111$ kW [1 mark]

Overall efficiency = $0.96 \times 0.98 \times 0.97 = 0.9126$ [1 mark]

Result: Power = $6,111 \times 0.9126 = 5,577$ kW (≈ 5.58 MW) [1 mark]

b) H:P and EUF (3 marks)

Formula: H:P = process heat/power; EUF = (power + process heat)/fuel heat input

Result: Process heat = $40,000 \times (2,800 - 440)/3,600 = 26,222$ kW; H:P = $26,222/5,577 = 4.70$ (within 4.0–14.3 for back-pressure turbines) [1 mark]

Fuel heat input = $40,000 \times (3,350 - 440)/0.85 = 13,69,41,176$ kJ/h = $38,039$ kW [1 mark]

Result: EUF = $(5,577 + 26,222)/38,039 = 83.6\%$ [1 mark]

c) Economics (4 marks)

Formula: Extra fuel heat = $m(h_1 - h_{fw})/\eta_{\text{new}} - m(h_g - h_{fw})/\eta_{\text{old}}$; payback = investment/net annual benefit

Old boiler heat input = $40,000 \times (2,740 - 440)/0.82 = 11,21,95,122$ kJ/h; incremental = $13,69,41,176 - 11,21,95,122 = 2,47,46,054$ kJ/h [1 mark]

Coal GCV = $4,200 \times 4.1868 = 17,585$ kJ/kg; extra coal = $2,47,46,054/17,585 = 1,407$ kg/h; cost = $1.407 \times 6,500 = ₹ 9,147$ /h [1 mark]

Result: Grid power avoided = $5,577 \times 8.50 = ₹ 47,403$ /h; net benefit = $₹ 38,256$ /h $\times 8,000 = ₹ 30.6$ crore/year [1 mark]

Result: Payback = $42/30.6 = 1.37$ years (≈ 16.5 months) [1 mark]

Insight: the extra fuel needed for 5.58 MW is only 1,407 kg/h of coal, a marginal heat rate of about 4,440 kJ/kWh, because the exhaust heat is used in the process. This is the core cogeneration advantage.

L-5 [1P2CEM063 | Chapter 8: Waste Heat Recovery | Waste heat recovery from DG exhaust and heat pump application]

A textile plant runs a 2 MW furnace-oil DG set for 7,000 h/year. The exhaust gas flow is 11,500 kg/h at 460 °C ($C_p = 0.25$ kcal/kg °C). A waste heat boiler is proposed to cool the exhaust to 180 °C (kept above the acid dew point) and generate saturated steam at 8 kg/cm²(g) (enthalpy 660 kcal/kg) from feed water at 80 °C. The steam will displace steam from an existing oil-fired boiler (efficiency 84%, GCV 10,200 kcal/kg, oil ₹ 52,000 per tonne). The WHRB costs ₹ 1.2 crore installed.

Separately, a 120 kW electric heater (efficiency 98%) that heats wash water to 70 °C is to be replaced by a heat pump with COP 3.6 using warm effluent as the heat source. Electricity costs ₹ 8.50/kWh and the heater runs 6,000 h/year.

a) Calculate the heat recoverable from the exhaust. (2 Marks)

b) Calculate the steam generated in the WHRB. (2 Marks)

c) Calculate the annual fuel oil and cost saving and the simple payback period of the WHRB. (3 Marks)

d) Calculate the power drawn by the heat pump and the annual saving compared with the electric heater. State why the heat pump is attractive here. (3 Marks)

L-5 Ans (model answer with marking scheme)

Given: Exhaust = 11,500 kg/h, 460 → 180 °C, $C_p = 0.25$ kcal/kg °C (≈ 1.05 kJ/kg·K); steam at 8 kg/cm²(g) (≈ 7.85 bar(g)), $h_g = 660$ kcal/kg ($\approx 2,763$ kJ/kg); feed water 80 °C ($h_{fw} = 80$ kcal/kg (≈ 335 kJ/kg)); boiler $\eta = 0.84$, GCV = 10,200 kcal/kg ($\approx 42,705$ kJ/kg), oil = ₹ 52,000/t; 7,000 h/year; WHRB = ₹ 1.2 crore. Heater: 120 kW, $\eta = 0.98$; heat pump COP = 3.6; ₹ 8.50/kWh; 6,000 h/year.

a) Heat recoverable (2 marks)

Result: $Q = m \times C_p \times \Delta T = 11,500 \times 0.25 \times (460 - 180) = 8,05,000 \text{ kcal/h} (\approx 936 \text{ kW})$ [2 marks]

b) Steam generation (2 marks)

Formula: $\text{Steam} = Q / (h_g - h_{fw})$

Result: $\text{Steam} = Q / (h_g - h_{fw}) = 8,05,000 / (660 - 80) = 1,388 \text{ kg/h}$ [2 marks]

c) Savings and payback (3 marks)

Formula: $\text{Oil saved} = Q / (\text{GCV} \times \eta)$; $\text{payback} = \text{investment} / \text{annual saving}$

Result: $\text{Oil saved} = 8,05,000 / (10,200 \times 0.84) = 93.95 \text{ kg/h}$; $\text{annual} = 93.95 \times 7,000 / 1,000 = 657.7 \text{ t/year}$ [1 mark]

Result: $\text{Cost saving} = 657.7 \times 52,000 = ₹ 3.42 \text{ crore/year}$ [1 mark]

Result: $\text{Payback} = 1.20 / 3.42 \times 12 = \approx 4.2 \text{ months}$ [1 mark]

d) Heat pump (3 marks)

Formula: $\text{Heat pump power} = \text{heat delivered} / \text{COP}$; $\text{heater input} = \text{heat delivered} / \eta$

Result: $\text{Heat pump power} = 120 / 3.6 = 33.3 \text{ kW}$; $\text{electric heater input} = 120 / 0.98 = 122.4 \text{ kW}$ [1 mark]

Result: $\text{Saving} = (122.4 - 33.3) \times 6,000 \times 8.50 = 89.1 \times 51,000 = ₹ 45.4 \text{ lakh/year}$ [1 mark]

Reason: the heat pump upgrades low-grade effluent heat to useful temperature and delivers more than twice (here 3.6 times) the energy it consumes. The temperature lift is small (warm effluent to 70 °C), which keeps the COP high, and it also cools the effluent before discharge. [1 mark]

L-6 [1P2CEM064 | Chapter 6: FBC Boilers | Conversion of oil-fired boiler to AFBC coal firing]

A 10 TPH oil-fired package boiler (efficiency 86%) generates steam of enthalpy 665 kcal/kg from feed water at 90 °C. Management plans to replace it with a 10 TPH AFBC boiler (efficiency 80%) firing Indian coal (GCV 3,800 kcal/kg, sulphur 0.8%), with limestone dosing for SO₂ control.

Data	Value
GCV / cost of furnace oil	10,200 kcal/kg / ₹ 52,000 per tonne
Cost of coal	₹ 7,500 per tonne
Cost of limestone	₹ 3,000 per tonne
Additional auxiliary power for FBC (fans, coal and ash handling)	45 kW at ₹ 8.00/kWh
Operating hours	7,200 h/year
Investment in AFBC boiler with auxiliaries	₹ 3.5 crore

a) Calculate the hourly furnace oil consumption and cost of the existing boiler. (2 Marks)

b) Calculate the hourly coal and limestone consumption of the AFBC boiler (use the guidebook limestone rule). (2 Marks)

c) Calculate the net annual saving and the simple payback period. (3 Marks)

d) Give three reasons from the guidebook why FBC is well suited to high-ash Indian coal. (3 Marks)

L-6 Ans (model answer with marking scheme)

Given: $\text{Steam} = 10,000 \text{ kg/h}$; $h_g = 665 \text{ kcal/kg} (\approx 2,784 \text{ kJ/kg})$; $\text{feed water } 90^\circ\text{C} (h_{fw} = 90 \text{ kcal/kg} (\approx 377 \text{ kJ/kg}))$; $\eta_{\text{oil}} = 0.86$, $\eta_{\text{AFBC}} = 0.80$; $\text{GCV oil} = 10,200 \text{ kcal/kg} (\approx 42,705 \text{ kJ/kg})$, $\text{coal} = 3,800 \text{ kcal/kg} (\approx 15,910 \text{ kJ/kg})$; $S = 0.8\%$; $\text{oil } ₹ 52,000/\text{t}$, $\text{coal } ₹ 7,500/\text{t}$, $\text{limestone } ₹ 3,000/\text{t}$; $\text{aux power } 45 \text{ kW at } ₹ 8.00/\text{kWh}$; $7,200 \text{ h/year}$; $\text{investment } ₹ 3.5 \text{ crore}$.

Formula: $Q = m \times (h_g - h_{fw})$; $\text{fuel} = Q / (\text{GCV} \times \eta)$; $\text{limestone} = 3\% \text{ of coal per } 1\% S$

Heat output: $Q = 10,000 \times (665 - 90) = 57,50,000 \text{ kcal/h} (\approx 6,686 \text{ kW})$

a) Oil boiler (2 marks)

Result: Oil = $57,50,000 / (10,200 \times 0.86) = 655.5 \text{ kg/h}$; cost = $0.6555 \times 52,000 = ₹ 34,086/\text{h}$ [2 marks]

b) AFBC (2 marks)

Result: Coal = $57,50,000 / (3,800 \times 0.80) = 1,891 \text{ kg/h}$; cost = $1.891 \times 7,500 = ₹ 14,186/\text{h}$ [1 mark]

Result: Limestone = 3% per 1% S $\rightarrow 3 \times 0.8 = 2.4\%$ of coal = $0.024 \times 1,891 = 45.4 \text{ kg/h}$; cost = ₹ 136/h [1 mark]

c) Savings and payback (3 marks)

Aux power cost = $45 \times 8 = ₹ 360/\text{h}$; FBC total = $14,186 + 136 + 360 = ₹ 14,682/\text{h}$ [1 mark]

Result: Net saving = $34,086 - 14,682 = ₹ 19,404/\text{h} \times 7,200 = ₹ 1,397 \text{ lakh} \approx ₹ 13.97 \text{ crore/year}$ [1 mark]

Result: Payback = $3.5 / 13.97 \times 12 = \approx 3.0 \text{ months}$ [1 mark]

d) Reasons (3 marks, 1 each; any three)

- Ability to burn low-grade fuel: FBC can fire coals with ash up to 62% and CV as low as 2,500 kcal/kg ($\approx 10,467 \text{ kJ/kg}$).
- No clinker formation: bed temperature of 750–900 °C (combustion at 840–950 °C) is below the ash fusion temperature, so even low ash-fusion coals burn without clinker, and ash removal is easier.
- Ability to burn fines below 6 mm, plus fuel flexibility (coal, washery rejects, biomass).
- Pollution control: SO_2 is captured in the bed with limestone, and the low combustion temperature limits NO_x .
- High heat transfer in the bed allows a compact boiler with high combustion efficiency.

..... End of Section III

Answer key – Section I

Q	Ans	Q	Ans	Q	Ans	Q	Ans	Q	Ans
1	c	11	c	21	a	31	c	41	d
2	b	12	a	22	d	32	c	42	b
3	a	13	c	23	c	33	d	43	a
4	d	14	a	24	a	34	d	44	b
5	a	15	d	25	c	35	a	45	b
6	d	16	c	26	d	36	b	46	a
7	c	17	d	27	b	37	b	47	d
8	a	18	c	28	c	38	a	48	b
9	d	19	b	29	b	39	b	49	c
10	b	20	a	30	a	40	d	50	b