

PRACTICE PAPER — SET 2

NATIONAL CERTIFICATION EXAMINATION FOR ENERGY MANAGERS & ENERGY AUDITORS

PAPER – 2: ENERGY EFFICIENCY IN THERMAL UTILITIES

Question Code: 2P2CEM — 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 ceramic kiln pumps 1,800 kg/h of furnace oil through an electric outflow heater that raises the oil from 35 °C to 105 °C for atomisation. Taking the specific heat of the oil as 0.24 kcal/kg °C, the heater rating required is closest to:

[2P2CEM001]

- a) 30.2 kW
- b) 35.2 kW**
- c) 52.7 kW
- d) 73.3 kW

Correct answer: (b) 35.2 kW.

Given: oil flow $m = 1,800$ kg/h; $C_p = 0.24$ kcal/kg °C (≈ 1.00 kJ/kg·K); $t_1 = 35$ °C, $t_2 = 105$ °C; 1 kW = 860 kcal/h.

Formula: Heat duty $Q = m \times C_p \times (t_2 - t_1)$; heater kW = $Q/860$.

Substitution: $Q = 1,800 \times 0.24 \times (105 - 35) = 1,800 \times 0.24 \times 70 = 30,240$ kcal/h; kW = $30,240/860$.

Result: **Heater rating ≈ 35.2 kW.**

Fuel oil C_p is 0.22–0.28 kcal/kg °C (guidebook); an outflow heater heats only the oil being drawn.

Why not the others: (d) 73.3 kW uses a specific heat of 0.5 kcal/kg °C, which is typical of water-like liquids, not fuel oil. (c) 52.7 kW takes the full outlet temperature (105 °C) as the rise and ignores the 35 °C inlet. (a) 30.2 kW divides kcal/h by 1,000 instead of 860, a unit error.

Ref: BEE Guidebook Paper 2, Ch. 1 (Specific heat; Pumping and storage temperature of fuel oil).

Chapter 1: Fuels and Combustion | Electric outflow heater sizing for furnace oil

2. A textile process house fires 1,200 kg/h of LSHS containing 3.5% sulphur by mass. Assuming all the sulphur burns to SO₂ (S = 32, O = 16), the SO₂ emitted is about: [2P2CEM002]

- a) 42 kg/h
- b) 84 kg/h**
- c) 126 kg/h
- d) 168 kg/h

Correct answer: (b) 84 kg/h.

Given: fuel = 1,200 kg/h; sulphur = 3.5% by mass; atomic masses S = 32, O = 16.

Formula: $S + O_2 \rightarrow SO_2$, i.e. 32 kg S gives 64 kg SO₂; $SO_2 = 2 \times (\text{mass of sulphur burnt})$.

Substitution: Sulphur fired = $1,200 \times 3.5/100 = 42 \text{ kg/h}$; $SO_2 = 42 \times 64/32 = 42 \times 2$.

Result: **SO₂ ≈ 84 kg/h** (about 2 t per day of continuous firing).

This is why the guidebook warns that sulphur in fuel oil leads to SO₂/SO₃ in flue gas, low-temperature acid corrosion in economisers and chimneys, and a need to keep the stack above the acid dew point.

Why not the others: (a) 42 kg/h is only the sulphur fired; the two oxygen atoms that double the mass are forgotten. (c) 126 kg/h treats the product as SO₃-like by multiplying by 3. (d) 168 kg/h multiplies by 4, double-counting the oxygen.

Ref: BEE Guidebook Paper 2, Ch. 1 (Sulphur in fuel oils; combustion chemistry).

Chapter 1: Fuels and Combustion / Sulphur in fuel oil and SO₂ emission

3. The proximate analysis of a washed coal for a captive plant gives moisture 8%, volatile matter 26% and ash 38% (as received). The fixed carbon and the fuel ratio (fixed carbon/volatile matter) are respectively: [2P2CEM003]

- a) FC 28%; fuel ratio 1.08**
- b) FC 28%; fuel ratio 0.93
- c) FC 36%; fuel ratio 1.38
- d) FC 74%; fuel ratio 2.85

Correct answer: (a) FC 28%; fuel ratio 1.08.

Given: M = 8%, VM = 26%, Ash = 38% (as received).

Formula: Fixed carbon FC = $100 - (M + VM + \text{Ash})$; fuel ratio = FC/VM.

Substitution: FC = $100 - (8 + 26 + 38) = 100 - 72 = 28\%$; fuel ratio = $28/26$.

Result: **FC = 28%; fuel ratio ≈ 1.08**.

The guidebook explains that fixed carbon is the solid fuel left after volatile matter is distilled off and gives a rough estimate of heating value, while volatile matter governs flame length and ease of ignition. A fuel ratio near 1 indicates a coal that ignites readily but still needs adequate residence time for char burn-out.

Why not the others: (b) 0.93 is VM/FC, the inverse of the fuel ratio. (c) FC = 36% forgets to subtract moisture (a common error on as-received data). (d) FC = 74% subtracts only the volatile matter and ignores both ash and moisture.

Ref: BEE Guidebook Paper 2, Ch. 1, §1.3 (Proximate analysis of coal).

Chapter 1: Fuels and Combustion / Fixed carbon and fuel ratio from proximate analysis

4. A coal lab reports GCV of 4,800 kcal/kg on a dry basis. The coal arrives at the boiler with 16% total moisture. The GCV on an as-received basis to be used for boiler efficiency is about: [2P2CEM004]

- a) 3,939 kcal/kg
- b) 4,032 kcal/kg**
- c) 4,138 kcal/kg
- d) 4,707 kcal/kg

Correct answer: (b) 4,032 kcal/kg.

Given: GCV (dry basis) = 4,800 kcal/kg (≈ 20,097 kJ/kg); total moisture M = 16% as received.

Formula: GCV (as received) = $GCV (\text{dry}) \times (100 - M)/100$, because only the dry fraction of each kg carries heat.

Substitution: GCV (as received) = $4,800 \times (100 - 16)/100 = 4,800 \times 0.84$.

Result: **GCV (as received) $\approx$ 4,032 kcal/kg ($\approx$ 16,881 kJ/kg).**

Efficiency must be computed on the as-fired basis that matches the weighed coal; using the dry-basis value would understate boiler efficiency by about 16%. Moisture is still accounted for separately as a loss in the indirect method.

Why not the others: (c) 4,138 divides by 1.16 instead of multiplying by 0.84. (d) 4,707 subtracts only 0.16×584 kcal (latent heat of the moisture) from the dry value. (a) 3,939 converts the basis and also subtracts the latent heat, which turns a GCV into a net value.

Ref: BEE Guidebook Paper 2, Ch. 1 (Proximate analysis; moisture in coal) and Ch. 2 (Fuel GCV basis).

Chapter 1: Fuels and Combustion | Converting coal GCV from dry to as-received basis

5. A burner supplier claims that good combustion depends on the 'three T's'. Which of the following is NOT one of the three T's described in the guidebook? [2P2CEM005]

a) Thermal conductivity of the burner block

b) Temperature high enough to ignite fuel

c) Turbulence for intimate fuel–air mixing

d) Time sufficient for complete combustion

Correct answer: (a) Thermal conductivity of the burner block.

The guidebook states that the objective of good combustion is to release all the heat in the fuel, achieved by controlling the three T's: (1) Temperature high enough to ignite and maintain ignition, (2) Turbulence or intimate mixing of fuel and oxygen, and (3) Time sufficient for complete combustion.

Thermal conductivity of the burner block is a refractory property; it has nothing to do with the three T's.

Why not the others: (b) Temperature is the first T — without it the mixture will not ignite or stay lit. (c) Turbulence is the second T — poor mixing leaves CO in the stack even with excess air. (d) Time is the third T — the fuel particles must remain in the hot zone long enough to burn out.

Ref: BEE Guidebook Paper 2, Ch. 1, §1.5 (Principles of combustion).

Chapter 1: Fuels and Combustion | Three T's of combustion

6. A plant stores furnace oil in a large insulated tank and heats the entire tank to 70 °C with steam coils, although the burner needs 110 °C and only the pumping line needs warm oil. Which change follows the guidebook advice? [2P2CEM006]

a) Heat only the oil drawn off, using an outflow heater

b) Raise the tank temperature to 110 °C to aid atomising

c) Remove insulation so the tank cannot overheat the oil

d) Stop all heating, as oil is pumpable at any temperature

Correct answer: (a) Heat only the oil drawn off, using an outflow heater.

The guidebook explains that furnace oil and LSHS become difficult to pump at low ambient temperatures, and that preheating can be done either by heating the whole tank (bulk heating with steam coils) or by heating the oil only as it flows out, with an outflow heater. To reduce steam requirement and heat loss, the oil should not be stored at temperatures higher than needed for pumping; the final atomising temperature is reached in a line heater near the burner.

Why not the others: (b) Heating the whole tank to the atomising temperature multiplies surface losses and wastes steam.

(c) Removing insulation increases tank losses and does not help pumping. (d) Viscosity rises steeply as temperature falls; below about 25 °C furnace oil is not easily pumpable, so some heating is needed.

Ref: BEE Guidebook Paper 2, Ch. 1 (Storage and pumping temperature of fuel oil).

Chapter 1: Fuels and Combustion | Outflow heating versus bulk tank heating of oil

7. A glass plant is switching from furnace oil to piped natural gas. Which statement about natural gas is CORRECT as per the guidebook? [2P2CEM007]

a) It is heavier than air and settles in pits

b) It produces soot unless it is finely atomised first

c) It needs on-site storage tanks and also preheating

d) It has no sulphur and is lighter than air

Correct answer: (d) It has no sulphur and is lighter than air.

The guidebook describes natural gas as a high calorific value fuel requiring no storage facilities. It mixes with air readily, does not produce smoke or soot, has no sulphur content, and is lighter than air, so it disperses easily in case of a leak. Its carbon content per unit of heat is also the lowest among coal, oil and gas (Table 1.13), so CO₂ per kcal fired is lower.

For the glass plant this means no SO₃ attack on regenerator checkers and the possibility of cooling the flue gas further before the stack.

Why not the others: (a) Heavier-than-air behaviour applies to LPG vapour, not natural gas. (b) Gas does not need atomisation and burns without soot. (c) Natural gas is supplied by pipeline and needs neither storage tanks nor preheating, unlike furnace oil.

Ref: BEE Guidebook Paper 2, Ch. 1, §1.4 (Properties of gaseous fuels; Natural gas).

Chapter 1: Fuels and Combustion | Properties of natural gas as a fuel

8. A furnace oil sample shows an ash value of 0.25%, against the guidebook's typical range for fuel oils. What is the most likely consequence of firing such oil? [2P2CEM008]

a) Fouling deposits, burner tip erosion and refractory damage

b) Lower viscosity, so preheating is no longer needed

c) Lower flash point, creating an immediate storage hazard

d) Higher calorific value due to the extra mineral matter

Correct answer: (a) Fouling deposits, burner tip erosion and refractory damage.

The guidebook states that ash in fuel oil comes from inorganic salts (sodium, vanadium, calcium, magnesium, silicon, iron, nickel and so on), that the ash value is typically 0.03–0.07%, and that excessive ash causes fouling deposits in combustion equipment, has an erosive effect on burner tips, damages refractories at high temperatures and gives high-temperature corrosion. An ash value of 0.25% is several times the typical level, so these effects are expected.

Why not the others: (b) Viscosity is governed by the hydrocarbon fraction and temperature, not by ash. (c) Flash point depends on volatile fractions; ash does not lower it. (d) Mineral matter is non-combustible, so more ash lowers, not raises, the heat per kg.

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

Chapter 1: Fuels and Combustion | Ash content of residual fuel oil

9. An oil burner rated for 600 kg/h is often run at 120 kg/h during night shifts. Flue gas analysis shows higher O₂ at this low firing rate. Which explanation matches the guidebook? [2P2CEM009]

a) The fuel's calorific value drops at low firing rates of the burner

b) The O₂ analyser over-reads whenever the flue gas temperature falls

c) Lower firing always gives complete combustion with less air needed

d) Lower air velocity reduces turbulence, so more excess air is needed

Correct answer: (d) Lower air velocity reduces turbulence, so more excess air is needed.

The guidebook explains that the velocity of air affects turbulence, so at higher turndown ratios (low firing rates) it becomes harder to get good fuel–air mixing because the air amount is reduced. Towards the highest turndown ratios of any burner, more excess air is needed to obtain enough turbulence for proper mixing. A better burner design is one that can mix air and fuel properly at lower excess air over its turndown range. Here 600/120 is a 5:1 turndown, so rising O₂ at night is expected; consolidating load or using a smaller burner would help.

Why not the others: (a) The calorific value is a fuel property and does not change with firing rate. (b) There is no such systematic analyser error described. (c) Low firing makes mixing poorer, not better.

Ref: BEE Guidebook Paper 2, Ch. 1 (Burner turndown; Figure 1.4).

Chapter 1: Fuels and Combustion | Burner turndown and excess air

10. A 12 TPH coal-fired boiler in a paper mill had an evaporation ratio of 5.2 when new. It now gives 4.7 at the same steam output and steam/feed conditions. The additional coal now being fired is about: [2P2CEM010]

- a) 222 kg/h
- b) 245 kg/h**
- c) 272 kg/h
- d) 600 kg/h

Correct answer: (b) 245 kg/h.

Given: steam = 12,000 kg/h; ER (new) = 5.2; ER (now) = 4.7 kg steam/kg coal.

Formula: Coal fired = steam output ÷ evaporation ratio; extra coal = steam/ER₂ – steam/ER₁.

Substitution: Coal (new) = 12,000/5.2 = 2,308 kg/h; coal (now) = 12,000/4.7 = 2,553 kg/h; extra = 2,553 – 2,308.

Result: **Additional coal ≈ 245 kg/h** (about 10.6% more than the new-boiler figure).

The guidebook recommends trending the evaporation ratio because a falling ER flags fouling, poor combustion or water-side scale before efficiency tests are done.

Why not the others: (a) 222 kg/h applies 9.6% (0.5/5.2) to the old coal rate; the correct base for the increase is the new ER. (c) 272 kg/h applies 10.6% to the present coal rate, double-counting the increase. (d) 600 kg/h simply multiplies the 0.5 drop in ER by 1,200, which has no physical meaning.

Ref: BEE Guidebook Paper 2, Ch. 2 (Evaporation ratio; performance evaluation).

Chapter 2: Boilers | Fall in evaporation ratio and extra coal

11. In a sugar-refinery boiler firing 2,400 kg/h of coal, the stack temperature has risen well above the clean-boiler value and an inspection finds about 3 mm of soot on the tubes. With coal at ₹ 5,800 per tonne and 7,200 operating hours a year, the annual cost of this soot, using the guidebook estimate, is about: [2P2CEM011]

- a) ₹ 10.0 lakh
- b) ₹ 25.1 lakh**
- c) ₹ 30.5 lakh
- d) ₹ 50.1 lakh

Correct answer: (b) ₹ 25.1 lakh.

Given: coal = 2,400 kg/h; soot = 3 mm; coal price = ₹ 5,800/t; hours = 7,200 h/yr.

Formula (guidebook): 3 mm of soot raises fuel consumption by about 2.5%; extra cost = fuel rate × 2.5% × hours × price.

Substitution: Extra coal = 2,400 × 0.025 = 60 kg/h; per year = 60 × 7,200/1,000 = 432 t; cost = 432 × 5,800 = ₹ 25,05,600.

Result: **Annual cost of soot ≈ ₹ 25.1 lakh.**

The guidebook also notes that a rise of about 20 °C in stack temperature over a freshly cleaned boiler is the signal to blow soot.

Why not the others: (a) ₹ 10.0 lakh uses 1% extra fuel, not the 2.5% quoted for 3 mm of soot. (d) ₹ 50.1 lakh doubles the penalty to 5%. (c) ₹ 30.5 lakh uses 8,760 h instead of the stated 7,200 operating hours.

Ref: BEE Guidebook Paper 2, Ch. 2 (Soot blowing and soot deposit reduction).

Chapter 2: Boilers | Soot deposition and annual fuel cost

12. A 15 TPH boiler runs continuous blowdown equal to 4% of feed water. The blowdown water leaves at 190 °C (sensible heat 190 kcal/kg) and the feed water enters at 85 °C. With boiler efficiency 85% and oil GCV 10,200 kcal/kg, the furnace oil spent only to heat the blowdown water is about: [2P2CEM012]

- a) 6.4 kg/h
- b) 7.3 kg/h
- c) 7.6 kg/h**
- d) 13.7 kg/h

Correct answer: (c) 7.6 kg/h.

Given: steam = 15,000 kg/h; blowdown = 4% of feed; $h(\text{blowdown}) = 190 \text{ kcal/kg}$ ($\approx 795 \text{ kJ/kg}$); $h(\text{feed}) = 85 \text{ kcal/kg}$ ($\approx 356 \text{ kJ/kg}$); $\eta = 0.85$; GCV = 10,200 kcal/kg ($\approx 42,705 \text{ kJ/kg}$).

Formula: Feed = steam/(1 – 0.04); blowdown = feed – steam; heat lost = blowdown $\times$ ($h_{\text{bd}} - h_{\text{fw}}$); oil = heat/($\eta \times \text{GCV}$).

Substitution: Feed = 15,000/0.96 = 15,625 kg/h; blowdown = 625 kg/h; heat = 625 $\times$ (190 – 85) = 65,625 kcal/h; oil = 65,625/(0.85 $\times$ 10,200).

Result: **Oil spent on blowdown $\approx 7.6 \text{ kg/h}$.**

Why not the others: (b) 7.3 kg/h takes blowdown as 4% of steam (600 kg/h), but the percentage is on feed water. (a) 6.4 kg/h ignores boiler efficiency, so it equates heat to fuel energy. (d) 13.7 kg/h charges the full 190 kcal/kg of blowdown heat and forgets that feed water already carried 85 kcal/kg.

Ref: BEE Guidebook Paper 2, Ch. 2 (Boiler blowdown; heat loss in blowdown).

Chapter 2: Boilers | Heat lost in blowdown water

13. A thermic fluid heater serving a laminate press circulates 60 m³/h of fluid (density 850 kg/m³, specific heat 0.6 kcal/kg °C) with supply at 280 °C and return at 260 °C. With heater efficiency 80% and oil GCV 10,200 kcal/kg, the oil fired is about: [2P2CEM013]

a) 60.0 kg/h

b) 75.0 kg/h

c) 93.8 kg/h

d) 125.0 kg/h

Correct answer: (b) 75.0 kg/h.

Given: V = 60 m³/h; $\rho = 850 \text{ kg/m}^3$; $C_p = 0.6 \text{ kcal/kg } ^\circ\text{C}$ ($\approx 2.51 \text{ kJ/kg}\cdot\text{K}$); $t_{\text{supply}} = 280 \text{ }^\circ\text{C}$, $t_{\text{return}} = 260 \text{ }^\circ\text{C}$; $\eta = 0.80$; GCV = 10,200 kcal/kg ($\approx 42,705 \text{ kJ/kg}$).

Formula: Heat duty $Q = V \times \rho \times C_p \times (t_s - t_r)$; oil = $Q/(\eta \times \text{GCV})$.

Substitution: $Q = 60 \times 850 \times 0.6 \times 20 = 6,12,000 \text{ kcal/h}$; oil = 6,12,000/(0.80 $\times$ 10,200) = 6,12,000/8,160.

Result: **Oil fired $\approx 75.0 \text{ kg/h}$** (heat duty $\approx 712 \text{ kW}$).

Why not the others: (a) 60.0 kg/h ignores the heater efficiency and equates useful heat to fuel heat. (d) 125.0 kg/h uses $C_p = 1 \text{ kcal/kg } ^\circ\text{C}$ (water) instead of the thermic fluid value. (c) 93.8 kg/h divides by the efficiency twice (0.8 $\times$ 0.8).

Ref: BEE Guidebook Paper 2, Ch. 2, §2.8 (Thermic fluid heaters).

Chapter 2: Boilers | Thermic fluid heater duty and fuel

14. A plywood plant needs heat at about 290 °C for its hot press. Why does the guidebook favour a thermic fluid heater over steam for this duty? [2P2CEM014]

a) It reaches about 300 °C at atmospheric pressure; steam needs about 85 bar

b) It works at 85 bar, so heat transfer is far better than in steam coils

c) It needs regular blowdown and condensate return like a steam boiler

d) Its fluid is water with additives, so treatment cost is very low

Correct answer: (a) It reaches about 300 °C at atmospheric pressure; steam needs about 85 bar.

The guidebook states that in thermic fluid heaters a special synthetic or mineral oil is used as the heat carrier and can be heated up to 300 °C at atmospheric pressure, whereas steam would need a pressure of about 85 bar to reach this temperature. Listed advantages include high-temperature operation at atmospheric pressure, optional temperature set points, no water treatment and no flash-steam loss from condensate, and no risk of corrosion.

For a 290 °C press, a steam system would need a high-pressure boiler and heavy piping; thermic fluid avoids this.

Why not the others: (b) The 85 bar figure refers to the steam alternative, not to the thermic fluid circuit. (c) Blowdown and condensate return belong to steam systems; thermic fluid circuits are closed. (d) The heat carrier is an oil, not water with additives.

Ref: BEE Guidebook Paper 2, Ch. 2, §2.8 (Thermic fluid heaters).

Chapter 2: Boilers | Advantages of thermic fluid over steam

15. A refinery keeps Boiler-A as a hot standby that may be needed at short notice, while Boiler-B will be idle for four months during a plant revamp. Which preservation plan is as per the guidebook? [2P2CEM015]

a) **A: wet method with treated water; B: dry method with desiccant trays**

b) A: dry method with desiccant trays; B: wet method with treated water

c) A and B: drain fully and leave manholes open to the plant air

d) A and B: fill with raw water to the brim and isolate all valves

Correct answer: (a) A: wet method with treated water; B: dry method with desiccant trays.

The guidebook gives two preservation methods. The wet method is for boilers kept ready for standby service that may be needed suddenly: the boiler is filled to normal level with water at pH 10.5–11, dosed with about 200 ppm hydrazine and steamed to distribute chemicals and remove oxygen. The dry method is for boilers out of service for a long period: the boiler is drained hot, dried with hot air, and trays of silica gel or activated alumina (or quicklime/calcium chloride) are placed in the drum before closing up.

Why not the others: (b) This reverses the two methods; a dry-laid-up boiler cannot be fired at short notice. (c) Leaving a drained boiler open to humid air promotes oxygen corrosion. (d) Raw water without pH control and oxygen scavenging corrodes the internals.

Ref: BEE Guidebook Paper 2, Ch. 2 (Preservation of boiler).

Chapter 2: Boilers | Wet and dry preservation of idle boilers

16. In a gas-fired boiler with efficiency 80%, tuning the burner brings flue gas O₂ down from 4.2% to 3.5%. Using the guidebook rule of about 0.6% efficiency gain per 1% reduction in excess air, the resulting fuel saving is closest to:

[2P2CEM016]

a) 0.4%

b) 3.0%

c) **3.6%**

d) 3.8%

Correct answer: (c) 3.6%.

Given: $\eta_1 = 80\%$; O₂ before = 4.2%, after = 3.5%; rule: 1% less excess air $\approx$ 0.6% higher efficiency.

Formula: $EA\% = O_2 / (21 - O_2) \times 100$; $\eta_2 = \eta_1 + 0.6 \times \Delta EA$; fuel saving = $1 - \eta_1 / \eta_2$.

Substitution: $EA_1 = 4.2 / 16.8 \times 100 = 25\%$; $EA_2 = 3.5 / 17.5 \times 100 = 20\%$; $\Delta EA = 5$ points; $\eta_2 = 80 + 0.6 \times 5 = 83\%$; saving = $1 - 80 / 83 = 0.0361$.

Result: **Fuel saving $\approx$ 3.6%.**

Why not the others: (b) 3.0% is the gain in efficiency points, not the fractional fuel saving; fuel saving = $(\eta_2 - \eta_1) / \eta_2$. (a) 0.4% applies the 0.6 rule to the 0.7-point O₂ change instead of the excess-air change. (d) 3.8% divides the 3-point gain by the old efficiency (3/80) instead of the new one.

Ref: BEE Guidebook Paper 2, Ch. 2 (Energy conservation opportunities: excess air control).

Chapter 2: Boilers | Excess air reduction and fuel saving

17. Two identical boilers in a dairy each run at 40% load. The energy manager proposes running one boiler at 80% load and keeping the other on standby. According to the guidebook, at about what load does a boiler reach its maximum efficiency? [2P2CEM017]

a) Exactly at 100% of full load

b) Below one-third of full load

c) At any load, as it is constant

d) **About two-thirds of full load**

Correct answer: (d) About two-thirds of full load.

The guidebook states that the maximum efficiency of a boiler does not occur at full load but at about two-thirds of full load. If the load decreases further, efficiency also falls; at zero output the efficiency is zero and any fuel fired only supplies

the losses. This is because radiation and convection losses from the shell, and purge and cycling losses, are nearly fixed in kcal/h, so their share rises as output falls.

Running one boiler near 80% instead of two at 40% therefore moves operation close to the efficient zone and halves the fixed shell losses.

Why not the others: (a) Full load gives higher flue gas temperature and is not the peak point. (b) Below one-third load the fixed losses dominate and efficiency drops sharply. (c) Efficiency clearly varies with load.

Ref: BEE Guidebook Paper 2, Ch. 2 (Effect of boiler loading on efficiency).

Chapter 2: Boilers | Effect of boiler loading on efficiency

18. A boiler firing furnace oil with 3% sulphur has a stack temperature of 235 °C. The operator wants to cool the gas to 110 °C in a new economiser to save fuel. What is the guidebook's position? [2P2CEM018]

a) Above 200 °C shows recovery scope, but avoid sulphur dew point corrosion

b) Any stack temperature above 100 °C should be recovered fully with no limit

c) 235 °C stack temperature means the boiler is clean and needs no attention

d) Cooling flue gas lower always lowers SO₂ emissions and boiler corrosion

Correct answer: (a) Above 200 °C shows recovery scope, but avoid sulphur dew point corrosion.

The guidebook advises that the stack temperature should be as low as possible but not so low that water vapour in the exhaust condenses on the stack walls; this matters especially for fuels with significant sulphur, because low temperature can cause sulphur dew point corrosion. Stack temperatures above 200 °C indicate potential for waste heat recovery and may also indicate scaling of heat transfer surfaces needing early cleaning.

So an economiser is justified at 235 °C, but with 3% sulphur the exit should be kept well above the acid dew point rather than at 110 °C.

Why not the others: (b) Ignores the acid dew point limit. (c) A high stack temperature points to recovery potential or fouling, not a clean boiler. (d) Cooling does not reduce SO₂ formed; it increases acid condensation risk.

Ref: BEE Guidebook Paper 2, Ch. 2 (Stack temperature; feed water preheating using economiser).

Chapter 2: Boilers | Stack temperature as an indicator

19. A dye-house tank holds 5,000 kg of water that must be heated from 30 °C to 90 °C in one hour by a steam coil. Steam is supplied dry saturated (latent heat 504 kcal/kg, total enthalpy 656 kcal/kg) and the trap discharges condensate at saturation temperature. The steam consumption is about: [2P2CEM019]

a) 457 kg/h

b) 479 kg/h

c) 530 kg/h

d) 595 kg/h

Correct answer: (d) 595 kg/h.

Given: $m_w = 5,000$ kg per hour; $t_1 = 30$ °C, $t_2 = 90$ °C; $C_p(\text{water}) = 1$ kcal/kg °C (≈ 4.19 kJ/kg·K); latent heat $L = 504$ kcal/kg ($\approx 2,110$ kJ/kg); total enthalpy = 656 kcal/kg ($\approx 2,747$ kJ/kg).

Formula: Heat required $Q = m \times C_p \times \Delta t$; for indirect heating with condensate leaving at saturation, only latent heat is given up: steam = Q/L .

Substitution: $Q = 5,000 \times 1 \times (90 - 30) = 3,00,000$ kcal/h; steam = $3,00,000/504$.

Result: **Steam ≈ 595 kg/h** (heat duty ≈ 349 kW).

In indirect heating only latent heat is used; condensate heat should be recovered.

Why not the others: (a) 457 kg/h uses the total enthalpy 656, as if the condensate also gave up its sensible heat inside the coil. (b) 479 kg/h uses $656 - 30$, treating it as direct injection into 30 °C water. (c) 530 kg/h uses $656 - 90$, the direct-injection value at the final temperature.

Ref: BEE Guidebook Paper 2, Ch. 3 (Steam utilisation; latent heat).

Chapter 3: Steam System | Indirect steam heating of a process tank

20. A food plant heats 10,000 kg of process water from 25 °C to 85 °C per batch by injecting steam directly into the water through a sparger. The steam has a total enthalpy of 660 kcal/kg. The steam needed per batch is about:

[2P2CEM020]

- a) 909 kg
- b) 945 kg
- c) 1,043 kg**
- d) 1,212 kg

Correct answer: (c) 1,043 kg.

Given: $m_w = 10,000$ kg; $t_1 = 25$ °C, $t_2 = 85$ °C; steam enthalpy $h_s = 660$ kcal/kg ($\approx 2,763$ kJ/kg); $C_p(\text{water}) = 1$ kcal/kg °C (≈ 4.19 kJ/kg·K).

Formula: In direct injection the steam condenses and mixes, ending at the final water temperature; heat balance: $m_s \times (h_s - t_2) = m_w \times (t_2 - t_1)$.

Substitution: $m_s \times (660 - 85) = 10,000 \times (85 - 25) = 6,00,000$ kcal; $m_s = 6,00,000/575$.

Result: **Steam $\approx 1,043$ kg per batch.**

Direct injection uses latent and part of the sensible heat, but the condensate is lost, raising boiler make-up.

Why not the others: (a) 909 kg divides by the full 660, assuming the condensate ends at 0 °C. (b) 945 kg uses $660 - 25$, the initial water temperature instead of the final mixed temperature. (d) 1,212 kg uses only a latent heat of about 495 kcal/kg, ignoring that the condensate gives up sensible heat down to 85 °C.

Ref: BEE Guidebook Paper 2, Ch. 3 (Steam utilisation; heat balance).

Chapter 3: Steam System | Direct steam injection heating

21. The guidebook estimates that a 3 mm hole in a 7 kg/cm² steam line wastes about 33 kL of fuel oil a year. A plant finds a single 6 mm hole in a 7 kg/cm² header. With fuel oil at ₹ 52,000 per kL, the annual loss is about: [2P2CEM021]

- a) ₹ 17.2 lakh
- b) ₹ 34.3 lakh
- c) ₹ 68.6 lakh**
- d) ₹ 137.3 lakh

Correct answer: (c) ₹ 68.6 lakh.

Given: 3 mm hole at 7 kg/cm² (≈ 6.86 bar) wastes 33 kL fuel oil/yr; new hole $d = 6$ mm at the same pressure; oil = ₹ 52,000/kL.

Formula: Leak flow through an orifice $\propto$ hole area $\propto d^2$; $\text{loss}_2 = \text{loss}_1 \times (d_2/d_1)^2$; $\text{cost} = \text{kL} \times \text{price}$.

Substitution: $\text{Loss} = 33 \times (6/3)^2 = 33 \times 4 = 132$ kL/yr; $\text{cost} = 132 \times 52,000 = ₹ 68,64,000$.

Result: **Annual loss $\approx ₹ 68.6$ lakh.**

The guidebook calls steam leakage a visible indicator of waste; doubling the hole diameter quadruples the steam lost, so even small leaks deserve prompt repair.

Why not the others: (b) ₹ 34.3 lakh scales the loss linearly with diameter (66 kL). (a) ₹ 17.2 lakh is the loss of a 3 mm hole only. (d) ₹ 137.3 lakh scales with the cube of diameter (264 kL), which has no physical basis.

Ref: BEE Guidebook Paper 2, Ch. 3 (Avoiding steam leakages).

Chapter 3: Steam System | Cost of a steam leak scaled by hole size

22. In a multiple-effect evaporator, vapour from the last stage is at too low a pressure to reuse. What does a thermocompressor do in such a case, as described in the guidebook? [2P2CEM022]

- a) Uses an electric compressor to condense vapour into hot water
- b) Reduces steam pressure isenthalpically to give superheated steam
- c) Separates water droplets from wet steam before process use
- d) Uses high-pressure motive steam to raise low-pressure vapour for reuse**

Correct answer: (d) Uses high-pressure motive steam to raise low-pressure vapour for reuse.

The guidebook explains that where condensate or vapour is available at low pressure, a thermocompressor allows this low-pressure steam to be compressed by high-pressure motive steam and reused as medium-pressure steam. Motive steam enters through a nozzle; its high velocity entrains the low-pressure steam; momentum exchange occurs in the mixing chamber and, in the diffuser, velocity falls and pressure rises. A typical application is in evaporators, where boiling vapour is recompressed and used as heating steam. Because most of the energy in steam is latent heat, the recovery is large.

Why not the others: (a) A thermocompressor is steam-driven (an ejector), not an electric machine, and it does not condense the vapour. (b) That describes a pressure reducing valve. (c) That describes a steam separator.

Ref: BEE Guidebook Paper 2, Ch. 3 (Thermocompressor).

Chapter 3: Steam System / Thermocompressor application

23. During a trap survey, an auditor measures the outlet pipe temperature of a trap draining a 10 kg/cm² line and finds it close to steam saturation temperature. What can be concluded? [2P2CEM023]

a) Temperature alone cannot confirm a fault; use sound or sight checks

b) The trap is definitely passing live steam and must be replaced now

c) The trap is definitely blocked, because hot condensate is held back

d) The trap is oversized, because outlet temperature equals saturation

Correct answer: (a) Temperature alone cannot confirm a fault; use sound or sight checks.

In a working trap, condensate leaves at or near saturation temperature, and a trap leaking live steam also shows saturation temperature at the outlet, so a temperature reading alone cannot distinguish a good trap from a leaking one. The guidebook describes visual testing (test valve or sight glass), sound testing (ultrasonic or stethoscope listening for the operating cycle) and temperature testing, and recommends observing the discharge: a continuous blue stream indicates leaking steam, while an intermittent whitish cloud is flash steam.

Temperature testing is most useful to detect blocked or cold traps (a markedly low reading).

Why not the others: (b) and (c) both claim certainty that a temperature reading cannot give. (d) Oversizing is not inferred from outlet temperature; it shows up as cycling behaviour or noise.

Ref: BEE Guidebook Paper 2, Ch. 3 (Steam trap testing; flash steam vs leaking steam).

Chapter 3: Steam System / Testing steam traps

24. Two trap discharges to atmosphere are observed in a tyre plant: Trap-1 shows steam floating out intermittently as a whitish cloud; Trap-2 shows a continuous blue jet near the outlet. Which interpretation agrees with the guidebook? [2P2CEM024]

a) Trap-1 is leaking live steam; Trap-2 shows flash steam

b) Both traps are leaking and both need immediate repair

c) Both are normal, because any visible steam is flash

d) Trap-1 shows flash steam; Trap-2 is leaking live steam

Correct answer: (d) Trap-1 shows flash steam; Trap-2 is leaking live steam.

The guidebook notes that users often confuse flash steam with leaking steam and gives a simple field guide: if steam blows out continuously in a blue stream, it is leaking steam; if steam floats out intermittently in a whitish cloud, it is flash steam. Flash steam forms when hot condensate at high pressure is released to atmospheric pressure and is a normal result of correct trap operation; leaking live steam means the trap has failed open.

So Trap-1 is working and Trap-2 should be repaired or replaced, and the flash from Trap-1 could be recovered in a flash vessel.

Why not the others: (a) reverses the identification. (b) wrongly condemns a working trap. (c) ignores the continuous blue stream that indicates live steam passing.

Ref: BEE Guidebook Paper 2, Ch. 3 (Steam trap inspection: flash steam vs leaking steam).

Chapter 3: Steam System / Distinguishing flash steam from leaking steam

25. A new 300 m long steam main in a pharma plant is being laid. Which drainage practice follows the guidebook's recommendations? [2P2CEM025]

- a) A single drain point at the far end of the main is enough
- b) Drain points every 150 m via a small side-branch reducing tee
- c) Drain points every 30–45 m, at low points and risers, via equal tees**
- d) No drain points at all, as superheat in the main prevents condensate

Correct answer: (c) Drain points every 30–45 m, at low points and risers, via equal tees.

The guidebook recommends that steam mains be laid with a fall in the direction of steam flow, that drain points be provided at intervals of 30–45 m along the main, at low points and where the main rises, and ideally at the bottom of expansion joints and before reduction and stop valves. Drain points should be taken through an equal tee so that condensate running along the pipe bottom falls into the pocket; open bucket or thermodynamic traps are preferred for their resilience. Proper drainage prevents water hammer and delivers drier steam.

Why not the others: (a) A single end drain lets condensate accumulate and be carried by fast steam, causing water hammer. (b) 150 m spacing is far too wide, and a small branch tee lets condensate run past the pocket. (d) Even superheated mains form condensate during warm-up and need drainage.

Ref: BEE Guidebook Paper 2, Ch. 3 (Steam distribution: drainage of mains).

Chapter 3: Steam System | Drainage of steam mains

26. A chemical plant reduces dry saturated steam from 17 kg/cm²(g) to 4 kg/cm²(g) through a pressure reducing valve before a jacketed reactor. Which statement about the steam leaving the PRV is correct as per the guidebook? [2P2CEM026]

- a) It is slightly superheated, so desuperheating may be needed**
- b) It becomes wet because pressure reduction removes enthalpy
- c) It has lower enthalpy, as a PRV is an isentropic expander
- d) It stays exactly saturated at the reduced lower pressure

Correct answer: (a) It is slightly superheated, so desuperheating may be needed.

The guidebook states that reduction of steam pressure through a pressure reducing valve is an isenthalpic process: the enthalpy of steam after the valve equals that before it. Because saturated steam at a lower pressure needs less enthalpy to be saturated, the excess appears as superheat. Since most processes need saturated steam for efficient condensing heat transfer, desuperheating (spraying water to bring the steam close to saturation) is often required after a PRV. This also explains why steam is generated at high pressure in the boiler (smaller pipes, drier steam) and conditioned near the user.

Why not the others: (b) Isenthalpic reduction of dry saturated steam gives superheat, not wetness. (c) A PRV is isenthalpic, not isentropic; only a turbine extracts work and lowers enthalpy. (d) The steam does not stay exactly saturated, for the reason above.

Ref: BEE Guidebook Paper 2, Ch. 3 (Pressure reducing and desuperheating station).

Chapter 3: Steam System | Pressure reduction and desuperheating

27. A heat-treatment furnace door is opened for the same time each hour. If the furnace temperature is raised from 1,000 °C to 1,200 °C, the radiation loss through the opening (per the guidebook's black-body formula) increases by about: [2P2CEM027]

- a) 16%
- b) 20%
- c) 44%
- d) 79%**

Correct answer: (d) 79%.

Given: $T_1 = 1,000\text{ °C} = 1,273\text{ K}$; $T_2 = 1,200\text{ °C} = 1,473\text{ K}$; same opening area, factor of radiation and open time.

Formula (guidebook): $Q = 4.88 \times (T/100)^4 \times a \times A \times H$, with T in kelvin; so $Q_2/Q_1 = (T_2/T_1)^4$.

Substitution: $Q_2/Q_1 = (1,473/1,273)^4 = (1.157)^4 = 1.793$.

Result: **Opening loss rises by $\approx 79\%$.**

Because radiation varies with the fourth power of absolute temperature, high-temperature furnaces should keep doors shut, use smaller inspection ports and curtains, and avoid running hotter than the process needs.

Why not the others: (b) 20% treats loss as proportional to temperature in °C (1,200/1,000). (a) 16% is the ratio of absolute temperatures (1.157) without the fourth power. (c) 44% squares the °C ratio, which follows no heat transfer law.

Ref: BEE Guidebook Paper 2, Ch. 4 (Heat loss through openings).

Chapter 4: Furnaces | Opening radiation loss and furnace temperature

28. In a forging furnace the burner flames are seen striking the billets and the hearth refractory. Which consequence is described in the guidebook? [2P2CEM028]

- a) Better heat transfer, so flames should be aimed at the stock
- b) Lower excess air need, as the stock completes the combustion
- c) No effect, as flame shape does not change furnace performance

d) Higher scale losses on stock and refractory attack by unburnt products

Correct answer: (d) Higher scale losses on stock and refractory attack by unburnt products.

Under 'proper heat distribution' the guidebook advises that the flame should not touch any solid object and should propagate clear of it. Any obstruction de-atomises the fuel particles, affecting combustion and creating black smoke. If the flame impinges on the stock, scale losses increase; if it impinges on refractories, incomplete combustion products can settle and react with refractory constituents at high flame temperature, shortening lining life. Burners should therefore be aligned so flames develop freely in the combustion space and heat reaches the stock by radiation from flame and walls.

Why not the others: (a) Impingement does not improve useful heat transfer; it quenches combustion and oxidises the surface. (b) Cold stock quenches the flame, so combustion becomes less complete, not more. (c) Flame shape and placement clearly influence furnace performance.

Ref: BEE Guidebook Paper 2, Ch. 4 (Proper heat distribution).

Chapter 4: Furnaces | Burner flame impingement

29. A furnace supplier proposes spraying a high-emissivity ceramic coating on the hot face of a reheating furnace. What property makes these coatings save energy, according to the guidebook? [2P2CEM029]

a) Their emissivity rises with temperature, whereas that of common refractories falls

- b) They reduce emissivity, so walls reflect heat back to the stock
- c) They raise thermal conductivity, so the walls lose more heat outside
- d) They work only below 300 °C, so suit outer furnace casings

Correct answer: (a) Their emissivity rises with temperature, whereas that of common refractories falls.

The guidebook notes that ceramic coatings in the furnace chamber promote rapid and efficient heat transfer, uniform heating and longer refractory life. The emissivity of conventional refractories decreases with increasing temperature, whereas for ceramic coatings it increases, and this property is used for hot-face application. The coatings have long life at temperatures up to about 1,350 °C, are water-based, are sprayed and air-dried quickly during a shutdown, and energy savings of about 8–20% are reported depending on furnace type and operating conditions.

Why not the others: (b) They are high-emissivity, not low-emissivity, coatings. (c) Higher wall conductivity would increase losses, which is the opposite of the purpose. (d) They are designed for the hot face at high temperature, not for low-temperature outer casings.

Ref: BEE Guidebook Paper 2, Ch. 4 (Use of ceramic coatings).

Chapter 4: Furnaces | High-emissivity ceramic coatings

30. A walking-beam furnace's flue gases leave at a temperature well above the stock temperature. What share of the furnace heat input is typically carried away by flue gases, as stated in the guidebook? [2P2CEM030]

- a) 5 to 10 per cent

b) 60 to 80 per cent

c) 35 to 55 per cent

d) 15 to 25 per cent

Correct answer: (c) 35 to 55 per cent.

The guidebook explains that in any industrial furnace the products of combustion leave at a temperature higher than the stock temperature, because heat can only flow from gas to stock while the gas is hotter. The sensible heat in the flue gases leaving the chimney carries 35 to 55 per cent of the heat input to the furnace. The higher the furnace temperature, the larger this loss, which is why recuperators, regenerators and charge preheating give large savings in high-temperature furnaces.

Why not the others: (a) 5–10% is typical of a well-designed boiler's dry flue gas loss, not a high-temperature furnace. (b) 60–80% overstates the typical range given. (d) 15–25% is achievable only after substantial waste heat recovery, not the typical uncorrected loss.

Ref: BEE Guidebook Paper 2, Ch. 4 (Waste heat recovery from furnace flue gases).

Chapter 4: Furnaces | Sensible heat carried away by furnace flue gases

31. A plant compares a car-bottom (bogie hearth) furnace with a rotary hearth furnace for continuous heating of forgings. Which advantage of the rotary hearth furnace is noted in the guidebook? [2P2CEM031]

a) It has a simple rectangular hearth with no moving parts

b) It suits only batch loads, so it saves charging time

c) Its open sides allow faster cooling of the furnace lining

d) No bogies enter and leave, so heat storage losses are lower

Correct answer: (d) No bogies enter and leave, so heat storage losses are lower.

The guidebook describes the rotary hearth furnace as having an annular revolving hearth on which stock is charged and discharged at adjacent doors. Because the cooling and reheating effects introduced by bogies (which are pulled out with the load and pushed back cold) are eliminated, heat storage losses are less. The trade-off is a more complex design with an annular shape and a revolving hearth that needs seals and drives.

Heat storage in the furnace structure, conveyors, fixtures and trays is listed in the guidebook among furnace losses, so eliminating cyclic heating of bogies directly reduces fuel.

Why not the others: (a) It has an annular revolving hearth, so it is more complex, not simpler. (b) It is used for continuous operation, not only batch loads. (c) Open sides would increase losses; the furnace is enclosed.

Ref: BEE Guidebook Paper 2, Ch. 4 (Types of furnaces: rotary hearth furnace; furnace losses).

Chapter 4: Furnaces | Rotary hearth and storage losses

32. While insulating a 200 °C hot oil line, the designer plots insulation cost and heat-loss cost against thickness. The economic thickness of insulation is the thickness at which: [2P2CEM032]

a) Heat loss becomes zero and the surface reaches ambient

b) Insulation cost equals the yearly value of heat loss

c) Total of insulation cost and heat-loss cost is the least

d) The outer surface temperature equals the hot oil temperature

Correct answer: (c) Total of insulation cost and heat-loss cost is the least.

The guidebook explains that as insulation thickness increases, the heat loss and its cost fall, while the capital cost of insulation rises. Beyond a point, each extra millimetre saves less heat than its own cost. The economic thickness of insulation (ETI) is therefore found where the sum of the annualised insulation cost and the cost of heat lost is a minimum. For example, the guidebook shows that 50 mm insulation cuts the loss from a bare pipe from about 275 to 25 kcal/m ($\approx 1,151$ to 105 kJ/m), but doubling to 100 mm only saves another 20 kcal/m (≈ 84 kJ/m).

Why not the others: (a) Heat loss never reaches zero with finite insulation. (b) The minimum total-cost point is not, in general, where the two cost curves intersect. (d) A surface at the line temperature means no insulation at all.

Ref: BEE Guidebook Paper 2, Ch. 5 (Economic thickness of insulation).

33. A container-glass furnace crown is being rebuilt. Which description of silica (Dinas) brick matches the guidebook?

[2P2CEM033]

- a) Mainly MgO, used where basic slags attack the furnace lining
- b) At least 93% SiO₂, high refractoriness, used in glass and steel**
- c) Mainly Al₂O₃ and SiO₂ with low alumina, for low-duty work
- d) Very low density fibre, used as a hot-face veneer in kilns

Correct answer: (b) At least 93% SiO₂, high refractoriness, used in glass and steel.

The guidebook defines silica brick (Dinas) as a refractory containing at least 93% SiO₂, made from quality quartzite rock.

Grades of silica brick are widely used in iron and steel melting furnaces and in glass making; besides a high fusion point, the guidebook highlights their high refractoriness and resistance to thermal shock (spalling) as important properties.

For a glass furnace crown, silica brick is the classical choice because it retains strength close to its melting point.

Why not the others: (a) MgO-based refractories are magnesite bricks, used against basic slags. (c) Al₂O₃–SiO₂ bricks with modest alumina are fireclay bricks. (d) Low-density fibre describes ceramic fibre, an insulating refractory, not silica brick.

Ref: BEE Guidebook Paper 2, Ch. 5 (Types of refractories: silica brick).

Chapter 5: Insulation and Refractories | Silica refractory bricks

34. The flat wall of an oven has 30 m² of mineral wool 100 mm thick (thermal conductivity 0.045 W/m K). The hot face is at 270 °C and the cold face at 20 °C. The steady conduction heat flow through the insulation is about:

[2P2CEM034]

- a) 112.5 W
- b) 3,375 W**
- c) 6,750 W
- d) 33,750 W

Correct answer: (b) 3,375 W.

Given: A = 30 m²; x = 100 mm = 0.1 m; k = 0.045 W/m K; t_{hot} = 270 °C, t_{cold} = 20 °C.

Formula (Fourier's law): $Q = k \times A \times (t_{\text{hot}} - t_{\text{cold}})/x$.

Substitution: $Q = 0.045 \times 30 \times (270 - 20)/0.1 = 0.045 \times 30 \times 250/0.1 = 337.5/0.1$.

Result: **Heat flow ≈ 3,375 W (≈ 3.4 kW, about 2,900 kcal/h).**

The guidebook lists low thermal conductivity as the key property of insulation; heat flow is directly proportional to k and ΔT and inversely proportional to thickness, which is also why the k unit is W/m °C.

Why not the others: (a) 112.5 W is the flux per m² (W/m²), not the total for 30 m². (c) 6,750 W uses 50 mm instead of 100 mm. (d) 33,750 W uses x = 0.01 m, a millimetre-to-metre conversion error.

Ref: BEE Guidebook Paper 2, Ch. 5 (Insulation: thermal conductivity) and Ch. 9 (Conduction).

Chapter 5: Insulation and Refractories | Conduction heat flow through an insulation layer

35. A furnace builder adds a thick layer of back-up insulation behind the existing firebrick lining to cut wall losses. What side effect does the guidebook warn about? [2P2CEM035]

- a) The hot-face temperature rises, so a better quality refractory is needed**
- b) The hot-face temperature falls, so the brick can be a lower grade
- c) The shell temperature rises, increasing outside surface heat loss
- d) The firebrick conductivity becomes zero, so no heat reaches it

Correct answer: (a) The hot-face temperature rises, so a better quality refractory is needed.

The guidebook states that provision of back-up insulation conserves heat, but at the same time it increases the hot-face temperature, and hence the demand on the refractory quality increases. With insulation behind it, the firebrick runs hotter throughout its thickness, so it must withstand higher temperatures under load and possible slag attack. The designer may need a higher-grade brick (higher refractoriness and RUL) when adding back-up insulation.

Low thermal conductivity is desirable for heat conservation, while high conductivity is needed where heat must pass through brickwork (recuperators, muffles).

Why not the others: (b) The hot face becomes hotter, not cooler. (c) The shell becomes cooler, so outside losses fall. (d) Conductivity is a material property; it does not become zero.

Ref: BEE Guidebook Paper 2, Ch. 5 (Properties of refractories: thermal conductivity).

Chapter 5: Insulation and Refractories / Back-up insulation and hot-face temperature

36. Which description of a pressurised fluidised bed combustion (PFBC) system agrees with the guidebook?

[2P2CEM036]

- a) Bed at atmospheric pressure; solids are recycled to the bed through a hot cyclone
- b) Bed under vacuum to reduce NO_x; only a steam turbine is used for power
- c) Bed at up to 160 ata; it is used only in small package boilers for steam
- d) Bed at up to 16 ata; off-gas drives a gas turbine; steam drives a steam turbine**

Correct answer: (d) Bed at up to 16 ata; off-gas drives a gas turbine; steam drives a steam turbine.

The guidebook describes PFBC as a variation of fluid bed technology meant for large-scale coal burning. The bed vessel operates at pressure up to 16 ata (16 kg/cm² ≈ 15.7 bar). The off-gas from the fluidised bed combustor drives a gas turbine, while steam raised in tubes immersed in the bed drives a steam turbine; condensate is preheated using waste heat from the gas turbine exhaust and then used as feed water. PFBC can thus be used for cogeneration or combined cycle power generation with higher overall efficiency.

Why not the others: (a) Atmospheric operation with cyclone recycle describes CFBC. (b) PFBC is pressurised, not under vacuum, and uses both turbines. (c) The figure is 16 ata, not 160, and PFBC is for large-scale plants, not small package boilers.

Ref: BEE Guidebook Paper 2, Ch. 6, §6.3.3 (Pressurised fluid bed combustion).

Chapter 6: FBC Boilers / Pressurised fluidised bed combustion

37. An AFBC boiler's fluidising air fan delivers 20,000 m³/h measured at 30 °C. The bed operates at 850 °C and the air distributor area is 9 m². Neglecting pressure change, the superficial air velocity in the bed is about: [2P2CEM037]

- a) 0.62 m/s
- b) 2.3 m/s**
- c) 2.5 m/s
- d) 17.5 m/s

Correct answer: (b) 2.3 m/s.

Given: $V_1 = 20,000 \text{ m}^3/\text{h}$ at $t_1 = 30 \text{ °C}$ (303 K); bed temperature $t_2 = 850 \text{ °C}$ (1,123 K); distributor area $A = 9 \text{ m}^2$.

Formula: Gas volume $\propto$ absolute temperature (Charles' law): $V_2 = V_1 \times T_2/T_1$; velocity $v = V_2/(A \times 3,600)$.

Substitution: $V_2 = 20,000 \times 1,123/303 = 74,125 \text{ m}^3/\text{h}$; $v = 74,125/(9 \times 3,600) = 74,125/32,400$.

Result: **Superficial velocity $\approx 2.3 \text{ m/s}$** , within the 1.2–3.7 m/s range the guidebook gives for bubbling beds.

Why not the others: (a) 0.62 m/s ignores the expansion of air from 30 °C to 850 °C, which is below the fluidising range. (d) 17.5 m/s uses the ratio of Celsius temperatures (850/30), which is not valid for gas laws. (c) 2.5 m/s uses 273 K instead of the actual 303 K as the reference temperature.

Ref: BEE Guidebook Paper 2, Ch. 6 (AFBC: fluidising velocity; mechanism of fluidisation).

Chapter 6: FBC Boilers / Superficial fluidising velocity at bed temperature

38. A rice mill wants to burn husk, coal fines below 6 mm and some washery rejects in one boiler. Why does the guidebook consider an FBC boiler suitable? [2P2CEM038]

- a) It needs uniformly sized coal above 25 mm, so fines must be briquetted
- b) It burns only high-grade fuels with ash below 5% at bed temperatures
- c) It burns fines below 6 mm well, and about 1% combustibles sustain the bed**
- d) It needs bed temperatures above 1,200 °C, which melts ash into slag

Correct answer: (c) It burns fines below 6 mm well, and about 1% combustibles sustain the bed.

Among the advantages of FBC boilers the guidebook lists fuel flexibility (multi-fuel firing including biomass and rejects), the ability to burn low-grade fuels, and the ability to burn fines: coal containing fines below 6 mm can be burnt efficiently in an FBC boiler, which is very difficult in conventional firing. Because the bed is a large mass of hot inert material, combustibles of only about 1% by weight in the bed can sustain fluidised bed combustion, so high-ash and wet fuels burn steadily. The bed runs at about 800–950 °C, below ash fusion, so ash does not melt into clinker.

Why not the others: (a) Lump size above 25 mm suits stokers; FBC uses crushed fuel (1–10 mm). (b) FBC is valued precisely for low-grade, high-ash fuels. (d) Above about 950 °C clinkering begins, so FBC bed temperatures are kept far below 1,200 °C.

Ref: BEE Guidebook Paper 2, Ch. 6 (Advantages of FBC boilers).

Chapter 6: FBC Boilers | Fuel flexibility of FBC boilers

39. A paper mill passes 10,000 kg/h of steam through a PRV. A back-pressure microturbine is proposed in parallel; the isentropic enthalpy drop between the two pressures is 30 kcal/kg and the turbine's overall efficiency (isentropic × mechanical × generator) is 60%. The electrical output is about: [2P2CEM039]

- a) 126 kW
- b) 209 kW**
- c) 349 kW
- d) 581 kW

Correct answer: (b) 209 kW.

Given: steam $m = 10,000$ kg/h; isentropic drop $\Delta h_s = 30$ kcal/kg (≈ 126 kJ/kg); overall efficiency $\eta = 0.60$; 860 kcal/h = 1 kW.

Formula: Power (kW) = $m \times \Delta h_s \times \eta / 860$.

Substitution: Power = $10,000 \times 30 \times 0.60 / 860 = 1,80,000 / 860$.

Result: **Electrical output ≈ 209 kW.**

The guidebook notes that a PRV is isenthalpic and wastes the pressure energy, while a microturbine converts part of it to power; the steam leaves with lower enthalpy, so the process may need slightly more steam — power from back-pressure turbines is not entirely free.

Why not the others: (c) 349 kW ignores all turbine and generator losses (100% efficiency). (d) 581 kW divides by 0.6 instead of multiplying. (a) 126 kW applies the 60% efficiency twice (0.36).

Ref: BEE Guidebook Paper 2, Ch. 7, §7.13 (Microturbine) and Ch. 3 (Pressure reducing stations).

Chapter 7: Cogeneration | Microturbine across a pressure reducing station

40. A back-pressure turbine in a solvent extraction plant has an actual enthalpy drop of 120 kcal/kg (internal efficiency already included). With combined mechanical and generator efficiency of 95%, its specific steam consumption is about: [2P2CEM040]

- a) 6.81 kg/kWh
- b) 7.17 kg/kWh
- c) 7.54 kg/kWh**
- d) 9.43 kg/kWh

Correct answer: (c) 7.54 kg/kWh.

Given: actual enthalpy drop $\Delta h = 120$ kcal/kg (≈ 502 kJ/kg); $\eta(\text{mech} \times \text{gen}) = 0.95$; 1 kWh = 860 kcal ($\approx 3,601$ kJ).

Formula: Steam rate (kg/kWh) = $860 / (\Delta h \times \eta_{\text{mech} \times \text{gen}})$.

Substitution: Steam rate = $860 / (120 \times 0.95) = 860 / 114$.

Result: **Steam rate ≈ 7.54 kg/kWh**; e.g. 15,000 kg/h of process steam would generate about $15,000 / 7.54 \approx 1,990$ kW.

Why not the others: (b) 7.17 kg/kWh ignores mechanical and generator losses. (a) 6.81 kg/kWh multiplies by 0.95 instead of dividing, which would make the losses produce extra power. (d) 9.43 kg/kWh applies a further 80% internal efficiency, double-counting it because the stated drop is already the actual drop.

Ref: BEE Guidebook Paper 2, Ch. 7 (Steam turbine cogeneration; back-pressure turbines).

Chapter 7: Cogeneration | Steam rate of a back-pressure turbine

41. A frozen-food plant needs electricity, process steam and chilled water. The guidebook describes 'trigeneration' for such users. Which configuration fits the description? [2P2CEM041]

- a) Diesel set, electric chiller and separate oil-fired steam boiler
- b) Grid power, vapour compression chiller and electric steam heater
- c) Steam boiler, PRV station and evaporative cooling tower only
- d) Gas turbine, waste heat boiler and absorption chiller in one system**

Correct answer: (d) Gas turbine, waste heat boiler and absorption chiller in one system.

The guidebook defines trigeneration as the simultaneous generation of steam (heat), power and refrigeration through integrated systems, attractive for industries needing electricity, steam and cooling such as food processing and cold storages. A typical combined-cycle trigeneration plant consists of a gas turbine generator, a waste heat recovery boiler, a steam turbine and generator, and an absorption chiller that uses heat to produce chilled water; surplus power can be sold to the grid.

The key feature is that refrigeration is driven by recovered heat, not by separately purchased power.

Why not the others: (a) Separate units for each utility is conventional supply with no integration or heat recovery. (b) Grid power with electric chiller and heater is the least efficient arrangement. (c) This produces no power and no refrigeration from recovered heat.

Ref: BEE Guidebook Paper 2, Ch. 7, §7.12 (Trigeneration).

Chapter 7: Cogeneration | Trigeneration concept

42. A 3 MW gas-engine cogeneration plant at a hospital wants to maximise recovered heat. According to the guidebook, what are the two sources of heat recovery in a reciprocating engine system? [2P2CEM042]

- a) High-temperature exhaust gas and the low-temperature engine jacket cooling water**
- b) Generator winding losses and the flywheel bearing friction heat
- c) Only the exhaust gas; jacket water is too cold to use
- d) Only the fuel gas compressor; the engine has no losses

Correct answer: (a) High-temperature exhaust gas and the low-temperature engine jacket cooling water.

The guidebook describes reciprocating (I.C.) engine cogeneration systems as having high power generation efficiency compared with other prime movers, with two sources of heat for recovery: exhaust gas at high temperature and the engine jacket cooling water system at low temperature (Figure 7.5). Because recovery is efficient even in small systems, they suit smaller facilities that need more electricity than heat and where heat quality required is low, such as low-pressure steam or hot water — typical of hospitals and hotels. Their heat-to-power ratio is about 1.1–2.5, and they are less sensitive to ambient temperature than gas turbines.

Why not the others: (b) Generator and bearing losses are small and not practical recovery sources. (c) Jacket water heat is one of the two main recoverable sources, ideal for hot water. (d) Engines reject large amounts of heat; that is why cogeneration with them is attractive.

Ref: BEE Guidebook Paper 2, Ch. 7, §7.3.3 (Reciprocating engine cogeneration systems).

Chapter 7: Cogeneration | Heat recovery in reciprocating engine cogeneration

43. Why is cogeneration described as making much better use of fuel than a conventional condensing power plant? [2P2CEM043]

- a) A condensing plant has no boiler losses, so cogeneration adds extra heat
- b) A condensing plant rejects most fuel energy in the condenser; cogeneration uses it**
- c) Cogeneration plants produce more power per kg of fuel than condensing plants
- d) Cogeneration avoids all losses, so its efficiency is always close to 100%

Correct answer: (b) A condensing plant rejects most fuel energy in the condenser; cogeneration uses it.

The guidebook explains that in a conventional power plant only efficiency is only about 35% and the remaining 65% of energy is lost, the major loss being heat rejected to the surrounding water or air (condenser and cooling tower) due to the constraints of the thermodynamic cycle; a further 10–15% is lost in transmission and distribution. Cogeneration uses this otherwise wasted heat for process needs, so the overall fuel utilisation (power plus useful heat) can rise to roughly 80–90% for well-matched systems.

The advantage comes from using the rejected heat, not from producing more electricity per kg of fuel.

Why not the others: (a) Every plant has boiler losses; cogeneration does not add heat. (c) A cogeneration plant usually produces less power per kg of fuel than a condensing plant, because steam leaves at higher pressure. (d) No plant avoids all losses; overall efficiency is high but well below 100%.

Ref: BEE Guidebook Paper 2, Ch. 7, §7.1–7.2 (Need for cogeneration; principle).

Chapter 7: Cogeneration | Efficiency of conventional power generation versus cogeneration

44. A gas turbine's exhaust of 50 kg/s at 520 °C passes through an unfired HRSG and leaves the stack at 150 °C. The gas specific heat is 1.1 kJ/kg K. Steam is generated at 2,780 kJ/kg from feed water at 440 kJ/kg. The steam generated is about: [2P2CEM044]

- a) 26.4 t/h
- b) 28.5 t/h
- c) 31.3 t/h**
- d) 44.0 t/h

Correct answer: (c) 31.3 t/h.

Given: $m_g = 50 \text{ kg/s}$; $t_{in} = 520 \text{ °C}$, $t_{out} = 150 \text{ °C}$; $C_p = 1.1 \text{ kJ/kg K}$; $h_{steam} = 2,780 \text{ kJ/kg}$; $h_{feed} = 440 \text{ kJ/kg}$.

Formula: Heat recovered $Q = m_g \times C_p \times (t_{in} - t_{out})$; steam = $Q / (h_{steam} - h_{feed})$.

Substitution: $Q = 50 \times 1.1 \times (520 - 150) = 50 \times 1.1 \times 370 = 20,350 \text{ kW}$; steam = $20,350 / (2,780 - 440) = 20,350 / 2,340 = 8.70 \text{ kg/s}$; $\times 3.6 = 31.3 \text{ t/h}$.

Result: **Steam generated $\approx 31.3 \text{ t/h}$** ($\approx 8.70 \text{ kg/s}$).

Why not the others: (a) 26.4 t/h divides by the full 2,780 kJ/kg and ignores the heat already in the feed water. (d) 44.0 t/h cools the exhaust to 0 °C instead of 150 °C stack temperature. (b) 28.5 t/h uses $C_p = 1.0 \text{ kJ/kg K}$ instead of the given 1.1.

Ref: BEE Guidebook Paper 2, Ch. 7 (Gas turbine cogeneration with HRSG).

Chapter 7: Cogeneration | Steam from gas turbine exhaust in an HRSG

45. A glass melting furnace uses brick-checker regenerators. The operator wants to lengthen the reversal period to reduce valve operations. What effect does the guidebook describe? [2P2CEM045]

- a) Higher thermal storage and cost, lower average preheat and fuel economy**
- b) Higher average air preheat, so fuel economy improves steadily
- c) No effect, since the brick stores unlimited heat at all times
- d) Lower checker cost, since less brick is needed for longer periods

Correct answer: (a) Higher thermal storage and cost, lower average preheat and fuel economy.

The guidebook notes that regenerators, preferred for large capacities, are widely used in glass and steel melting furnaces, and that the size of the regenerator, the time between reversals, the brick thickness and conductivity, and the heat storage ratio are closely related. Long reversal periods mean higher thermal storage and hence higher cost; they also result in a lower average preheat temperature and consequently reduce fuel economy. Dust accumulation and slagging, wall losses and air in-leaks also reduce regenerator performance as the furnace ages.

Why not the others: (b) Average preheat falls with longer periods, because the checkers cool further during each air period. (c) Brick has finite heat capacity, which is why reversal timing matters. (d) Longer periods need more storage, i.e. more brick and cost.

Ref: BEE Guidebook Paper 2, Ch. 8 (Regenerator).

Chapter 8: Waste Heat Recovery | Regenerator reversal period

46. An auditor recommends a heat wheel for a printing unit. For which application does the guidebook say heat wheels are mainly used? [2P2CEM046]

- a) Recovery from 1,200 °C furnace gases carrying corrosive dust
- b) Transfer of heat between two separate liquid streams
- c) Raising high-pressure steam from gas turbine exhaust gases

d) Exchange between large air masses with small temperature differences

Correct answer: (d) Exchange between large air masses with small temperature differences.

The guidebook describes a heat wheel as a sizable porous disk of high heat capacity material that rotates slowly between two side-by-side ducts, one hot and one cold. Heat (and moisture carrying latent heat) is picked up from the hot stream and released to the cold stream as the disk turns; sensible heat recovery efficiency can be as high as 85%. Its main application is where heat exchange between large masses of air with small temperature differences is required, such as heating and ventilation systems and recovery from dryer exhaust air; a case example recovers heat from a printing press exhaust.

Why not the others: (a) Very hot, dusty, corrosive gases suit recuperators or regenerators. (b) Liquid-to-liquid exchange needs plate or shell-and-tube exchangers. (c) Gas turbine exhaust is best used in a waste heat boiler or HRSG.

Ref: BEE Guidebook Paper 2, Ch. 8 (Heat wheels).

Chapter 8: Waste Heat Recovery | Heat wheel applications

47. A refinery installs a waste heat recovery system on an incinerator. Which of the following is an INDIRECT benefit of waste heat recovery listed in the guidebook? [2P2CEM047]

- a) Lower fuel cost of the process from reduced utility consumption
- b) Smaller fans, ducts and stacks, with lower auxiliary power use**
- c) Higher process efficiency from returning heat to the process
- d) Lower purchased steam because recovered heat replaces boiler heat

Correct answer: (b) Smaller fans, ducts and stacks, with lower auxiliary power use.

The guidebook classifies the benefits of waste heat recovery into direct and indirect. Direct benefits are the reduced utility consumption and process cost from recovering heat (lower fuel or purchased steam, higher process efficiency). Indirect benefits are: (a) reduction in pollution, for example by burning toxic combustible wastes in incinerators that also recover heat; (b) reduction in equipment sizes, since lower fuel use means less flue gas, so fans, stacks, ducts and burners can be smaller; and (c) reduction in auxiliary energy consumption, such as electricity for fans and pumps.

Why not the others: (a), (c) and (d) all describe the direct benefit — lower utility consumption and cost — rather than an indirect one.

Ref: BEE Guidebook Paper 2, Ch. 8, §8.3 (Benefits of waste heat recovery).

Chapter 8: Waste Heat Recovery | Indirect benefits of waste heat recovery

48. During a performance test of a turbine lube-oil cooler, 5 kg/s of oil (specific heat 2.2 kJ/kg K) is brought down from 120 °C to 60 °C. Cooling tower water is allowed a rise from 32 °C to 42 °C (specific heat 4.18 kJ/kg K). What circulation rate must the water pump deliver? [2P2CEM048]

- a) 2.63 kg/s
- b) 3.76 kg/s
- c) 15.8 kg/s**
- d) 30.0 kg/s

Correct answer: (c) 15.8 kg/s.

Given: oil $m_h = 5$ kg/s, $C_{p,h} = 2.2$ kJ/kg K, $120 \rightarrow 60$ °C; water $C_{p,c} = 4.18$ kJ/kg K, $32 \rightarrow 42$ °C.

Formula: Heat lost by oil = heat gained by water: $m_h \times C_{p,h} \times \Delta t_h = m_c \times C_{p,c} \times \Delta t_c$.

Substitution: $Q = 5 \times 2.2 \times (120 - 60) = 660$ kW; $m_c = 660 / (4.18 \times (42 - 32)) = 660 / 41.8$.

Result: **Cooling water ≈ 15.8 kg/s (about 57 m³/h).**

Why not the others: (b) 3.76 kg/s uses the water outlet temperature (42 °C) as the rise instead of the 10 °C difference. (d) 30.0 kg/s uses the oil specific heat (2.2) for water. (a) 2.63 kg/s uses the oil temperature drop (60 °C) as the water temperature rise.

Ref: BEE Guidebook Paper 2, Ch. 9 (Heat exchanger heat balance; performance assessment).

Chapter 9: Heat Exchangers | Cooling water requirement from heat balance

49. After pinch analysis of a dairy's heat exchanger network, the consultant states three rules for achieving minimum energy targets. Which set is correct? [2P2CEM049]

- a) Transfer maximum heat across the pinch to cut the number of exchangers
- b) Hot utility only below the pinch, and cold utility only above the pinch
- c) No heat across the pinch; no hot utility below; no cold utility above it**
- d) Place all exchangers at the pinch, where the driving force is largest

Correct answer: (c) No heat across the pinch; no hot utility below; no cold utility above it.

Pinch analysis divides the process into a region above the pinch, which is a net heat sink, and a region below the pinch, which is a net heat source. To meet the minimum utility targets, three rules apply: do not transfer heat across the pinch; do not use hot utility below the pinch; and do not use cold utility above the pinch. Any violation increases both hot and cold utility by the same amount.

The guidebook presents pinch technology as a systematic method to set energy targets and design heat recovery networks before detailed design.

Why not the others: (a) Transfer across the pinch is exactly what raises utility use. (b) This reverses the rules: hot utility belongs above the pinch and cold utility below. (d) At the pinch the temperature difference is the smallest (ΔT_{min}), not the largest.

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

Chapter 9: Heat Exchangers | Golden rules of pinch analysis

50. A clean shell-and-tube heater has an overall heat transfer coefficient of 1,000 W/m² K. After some months of service, the combined fouling resistance is 0.0002 m² K/W. The fouled overall coefficient is about: [2P2CEM050]

- a) 800 W/m² K
- b) 833 W/m² K**
- c) 1,250 W/m² K
- d) 5,000 W/m² K

Correct answer: (b) 833 W/m² K.

Given: $U_{clean} = 1,000 \text{ W/m}^2 \text{ K}$; total fouling resistance $R_f = 0.0002 \text{ m}^2 \text{ K/W}$.

Formula: Resistances in series add: $1/U_{fouled} = 1/U_{clean} + R_f$.

Substitution: $1/U_{fouled} = 1/1,000 + 0.0002 = 0.0010 + 0.0002 = 0.0012 \text{ m}^2 \text{ K/W}$; $U_{fouled} = 1/0.0012$.

Result: **$U_{fouled} \approx 833 \text{ W/m}^2 \text{ K}$** (a 17% fall, so duty drops unless LMTD or area increases).

The guidebook lists fouling of heat transfer surfaces as a main cause of falling heat exchanger and boiler performance and recommends tracking U to schedule cleaning.

Why not the others: (c) 1,250 W/m² K subtracts the fouling resistance, which would make fouling improve heat transfer.

(a) 800 W/m² K subtracts $R_f \times 10^6$ (200) directly from U, mixing resistance and conductance. (d) 5,000 W/m² K is $1/R_f$ alone, the conductance of the fouling layer, not the overall coefficient.

Ref: BEE Guidebook Paper 2, Ch. 9 (Overall heat transfer coefficient; fouling).

Chapter 9: Heat Exchangers | Effect of fouling on overall heat transfer coefficient

..... 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 [2P2CEM051 | Chapter 1: Fuels and Combustion | Combustion air and flue gas volume for a natural gas mixture]

A float-glass annealing lehr burns 1,500 Nm³/h of natural gas with the following composition by volume: methane (CH₄) 90%, ethane (C₂H₆) 6%, nitrogen (N₂) 4%. The burners operate with 10% excess air. Air contains 21% O₂ and 79% N₂ by volume.

- a) Calculate the theoretical air required per Nm³ of gas. (2 Marks)
- b) Calculate the actual air supplied (Nm³/h) and the total wet flue gas volume (Nm³/h). (2 Marks)
- c) Estimate the CO₂ percentage in the dry flue gas. (1 Mark)

S-1 Ans (model answer with marking scheme)

Given: Gas flow = 1,500 Nm³/h; CH₄ = 0.90, C₂H₆ = 0.06, N₂ = 0.04 Nm³ per Nm³ gas; excess air = 10%; air = 21% O₂ + 79% N₂ (by volume).

Reactions (by volume): CH₄ + 2 O₂ → CO₂ + 2 H₂O; C₂H₆ + 3.5 O₂ → 2 CO₂ + 3 H₂O

a) Theoretical air (2 marks)

Formula: O₂ required = Σ (volume fraction × O₂ per volume of constituent); theoretical air = O₂ required/0.21

Substitution: O₂ = 0.90 × 2 + 0.06 × 3.5 = 1.80 + 0.21 = 2.01 Nm³/Nm³ gas [1 mark]; air = 2.01/0.21

Result: **Theoretical air ≈ 9.57 Nm³ air/Nm³ gas** [1 mark]

b) Actual air and wet flue gas (2 marks)

Formula: Actual air = (1 + EA/100) × theoretical air; flue gas = CO₂ + H₂O + N₂ (fuel N₂ + 0.79 × actual air) + excess O₂ (0.21 × excess air)

Substitution: Actual air = 1.10 × 9.571 = 10.53 Nm³/Nm³; CO₂ = 0.90 + 0.06 × 2 = 1.02; H₂O = 0.90 × 2 + 0.06 × 3 = 1.98; N₂ = 0.04 + 0.79 × 10.53 = 8.358; O₂ = 0.21 × (10.529 – 9.571) = 0.201; wet flue gas = 1.02 + 1.98 + 8.358 + 0.201 = 11.56 Nm³/Nm³ gas [1 mark]

Result: **Actual air ≈ 1.10 × 9.571 × 1,500 ≈ 15,790 Nm³/h; wet flue gas ≈ 11.56 × 1,500 ≈ 17,340 Nm³/h** [1 mark]

c) CO₂ in dry flue gas (1 mark)

Formula: CO₂ % (dry) = CO₂/(wet flue gas – H₂O) × 100

Substitution: Dry flue gas = 11.559 – 1.98 = 9.579 Nm³/Nm³; CO₂ % = 1.02/9.579 × 100

Result: **CO₂ ≈ 10.6% (dry basis)** [1 mark]

Marking note: accept ±1% rounding; award method marks if reaction stoichiometry is correct but arithmetic slips; deduct ½ mark if fuel N₂ is omitted from the flue gas.

S-2 [2P2CEM052 | Chapter 2: Boilers | Economiser heat recovery and payback]

A 15 TPH oil-fired shell boiler in a pharmaceutical plant has flue gas leaving at 260 °C. An economiser is proposed to cool the flue gas to 180 °C (well above the acid dew point) while heating the feed water. Data:

Parameter	Value
Flue gas flow	20,000 kg/h
Specific heat of flue gas	0.24 kcal/kg °C
Feed water flow	15,000 kg/h
Boiler efficiency (before economiser)	82%
GCV of furnace oil	10,200 kcal/kg

Furnace oil price	₹ 48,000 per tonne
Operating hours	8,000 h/yr
Installed cost of economiser	₹ 35,00,000

- Calculate the heat recovered and the rise in feed water temperature. (2 Marks)
- Calculate the annual fuel oil saving in tonnes and in ₹, and the simple payback period. (2 Marks)
- Why should the flue gas not be cooled below the acid dew point? (1 Mark)

S-2 Ans (model answer with marking scheme)

Given: $m_g = 20,000 \text{ kg/h}$; $C_{p_g} = 0.24 \text{ kcal/kg } ^\circ\text{C}$ ($\approx 1.00 \text{ kJ/kg}\cdot\text{K}$); $t_g: 260 \rightarrow 180 \text{ } ^\circ\text{C}$; $m_w = 15,000 \text{ kg/h}$; $\eta = 0.82$; $\text{GCV} = 10,200 \text{ kcal/kg}$ ($\approx 42,705 \text{ kJ/kg}$); oil = ₹ 48,000/t; 8,000 h/yr; investment = ₹ 35,00,000.

a) Heat recovered and feed water rise (2 marks)

Formula: $Q = m_g \times C_{p_g} \times (t_{in} - t_{out})$; $\Delta t_w = Q/(m_w \times 1)$

Substitution: $Q = 20,000 \times 0.24 \times (260 - 180) = 3,84,000 \text{ kcal/h}$ [1 mark]; $\Delta t_w = 3,84,000/15,000$

Result: **Heat recovered = 3,84,000 kcal/h ($\approx 447 \text{ kW}$); feed water temperature rise $\approx 25.6 \text{ } ^\circ\text{C}$** [1 mark]

b) Fuel saving and payback (2 marks)

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

Substitution: Oil saved = $3,84,000/(0.82 \times 10,200) = 45.9 \text{ kg/h}$; per year = $45.9 \times 8,000/1,000 = 367.3 \text{ t}$ [1 mark]; ₹ = $367.3 \times 48,000 = ₹ 1,76,29,840$; payback = $35,00,000/1,76,29,840 = 0.20 \text{ yr}$

Result: **Oil saving $\approx 367 \text{ t/yr} \approx ₹ 1.76 \text{ crore/yr}$; payback $\approx 0.2 \text{ year (about 2.4 months)}$** [1 mark]

c) Acid dew point (1 mark)

Sulphur in the oil forms SO_3 , which combines with water vapour to form sulphuric acid. If the gas or the metal surface falls below the acid dew point, acid condenses on the economiser tubes and stack, causing rapid corrosion; hence the outlet is limited (here $180 \text{ } ^\circ\text{C}$) and feed water entering the economiser should not be too cold. [1 mark]

Marking note: $\pm 1\%$ tolerance on numbers; payback accepted as 0.2 year or 2–3 months.

S-3 [2P2CEM053 | Chapter 3: Steam System | Effect of steam dryness on steam consumption]

A rubber vulcanising press needs 5,00,000 kcal/h of heat, which is supplied by condensing steam at $8 \text{ kg/cm}^2(\text{g})$ (latent heat 498 kcal/kg). The trap removes condensate at saturation. A test shows the steam arriving at the press has a dryness fraction of only 0.92 because the header lacks separators and drain points. Steam costs ₹ 2,200 per tonne and the press works 7,000 h/yr.

- Calculate the steam consumption with dry saturated steam and with steam of dryness 0.92. (2 Marks)
- Calculate the extra steam per year and its cost. (2 Marks)
- Suggest two measures to deliver dry steam to the press. (1 Mark)

S-3 Ans (model answer with marking scheme)

Given: Heat duty $Q = 5,00,000 \text{ kcal/h}$ ($\approx 581 \text{ kW}$); latent heat $L = 498 \text{ kcal/kg}$ ($\approx 2,085 \text{ kJ/kg}$); dryness $x = 0.92$; steam cost = ₹ 2,200/t; 7,000 h/yr.

a) Steam consumption (2 marks)

Formula: Useful heat per kg = $x \times L$ (only the dry fraction condenses and releases latent heat); steam = $Q/(x \times L)$

Substitution: Dry steam: $5,00,000/498 = 1,004 \text{ kg/h}$ [1 mark]; wet steam: $x \times L = 0.92 \times 498 = 458.2 \text{ kcal/kg}$; steam = $5,00,000/458.2$

Result: **Dry steam $\approx 1,004 \text{ kg/h}$; wet steam ($x = 0.92$) $\approx 1,091 \text{ kg/h}$** [1 mark]

b) Extra steam and cost (2 marks)

Formula: Extra steam = $m_{\text{wet}} - m_{\text{dry}}$; annual cost = extra $\times$ hours $\times$ price

Substitution: Extra = $1,091 - 1,004 = 87.3 \text{ kg/h}$ [1 mark]; per year = $87.3 \times 7,000/1,000 = 611 \text{ t}$; cost = $611 \times 2,200$

Result: **Extra steam $\approx 611 \text{ t/yr}$ costing $\approx ₹ 13.4 \text{ lakh/yr}$** [1 mark]

Note: wet steam also forms a thicker water film on the heat transfer surface, lowering the heat transfer rate and slowing the press cycle, so the real penalty is higher.

c) Measures for dry steam (1 mark; ½ mark each, any two)

- Install a steam separator with a trap ahead of the press (and after any PRV).
- Provide drain points every 30–45 m and at low points of the header, through equal tees with suitable traps.
- Insulate the header and branch lines fully, including flanges and valves.
- Avoid carry-over at the boiler: control TDS and drum water level, and do not overload the boiler.

Marking note: accept 1,090–1,092 kg/h; cost ₹ 13.3–13.5 lakh.

S-4 [2P2CEM054 | Chapter 4: Furnaces | Heat storage loss in an intermittent furnace lining]

A batch-type annealing furnace in a wire plant is heated and cooled once per cycle, with 300 cycles per year. During each heating, the existing dense firebrick lining (mass 16 t, specific heat $0.22 \text{ kcal/kg } ^\circ\text{C}$) rises from 40°C to a mean temperature of 700°C . It is proposed to reline the hot face with ceramic fibre modules; the heat-absorbing lining then becomes 2.0 t of fibre (specific heat $0.27 \text{ kcal/kg } ^\circ\text{C}$) with a mean temperature rise of 650°C . The furnace fuel (furnace oil, GCV 10,200 kcal/kg) delivers heat to the chamber with an available-heat fraction of 60%. Oil costs ₹ 50,000 per tonne.

a) Calculate the heat stored in the lining per cycle before and after relining. (2 Marks)

b) Calculate the oil saved per cycle and per year. (2 Marks)

c) Why does ceramic fibre save energy only in intermittent furnaces? (1 Mark)

S-4 Ans (model answer with marking scheme)

Given: Existing: $m = 16,000 \text{ kg}$, $C_p = 0.22 \text{ kcal/kg } ^\circ\text{C}$ ($\approx 0.921 \text{ kJ/kg}\cdot\text{K}$), $\Delta t = 700 - 40 = 660^\circ\text{C}$. Proposed: $m = 2,000 \text{ kg}$, $C_p = 0.27 \text{ kcal/kg } ^\circ\text{C}$ ($\approx 1.13 \text{ kJ/kg}\cdot\text{K}$), $\Delta t = 650^\circ\text{C}$. Available heat = 60%; GCV = 10,200 kcal/kg ($\approx 42,705 \text{ kJ/kg}$); 300 cycles/yr; oil = ₹ 50,000/t.

a) Heat stored per cycle (2 marks)

Formula: Heat stored = $m \times C_p \times \Delta t$

Substitution: Existing = $16,000 \times 0.22 \times 660 = 23,23,200 \text{ kcal/cycle}$ [1 mark]; proposed = $2,000 \times 0.27 \times 650 = 3,51,000 \text{ kcal/cycle}$

Result: **Heat stored falls from 23,23,200 to 3,51,000 kcal ($\approx 1,470 \text{ MJ}$) per cycle; reduction = 19,72,200 kcal ($\approx 8,257 \text{ MJ}$) per cycle** [1 mark]

b) Oil saving (2 marks)

Formula: Oil saved per cycle = heat saved/(available-heat fraction $\times$ GCV)

Substitution: = $19,72,200/(0.60 \times 10,200) = 19,72,200/6,120 = 322 \text{ kg/cycle}$ [1 mark]; per year = $322 \times 300/1,000 = 96.7 \text{ t}$; value = $96.7 \times 50,000$

Result: **Oil saving $\approx 322 \text{ kg per cycle} \approx 96.7 \text{ t/yr} \approx ₹ 48.3 \text{ lakh/yr}$** [1 mark]

c) Why intermittent furnaces only (1 mark)

Ceramic fibre is a low-thermal-mass refractory; its benefit is the small heat stored in the lining on each heat-up, plus faster heating and cooling. In a continuous furnace the lining stays hot and is not reheated every cycle, so the storage saving does not arise — only the (smaller) insulation benefit remains. [1 mark]

Marking note: $\pm 1\%$ tolerance; award method marks if the available-heat factor is applied correctly even with arithmetic slips.

S-5 [2P2CEM055 | Chapter 5: Insulation and Refractories | Selecting economic insulation thickness from cost data]

A 150 m long steam line in a distillery is to be insulated. The heat loss and installed insulation cost for four thicknesses are given below. Heat is generated in an oil-fired boiler (efficiency 82%, GCV 10,200 kcal/kg, oil ₹ 50/kg). The line operates 8,000 h/yr and the annualised capital charge is 25% of insulation cost.

Insulation thickness (mm)	Heat loss (kcal/h per m)	Installed cost (₹ per m)
25	160	1,800
50	95	3,600
75	72	6,800
100	60	11,000

- Calculate the cost of heat in ₹ per kcal delivered by the boiler. (1 Mark)
- Tabulate the annual heat-loss cost, annualised capital cost and total cost per metre for each thickness. (3 Marks)
- Select the economic thickness and state the total annual cost for the 150 m line. (1 Mark)

S-5 Ans (model answer with marking scheme)

Given: Length = 150 m; 8,000 h/yr; $\eta = 0.82$; GCV = 10,200 kcal/kg ($\approx 42,705$ kJ/kg); oil = ₹ 50/kg; capital charge = 25%/yr; losses and costs per metre as in the table.

a) Cost of heat (1 mark)

Formula: Cost of useful heat = oil price/(GCV $\times \eta$)

Substitution: $= 50/(10,200 \times 0.82) = 50/8,364$

Result: **Cost of heat $\approx$ ₹ 0.005978 per kcal ($\approx$ ₹ 5,978 per million kcal)** [1 mark]

b) Cost table per metre (3 marks)

Formula: Heat-loss cost = loss (kcal/h per m) $\times$ 8,000 $\times$ 0.005978; capital cost per year = 0.25 $\times$ installed cost; total = sum

Thickness (mm)	Heat-loss cost (₹/m·yr)	Capital charge (₹/m·yr)	Total (₹/m·yr)
25	7,652	450	8,102
50	4,543	900	5,443
75	3,443	1,700	5,143
100	2,869	2,750	5,619

Substitution (sample, 75 mm): $72 \times 8,000 \times 0.005978 = ₹ 3,443$; $0.25 \times 6,800 = ₹ 1,700$; total = ₹ 5,143 per m·yr [3 marks: 1 for heat-loss costs, 1 for capital charges, 1 for totals]

c) Economic thickness (1 mark)

Result: **Economic thickness = 75 mm (minimum total cost $\approx$ ₹ 5,143 per m·yr); for 150 m $\approx$ ₹ 7.71 lakh/yr** [1 mark]

Going from 75 to 100 mm saves ₹ 574 per m·yr of heat but adds ₹ 1,050 per m·yr of capital charge, so the extra thickness is not justified.

Marking note: accept totals within $\pm 1\%$; full marks for correct selection with a consistent table.

S-6 [2P2CEM056 | Chapter 6: FBC Boilers | Troubleshooting an AFBC boiler]

An energy auditor visiting a 20 TPH bubbling-bed (AFBC) boiler finds the following problems. For each, state the likely cause and the corrective action as per good FBC practice. (5 $\times$ 1 Mark)

- a) Clinkers are forming in the bed and fluidisation is patchy.
- b) Unburnt carbon in fly ash is high and CO is present at the boiler outlet.
- c) SO₂ emission is high although limestone is added with the coal.
- d) Coal fed through the under-bed pneumatic system blocks the feed pipes and the bed shows dead zones.
- e) The bed has 'slumped' after a short trip and coal is to be fed again.

S-6 Ans (model answer with marking scheme)

Answer in structured points; each part carries 1 mark (½ for cause, ½ for corrective action).

a) Clinker formation (1 mark)

Cause: bed temperature has exceeded about 950 °C (risk of clinker) — e.g. excess coal feed, low air or high-volatile fuel; poor fluidisation locally. Action: reduce coal feed/raise fluidising air to keep bed at 800–900 °C, check air nozzles/distributor for blockage, maintain bed material size and height.

b) High unburnt carbon and CO (1 mark)

Cause: bed temperature below about 800 °C (loss of combustion efficiency), oversize coal, or insufficient air/poor mixing; very fine coal elutriates before burning. Action: raise bed temperature to the 800–900 °C band, correct coal sizing (crushed to the specified 1–10 mm range), optimise primary/secondary air, consider fly-ash recycling.

c) High SO₂ despite limestone (1 mark)

Cause: bed temperature outside the 800–850 °C band needed for efficient sulphur retention, wrong limestone size or too low Ca/S feed ratio. Action: control bed at 800–850 °C, feed correctly sized limestone in proportion to sulphur in coal, ensure good mixing in the bed.

d) Feed pipe blockage and dead zones (1 mark)

Cause: coal for under-bed pneumatic feeding is too coarse or wet (it should be crushed to about 1–6 mm and dry enough to convey); too few feed points for the bed area. Action: correct crushing and moisture, maintain conveying air, provide adequate number of feed points so fuel is distributed uniformly across the bed.

e) Restart after slump (1 mark)

Cause/condition: after a trip the bed cools and settles; coal will ignite only if the bed is still above its ignition temperature. Action: re-fluidise and check bed temperature; if hot enough, resume coal feed gradually; if cooled, preheat the bed with the start-up (oil/gas) burner before feeding coal; avoid feeding coal into a cold bed (risk of accumulation and puffs).

Marking note: any technically correct cause with matching remedy earns the mark; mention of the guidebook temperature limits (800 °C, 800–850 °C for sulphur capture, 950 °C clinker) is expected for full marks.

S-7 [2P2CEM057 | Chapter 7: Cogeneration | Trigeneration with a gas engine and absorption chiller]

A cold-storage and food processing unit installs a natural gas engine generator of 2,000 kW electrical output at 40% electrical efficiency (on GCV). 1,000 kW of heat is recovered from the exhaust and drives a single-effect vapour absorption chiller of COP 0.7. A further 900 kW of jacket water heat is used as process hot water. Natural gas GCV is 9,000 kcal/Sm³.

- a) Calculate the fuel input in kW and the gas consumption in Sm³/h. (1 Mark)
- b) Calculate the refrigeration produced in kW and TR (1 TR = 3,024 kcal/h). (2 Marks)
- c) Calculate the energy utilisation factor of the system. (2 Marks)

S-7 Ans (model answer with marking scheme)

Given: P = 2,000 kW; η_{el} = 0.40; exhaust heat to VAM = 1,000 kW; COP = 0.7; jacket water heat used = 900 kW; GCV = 9,000 kcal/Sm³ (≈ 37.7 MJ/Sm³); 1 kW = 860 kcal/h; 1 TR = 3,024 kcal/h (≈ 3.52 kW).

a) Fuel input (1 mark)

Formula: Fuel input = P/η_{el} ; gas = fuel input $\times$ 860/GCV

Substitution: Fuel = $2,000/0.40 = 5,000$ kW; gas = $5,000 \times 860/9,000 = 43,00,000/9,000$

Result: **Fuel input = 5,000 kW; gas $\approx$ 478 Sm³/h** [1 mark]

b) Refrigeration (2 marks)

Formula: Cooling = COP $\times$ heat input to VAM; TR = kW $\times$ 860/3,024

Substitution: Cooling = $0.7 \times 1,000 = 700$ kW [1 mark]; TR = $700 \times 860/3,024$

Result: **Refrigeration $\approx$ 700 kW $\approx$ 199 TR** [1 mark]

c) Energy utilisation factor (2 marks)

Formula: EUF = (electrical output + useful thermal output)/fuel input

Substitution: Useful thermal = 1,000 (to VAM) + 900 (hot water) = 1,900 kW [1 mark]; EUF = $(2,000 + 1,900)/5,000$

Result: **EUF = 78%** (if refrigeration output is counted instead of VAM heat input: $(2,000 + 700 + 900)/5,000 = 72\%$) [1 mark]

Marking note: either EUF basis accepted if clearly stated; $\pm 1\%$ tolerance.

S-8 [2P2CEM058 | Chapter 9: Heat Exchangers | Heat exchanger performance test and fouling]

Operators logged these readings on a fertiliser-plant liquor cooler arranged counter-current: liquor 8 kg/s (specific heat 3.9 kJ/kg K) falling from 95 °C to 55 °C; cooling tower water rising from 30 °C to 45 °C (specific heat 4.18 kJ/kg K). Installed surface is 60 m²; the vendor's clean-surface overall coefficient is 750 W/m² K. Assess whether the unit needs cleaning.

a) Calculate the heat duty and the cooling water flow. (2 Marks)

b) Calculate the LMTD and the present overall heat transfer coefficient. (2 Marks)

c) Compare with design and estimate the fouling resistance. (1 Mark)

S-8 Ans (model answer with marking scheme)

Given: $m_h = 8$ kg/s; $C_{p,h} = 3.9$ kJ/kg K; $T_{h,1} = 95 \rightarrow 55$ °C; $T_{c,1} = 30 \rightarrow 45$ °C; $C_{p,c} = 4.18$ kJ/kg K; $A = 60$ m²; $U_{design} = 750$ W/m² K; counter-flow.

a) Duty and water flow (2 marks)

Formula: $Q = m_h \times C_{p,h} \times (T_{h,1} - T_{h,2})$; $m_c = Q/(C_{p,c} \times \Delta T_c)$

Substitution: $Q = 8 \times 3.9 \times (95 - 55) = 1,248$ kW [1 mark]; $m_c = 1,248/(4.18 \times 15) = 1,248/62.7$

Result: **Duty = 1,248 kW; cooling water $\approx$ 19.9 kg/s ($\approx$ 71.6 m³/h)** [1 mark]

b) LMTD and U (2 marks)

Formula: $LMTD = (\Delta T_1 - \Delta T_2)/\ln(\Delta T_1/\Delta T_2)$; $U = Q/(A \times LMTD)$

Substitution: $\Delta T_1 = 95 - 45 = 50$ °C; $\Delta T_2 = 55 - 30 = 25$ °C; $LMTD = 25/\ln 2 = 36.07$ °C [1 mark]; $U = 12,48,000/(60 \times 36.07)$

Result: **LMTD $\approx$ 36.1 °C; U(present) $\approx$ 577 W/m² K** [1 mark]

c) Fouling (1 mark)

Formula: $R_f = 1/U_{present} - 1/U_{design}$

Substitution: $R_f = 1/576.7 - 1/750 = 0.001734 - 0.001333$

Result: **U is $\approx$ 77% of design; fouling resistance $\approx$ 0.0004 m² K/W — cleaning is indicated** [1 mark]

Marking note: $\pm 1\%$ tolerance; award marks for LMTD by correct counter-flow terminal differences.

..... 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 [2P2CEM059 | Chapter 2: Boilers | Boiler load consolidation, shell losses and soot]

A tyre plant has two identical 10 TPH oil-fired package boilers. At present both run in parallel at 4.5 TPH each (total 9 TPH). Tests show efficiency of 76% for each boiler at 45% load and 84% at 90% load. The energy manager proposes running one boiler at 9 TPH with the second on hot standby.

Parameter	Value
Enthalpy of steam – enthalpy of feed water	600 kcal/kg
GCV of furnace oil	10,200 kcal/kg
Oil price	₹ 48,000 per tonne
Operating hours	8,000 h/yr
Radiation and convection loss at full load (10 TPH, η 84%)	1.5% of fuel input

- a) Calculate the oil consumption for both modes of operation and the annual saving (t and ₹). (4 Marks)
- b) The radiation and convection loss in kcal/h is nearly constant with load. Calculate it, and its percentage of fuel input for a boiler at 4.5 TPH. (2 Marks)
- c) After consolidation, the stack temperature of the running boiler is found 40 °C above the clean-boiler value. Assuming this reflects 3 mm soot, estimate the additional annual saving from soot blowing. (2 Marks)
- d) Explain why boiler efficiency is low at both very low and full load. (2 Marks)

L-1 Ans (model answer with marking scheme)

Given: Steam = 9,000 kg/h; Δh = 600 kcal/kg ($\approx$ 2,512 kJ/kg); η (45% load) = 0.76; η (90% load) = 0.84; GCV = 10,200 kcal/kg ($\approx$ 42,705 kJ/kg); oil = ₹ 48,000/t; 8,000 h/yr; shell loss = 1.5% of input at 10 TPH, η 84%.

a) Oil consumption and saving (4 marks)

Formula: Oil = steam $\times \Delta h / (\eta \times \text{GCV})$

Substitution: Two boilers at 4.5 TPH: $9,000 \times 600 / (0.76 \times 10,200) = 54,00,000 / 7,752 = 696.6 \text{ kg/h}$ [1 mark]

One boiler at 9 TPH: $9,000 \times 600 / (0.84 \times 10,200) = 54,00,000 / 8,568 = 630.3 \text{ kg/h}$ [1 mark]

Saving = $696.6 - 630.3 = 66.3 \text{ kg/h}$; per year = $66.3 \times 8,000 / 1,000 = 530.7 \text{ t}$; value = $530.7 \times 48,000$ [1 mark]

Result: **Oil saving $\approx$ 66.3 kg/h $\approx$ 531 t/yr $\approx$ ₹ 2.55 crore/yr** [1 mark]

b) Radiation and convection loss (2 marks)

Formula: Fuel at full load = $10,000 \times 600 / (0.84 \times 10,200)$; loss = $0.015 \times \text{fuel} \times \text{GCV}$

Substitution: Fuel = $60,00,000 / 8,568 = 700.3 \text{ kg/h}$; loss = $0.015 \times 700.3 \times 10,200 = 1,07,143 \text{ kcal/h}$ [1 mark]; fuel input at 4.5 TPH = $4,500 \times 600 / 0.76 = 35,52,632 \text{ kcal/h}$; % = $1,07,143 / 35,52,632 \times 100$

Result: **Shell loss $\approx$ 1,07,143 kcal/h ($\approx$ 125 kW) per boiler, i.e. $\approx$ 3.0% of input at 4.5 TPH (twice its full-load share);** running one boiler instead of two also eliminates one such loss. [1 mark]

c) Soot blowing (2 marks)

Formula (guidebook): a rise of about 20 °C above the clean-boiler stack temperature indicates soot; 3 mm soot $\approx$ 2.5% extra fuel. Saving = $0.025 \times \text{oil rate} \times \text{hours} \times \text{price}$

Substitution: 40 °C rise $>$ 20 °C $\rightarrow$ soot blowing needed [1 mark]; saving = $0.025 \times 630.3 = 15.8 \text{ kg/h}$; per year = $15.8 \times 8,000 / 1,000 = 126.1 \text{ t}$; value = $126.1 \times 48,000$

Result: **Additional saving $\approx$ 126 t/yr $\approx$ ₹ 60.5 lakh/yr** [1 mark]

d) Efficiency vs load (2 marks)

- Maximum efficiency occurs at about two-thirds of full load (guidebook). [½ mark]
- At low load the radiation, convection and purge/cycling losses, being nearly fixed in kcal/h, become a large share of the reduced input; burners also need more excess air at high turndown, raising flue gas loss. [1 mark]
- At full load, the higher gas flow raises the flue gas exit temperature (less residence time for heat transfer), so stack loss rises. [½ mark]

Marking note: accept ₹ 2.5–2.6 crore for (a); marks per step as shown.

L-2 [2P2CEM060 | Chapter 3: Steam System | Steam-heated dryer: efficiency and mechanical dewatering]

A steam-heated hot-air dryer in a textile yarn plant dries 1,000 kg/h of bone-dry yarn. The moisture content falls from 1.20 kg to 0.06 kg water per kg bone-dry yarn. Steam consumption is 1,800 kg/h at 4 kg/cm²(g) (latent heat 500 kcal/kg; condensate leaves at saturation and is returned). Take heat required per kg of water evaporated as 610 kcal (sensible heating from 30 °C to 100 °C plus 540 kcal/kg latent heat), and the yarn specific heat as 0.4 kcal/kg °C (heated from 30 °C to 80 °C).

- Calculate the water evaporated, the theoretical heat requirement and the dryer thermal efficiency. (4 Marks)
- Improved hydro-extraction (squeezing) is proposed to reduce the inlet moisture to 0.90 kg/kg bone-dry. At the same dryer efficiency, calculate the new steam consumption and the steam saved. (3 Marks)
- The squeezing system adds 30 kW of electric load and costs ₹ 75 lakh. With steam at ₹ 2,200 per tonne, power at ₹ 8 per kWh and 8,000 h/yr, calculate the net annual saving and simple payback. (3 Marks)

L-2 Ans (model answer with marking scheme)

Given: Bone-dry yarn = 1,000 kg/h; moisture in = 1.20, out = 0.06 kg/kg BD; steam = 1,800 kg/h, L = 500 kcal/kg (≈ 2,093 kJ/kg); heat per kg water evaporated = 610 kcal/kg (≈ 2,554 kJ/kg); Cp(yarn) = 0.4 kcal/kg °C (≈ 1.67 kJ/kg·K), 30 → 80 °C; proposed moisture in = 0.90 kg/kg BD; extra power = 30 kW; investment = ₹ 75,00,000; steam = ₹ 2,200/t; power = ₹ 8/kWh; 8,000 h/yr.

a) Present performance (4 marks)

Formula: Water evaporated = BD × (M_{in} – M_{out}); heat = evaporated × 610 + BD × Cp × Δt; efficiency = theoretical heat/(steam × L)

Substitution: Evaporated = 1,000 × (1.20 – 0.06) = 1,140 kg/h [1 mark]; heat for water = 1,140 × 610 = 6,95,400 kcal/h; heat for yarn = 1,000 × 0.4 × (80 – 30) = 20,000 kcal/h; theoretical = 7,15,400 kcal/h [1 mark]

Heat supplied = 1,800 × 500 = 9,00,000 kcal/h (≈ 1,047 kW) [1 mark]; efficiency = 7,15,400/9,00,000

Result: **Water evaporated = 1,140 kg/h; theoretical heat = 7,15,400 kcal/h (≈ 832 kW); dryer efficiency ≈ 79.5%** [1 mark]

b) With better squeezing (3 marks)

Formula: New steam = new theoretical heat/(L × efficiency)

Substitution: Evaporated = 1,000 × (0.90 – 0.06) = 840 kg/h; heat = 840 × 610 + 20,000 = 5,32,400 kcal/h [1 mark]; steam = 5,32,400/(500 × 0.7949) = 1,340 kg/h [1 mark]

Result: **New steam ≈ 1,340 kg/h; steam saved ≈ 1,800 – 1,340 = 460 kg/h (≈ 26%)** [1 mark]

c) Economics (3 marks)

Formula: Steam saving value = steam saved × hours × price; power cost = kW × hours × tariff; net = difference; payback = investment/net

Substitution: Steam = 460.4 × 8,000/1,000 = 3,683 t × 2,200 = ₹ 81,03,774 [1 mark]; power = 30 × 8,000 × 8 = ₹ 19,20,000 [1 mark]; net = ₹ 61,83,774; payback = 75,00,000/61,83,774

Result: **Net saving ≈ ₹ 61.8 lakh/yr; payback ≈ 1.2 years** [1 mark]

Key point: mechanical removal of water is far cheaper than thermal evaporation, so dewatering ahead of dryers is a standard steam-saving measure.

Marking note: $\pm 1\%$ tolerance; carry-forward errors penalised only once.

L-3 [2P2CEM061 | Chapter 4: Furnaces | Radiation loss through a forging furnace door]

An oil-fired forging furnace operates at $1,250^\circ\text{C}$. Billets are charged through a door of $0.75\text{ m} \times 0.8\text{ m}$, which stays fully open for 15 minutes in every hour. The factor of radiation (total radiation factor for the opening geometry) is 0.72. A modification is proposed: a smaller hinged charging port of 0.3 m^2 (factor of radiation 0.68) through which charging takes only 6 minutes per hour.

Use the guidebook relation: $Q = 4.88 \times (T/100)^4 \times a \times A \times H$ (kcal), where T is in K, a = factor of radiation, A = opening area (m^2), H = time open (h).

Data	Value
Available heat in the furnace at $1,250^\circ\text{C}$ (fraction of GCV)	50%
GCV of furnace oil	10,000 kcal/kg
Oil price	₹ 52 per kg
Operating hours	6,000 h/yr
Cost of modification	₹ 4,50,000

- Calculate the radiation loss through the existing door in kcal per hour of operation. (3 Marks)
- Calculate the loss after modification and the hourly heat saved. (3 Marks)
- Calculate the annual oil saving (kg/h, t/yr, ₹/yr) and simple payback. (2 Marks)
- List four other measures to reduce furnace opening and wall losses. (2 Marks)

L-3 Ans (model answer with marking scheme)

Given: $T = 1,250 + 273 = 1,523\text{ K}$; existing $A = 0.75 \times 0.8 = 0.6\text{ m}^2$, $a = 0.72$, $H = 15/60 = 0.25\text{ h}$ per hour; proposed $A = 0.3\text{ m}^2$, $a = 0.68$, $H = 6/60 = 0.1\text{ h}$ per hour; available heat = 50%; GCV = 10,000 kcal/kg ($\approx 41,868\text{ kJ/kg}$); oil = ₹ 52/kg; 6,000 h/yr; cost = ₹ 4,50,000.

a) Existing opening loss (3 marks)

Formula: $Q = 4.88 \times (T/100)^4 \times a \times A \times H$

Substitution: $(1,523/100)^4 = 15.23^4 = 53,802$ [1 mark]; $Q = 4.88 \times 53,802 \times 0.72 \times 0.6 \times 0.25$ [1 mark]

Result: **Existing loss $\approx 28,356\text{ kcal}$ ($\approx 119\text{ MJ}$) per hour of operation** [1 mark]

b) After modification (3 marks)

Substitution: $Q = 4.88 \times 53,802 \times 0.68 \times 0.3 \times 0.1$ [1 mark]

Result: **New loss $\approx 5,356\text{ kcal/h}$ ($\approx 6.23\text{ kW}$)** [1 mark]; **heat saved $\approx 28,356 - 5,356 = 23,000\text{ kcal/h}$ ($\approx 26.7\text{ kW}$)** [1 mark]

c) Oil saving and payback (2 marks)

Formula: Oil saved = heat saved/(available heat $\times$ GCV); payback = cost/annual saving

Substitution: Oil = $23,000/(0.50 \times 10,000) = 4.6\text{ kg/h}$; per year = $4.6 \times 6,000 = 27,600\text{ kg} = 27.6\text{ t}$; value = $27,600 \times 52 = ₹ 14,35,200$ [1 mark]; payback = $4,50,000/14,35,200 = 0.31\text{ yr}$

Result: **Oil saving $\approx 4.6\text{ kg/h} \approx 27.6\text{ t/yr} \approx ₹ 14.4\text{ lakh/yr}$; payback $\approx 0.31\text{ year}$ ($\approx 4\text{ months}$)** [1 mark]

Note: the heat lost through the opening must be made good by fuel whose useful (available) heat is only 50% at this furnace temperature, which is why the fuel saving is double the radiated heat.

d) Other measures (2 marks; ½ each, any four)

- Keep doors closed except when charging; use refractory curtains or fibre door seals.

- Maintain slightly positive furnace pressure to prevent cold air infiltration through openings.
- Reduce wall losses with back-up insulation, ceramic fibre veneers or high-emissivity coatings.
- Seal cracks and inspection ports; repair refractory regularly.
- Schedule production to avoid idle heating; improve loading so the furnace is not under-loaded.

Marking note: $\pm 1\%$ tolerance on numerical values.

L-4 [2P2CEM062 | Chapter 7: Cogeneration | Primary energy saving from a back-pressure cogeneration scheme]

A paper mill needs 6 MW of electricity and 27 MW of process heat (as low-pressure steam) continuously for 8,000 h/yr. Two options are compared:

Option 1 (separate production): power from the grid generated at 33% efficiency in a coal-fired condensing station; process heat from an on-site boiler of 85% efficiency.

Option 2 (cogeneration): a high-pressure boiler of 87% efficiency feeds a back-pressure steam turbine; turbine exhaust supplies the full 27 MW process heat. Mechanical $\times$ generator efficiency is 95% (turbine internal losses remain in the exhaust steam and are used by the process).

- Calculate the primary fuel energy required for Option 1. (3 Marks)
- Calculate the fuel energy required for Option 2. (3 Marks)
- Calculate the primary energy saving (MW and %), annual saving in toe, and the energy utilisation factor of Option 2. (2 Marks)
- Check the heat-to-power ratio and comment on the suitability of a back-pressure turbine. (2 Marks)

L-4 Ans (model answer with marking scheme)

Given: $P = 6$ MW; process heat $H = 27$ MW; $\eta_{\text{grid}} = 0.33$; $\eta_{\text{boiler(separate)}} = 0.85$; $\eta_{\text{boiler(cogen)}} = 0.87$; $\eta_{\text{mech} \times \text{gen}} = 0.95$; 8,000 h/yr; 1 toe = 10^7 kcal; 1 kWh = 860 kcal ($\approx 3,601$ kJ).

a) Option 1 – separate production (3 marks)

Formula: $\text{Fuel} = P/\eta_{\text{grid}} + H/\eta_{\text{boiler}}$

Substitution: Fuel for power = $6/0.33 = 18.18$ MW [1 mark]; fuel for heat = $27/0.85 = 31.76$ MW [1 mark]

Result: **Option 1 fuel ≈ 49.95 MW** [1 mark]

b) Option 2 – cogeneration (3 marks)

Formula: Energy into steam = $P/\eta_{\text{mech} \times \text{gen}} + H$; fuel = energy into steam/ η_{boiler}

Substitution: Energy into steam = $6/0.95 + 27 = 6.32 + 27 = 33.32$ MW [1 mark]; fuel = $33.32/0.87$ [1 mark]

Result: **Option 2 fuel ≈ 38.29 MW** [1 mark]

c) Saving and EUF (2 marks)

Formula: Saving = $\text{Fuel}_1 - \text{Fuel}_2$; % = $\text{saving}/\text{Fuel}_1 \times 100$; toe = $\text{saving (kWh)} \times 860/10^7$; EUF = $(P + H)/\text{Fuel}_2$

Substitution: Saving = $49.95 - 38.29 = 11.65$ MW (23.3%); annual = $11,650 \text{ kW} \times 8,000 \text{ h} = 9.32$ crore kWh; toe = $9,32,20,000 \times 860/10^7 = 8,017$ toe [1 mark]; EUF = $(6 + 27)/38.29$

Result: **Primary energy saving ≈ 11.65 MW ($\approx 23\%$) $\approx 8,017$ toe/yr (≈ 336 TJ/yr); EUF $\approx 86\%$** [1 mark]

d) Heat-to-power ratio (2 marks)

Formula: $H:P = \text{process heat/power}$

Substitution: $H:P = 27/6$

Result: **H:P = 4.5**, within the 4.0–14.3 range given in the guidebook for back-pressure steam turbines, so the scheme is technically matched [1 mark]. Since H:P is near the lower end, power output is limited by steam demand; if more power is needed later, an extraction-condensing turbine or a gas turbine with HRSG (lower H:P) can be considered, and any shortfall/surplus power is balanced through the grid [1 mark].

Marking note: $\pm 1\%$ tolerance; award marks if the student treats turbine internal losses as recovered in exhaust steam with a stated assumption.

L-5 [2P2CEM063 | Chapter 8: Waste Heat Recovery | Heat wheel for fresh-air pre-cooling in an air-conditioned plant]

A pharmaceutical formulation block takes 20,000 m³/h of 100% fresh air into its air handling units and exhausts the same quantity of conditioned room air. A rotary heat wheel is proposed between the exhaust and fresh-air streams. Data:

Parameter	Value
Air density	1.15 kg/m ³
Outdoor air (summer design)	40 °C, enthalpy 21.5 kcal/kg
Exhaust (room) air	24 °C, enthalpy 13.0 kcal/kg
Specific heat of air	0.24 kcal/kg °C
Wheel effectiveness (sensible and total)	70%
Chiller specific power	0.9 kW/TR
Additional fan + wheel drive power	7.5 kW
Operating hours	6,000 h/yr
Power tariff	₹ 8 per kWh
Installed cost of heat wheel	₹ 30,00,000

- Calculate the sensible heat recovered by a sensible-only wheel in kcal/h and TR. (3 Marks)
- Calculate the total (sensible + latent) heat recovered by an enthalpy wheel in kcal/h and TR. (3 Marks)
- For the enthalpy wheel, calculate the net power saving, annual saving and simple payback. (2 Marks)
- State two design precautions for using heat wheels in pharmaceutical facilities. (2 Marks)

L-5 Ans (model answer with marking scheme)

Given: $V = 20,000 \text{ m}^3/\text{h}$; $\rho = 1.15 \text{ kg/m}^3$; $t_{\text{out}} = 40 \text{ °C}$, $h_{\text{out}} = 21.5 \text{ kcal/kg}$ ($\approx 90.0 \text{ kJ/kg}$); $t_{\text{room}} = 24 \text{ °C}$, $h_{\text{room}} = 13.0 \text{ kcal/kg}$ ($\approx 54.4 \text{ kJ/kg}$); $C_p = 0.24 \text{ kcal/kg °C}$ ($\approx 1.00 \text{ kJ/kg·K}$); $\epsilon = 0.70$; 0.9 kW/TR ; extra power = 7.5 kW ; $6,000 \text{ h/yr}$; ₹ $8/\text{kWh}$; cost = ₹ $30,00,000$; $1 \text{ TR} = 3,024 \text{ kcal/h}$ ($\approx 3.52 \text{ kW}$).

a) Sensible recovery (3 marks)

Formula: $m = V \times \rho$; $Q_s = \epsilon \times m \times C_p \times (t_{\text{out}} - t_{\text{room}})$; $\text{TR} = Q/3,024$

Substitution: $m = 20,000 \times 1.15 = 23,000 \text{ kg/h}$ [1 mark]; $Q_s = 0.70 \times 23,000 \times 0.24 \times (40 - 24) = 0.70 \times 23,000 \times 0.24 \times 16$ [1 mark]

Result: **Sensible recovery $\approx 61,824 \text{ kcal/h}$ ($\approx 71.9 \text{ kW}$) $\approx 20.4 \text{ TR}$ ($\approx 71.7 \text{ kW}$)** [1 mark]

b) Total (enthalpy) recovery (3 marks)

Formula: $Q_t = \epsilon \times m \times (h_{\text{out}} - h_{\text{room}})$

Substitution: $Q_t = 0.70 \times 23,000 \times (21.5 - 13.0) = 0.70 \times 23,000 \times 8.5$ [1 mark]

Result: **Total recovery $\approx 1,36,850 \text{ kcal/h}$ ($\approx 159 \text{ kW}$)** [1 mark] **$\approx 45.3 \text{ TR}$ ($\approx 159 \text{ kW}$)**, more than double the sensible-only wheel because humid outdoor air carries large latent heat [1 mark]

c) Net saving and payback (2 marks)

Formula: Chiller power saved = $\text{TR} \times \text{kW/TR}$; net = saved – extra power; annual ₹ = net $\times$ hours $\times$ tariff; payback = cost/annual ₹

Substitution: Saved = $45.25 \times 0.9 = 40.7 \text{ kW}$; net = $40.7 - 7.5 = 33.2 \text{ kW}$; annual = $33.23 \times 6,000 \times 8 = ₹ 15,95,000$ [1 mark]; payback = $30,00,000/15,95,000$

Result: **Net saving $\approx 33.2 \text{ kW}$ $\approx ₹ 15.95 \text{ lakh/yr}$; payback $\approx 1.9 \text{ years}$** ; chiller capacity can also be reduced by about 45 TR ($\approx 158 \text{ kW}$) in new projects [1 mark]

d) Design precautions (2 marks; 1 each, any two)

- Minimise cross-contamination: use a purge sector, keep fresh-air side at higher pressure than exhaust side, and check leakage — or choose a heat pipe / run-around coil where zero carry-over is mandatory.
- Provide filters on both streams and bypass/stop the wheel when outdoor conditions make recovery negative (economiser mode).
- Select wheel material and desiccant compatible with cleaning agents and solvent vapours in the exhaust.

Marking note: $\pm 1\%$ tolerance on numbers; any two sound precautions earn full marks in (d).

L-6 [2P2CEM064 | Chapter 9: Heat Exchangers | Pinch analysis: minimum utility targets by problem table]

A specialty chemicals plant has the following process streams. The minimum approach temperature ($\Delta T_{\min}$) is 10 °C. CP is the heat capacity flow rate (mass flow $\times$ specific heat).

Stream	Type	Supply temperature (°C)	Target temperature (°C)	CP (kW/K)
H1	Hot	180	60	3.0
H2	Hot	150	30	1.5
C1	Cold	20	135	2.0
C2	Cold	70	160	4.0

- a) Calculate the total heating and cooling duties of the streams and the shifted temperature intervals. (3 Marks)
- b) Construct the problem table (heat cascade). (4 Marks)
- c) Determine the minimum hot utility, minimum cold utility and the pinch temperatures. (2 Marks)
- d) Compare with the present situation where all heating is by steam and all cooling by cooling water. (1 Mark)

L-6 Ans (model answer with marking scheme)

Given: H1: 180 $\rightarrow$ 60 °C, CP 3.0; H2: 150 $\rightarrow$ 30 °C, CP 1.5; C1: 20 $\rightarrow$ 135 °C, CP 2.0; C2: 70 $\rightarrow$ 160 °C, CP 4.0 (kW/K); $\Delta T_{\min}$ = 10 °C.

a) Duties and shifted temperatures (3 marks)

Formula: Duty = CP $\times$ ΔT ; shifted temperature: hot streams – $\Delta T_{\min}/2$, cold streams + $\Delta T_{\min}/2$

Substitution: H1 = 3.0 $\times$ 120 = 360 kW; H2 = 1.5 $\times$ 120 = 180 kW; total hot = 540 kW. C1 = 2.0 $\times$ 115 = 230 kW; C2 = 4.0 $\times$ 90 = 360 kW; total cold = 590 kW [1 mark]

Shifted: H1 175 $\rightarrow$ 55; H2 145 $\rightarrow$ 25; C1 25 $\rightarrow$ 140; C2 75 $\rightarrow$ 165 °C. Interval boundaries: 175, 165, 145, 140, 75, 55, 25 °C [2 marks]

b) Problem table (4 marks)

Formula: For each interval, $\Delta H = (\Sigma CP_{\text{hot}} - \Sigma CP_{\text{cold}}) \times \Delta T$; cascade heat from the top starting with zero hot utility

Interval (shifted °C)	Streams present	$\Sigma CP_{\text{hot}} - \Sigma CP_{\text{cold}}$ (kW/K)	ΔH (kW)	Cascade (kW)	Feasible cascade (kW)
175–165	H1	+3.0	+30	30	115
165–145	H1, C2	–1.0	–20	10	95
145–140	H1, H2, C2	+0.5	+2.5	12.5	97.5
140–75	H1, H2, C1, C2	–1.5	–97.5	–85	0 (pinch)
75–55	H1, H2, C1	+2.5	+50	–35	50
55–25	H2, C1	–0.5	–15	–50	35

[1 mark for intervals and streams, 2 marks for ΔH values, 1 mark for cascade]

c) Utility targets and pinch (2 marks)

Formula: $Q_{H,min} = -(\text{most negative cascade value})$; $Q_{C,min} = \text{final cascade value} + Q_{H,min}$

Substitution: Most negative = -85 kW at shifted 75 °C → $Q_{H,min} = 85 \text{ kW}$; $Q_{C,min} = -50 + 85 = 35 \text{ kW}$ [1 mark]

Result: **Minimum hot utility = 85 kW; minimum cold utility = 35 kW; pinch at shifted 75 °C, i.e. hot-stream pinch 80 °C and cold-stream pinch 70 °C** [1 mark]

Check: $Q_H - Q_C = 85 - 35 = 50 \text{ kW} = \text{total cold duty} - \text{total hot duty} (590 - 540) \checkmark$

d) Comparison (1 mark)

Result: **Without integration: steam 590 kW and cooling water 540 kW; with pinch targets: 85 kW and 35 kW — about 505 kW ($\approx 86\%$) of steam and $\approx 93.5\%$ of cooling water can be saved by heat recovery** [1 mark]

Marking note: method marks for correct shifting and cascading even with arithmetic slips; $\pm 1 \text{ kW}$ tolerance.

..... End of Section III

Answer key – Section I

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