Assignment 2: Packed-Tower Wet Scrubber Design Report - SO_2 Removal

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Objective: Design a counter-current packed-tower wet scrubber to remove **95% SO_2** from a small boiler flue gas using aqueous NaOH scrubbing liquor. The numbers in this report represent realistic plant-scale values and were used to produce the calculations.

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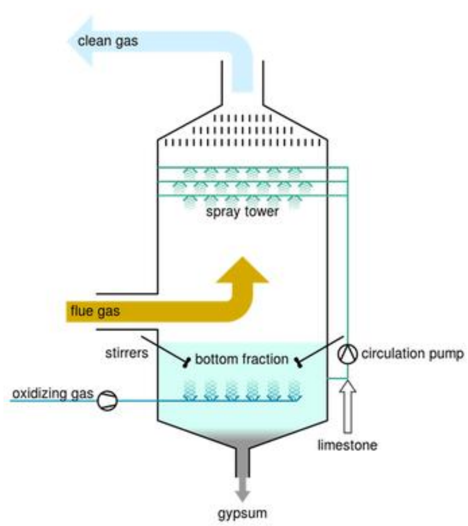
1. Working principle of wet (packed) scrubbers — (first page summary)

A wet packed-tower scrubber removes soluble or reactive gaseous pollutants (here SO_2) by contacting the polluted gas with a downward flowing liquid absorbent (here aqueous NaOH) across a packed bed.

Key phenomena and steps:

1. **Gas–liquid contact:** The gas enters at the bottom and flows counter-currently to the liquid that is introduced at the top. The packing (random or structured) creates high interfacial area and turbulence to promote mass transfer.
2. **Mass transfer:** Pollutant molecules transfer from the bulk gas to the gas-film, across the gas–liquid interface, then into the bulk liquid. For reactive scrubbing (SO_2 + NaOH), the chemical reaction in the liquid enhances driving force and increases overall uptake (often making the process liquid-film or reaction controlled).
3. **Chemical reaction:** SO_2 reacts with OH^- in the scrubbing liquor to form sulfite/bisulfite/sulfate species, consuming NaOH according to stoichiometry.
4. **Droplet disengagement:** Gas leaving the top passes through a mist eliminator to remove entrained droplets, preventing carryover and loss of scrubbing liquor.
5. **Recirculation and bleed:** The spent liquor is collected in a sump, pumped back (recirculation) through the distributor, and makeup NaOH is added to replace stoichiometric consumption. A controlled bleed prevents salt buildup.

Advantages of packed scrubbers: compact, efficient for gas-liquid contact, low liquid holdup (compared with trays), relatively low maintenance for corrosive systems when using appropriate materials.



2. Design basis (plant-realistic inputs)

- Flue gas volumetric flow (scrubber inlet, dry basis): **Q = 20,000 m^3/h** (5.5556 m^3/s).
- Inlet SO_2 concentration: **y_1 = 1,000 ppmv (0.001 mole fraction)**.
- Target removal: **95%** → **$y_2 = 0.05 \cdot y_1$ = 0.00005 mole fraction**.
- Inlet temperature: **T = 50 °C (323.15 K)**; pressure **1.0 atm**.
- Scrubbing liquid: **aqueous NaOH, 1.5 wt% (recirculated)**.
- Chosen gas superficial velocity (initial design): **U_g = 2.0 m/s** (conservative for packed towers).
- Packing: random or structured (vendor selection later); initial design reports active packing height and diameter.

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3. Calculation summary (detailed steps)

3.1 Cross-sectional area and column diameter

- Q = 20,000 m^3/h = 5.5556 m^3/s. With U_g = 2.0 m/s → $A = Q/U_g = 5.5556/2.0 = 2.7778$ m^2.
- Column diameter: $D = \sqrt{4A/\pi} = 1.881$ m → pick **D = 1.9 m** (practical).

3.2 Molar gas flow and molar flux

Ideal gas law at 50 °C, 1 atm:

- $\dot{n} = (QP)/(RT)$. Numerically: $QP \approx 20{,}000 \times 101{,}325 = 2.0265 \times 10^9$ (Pa·m^3/h) and $RT \approx 8.31446 \times 323.15 = 2{,}686.8$. So $\dot{n} \approx 2.0265 \times 10^9/2{,}686.8 = 754{,}650$ mol/h = **754.65 kmol/h**.
- Molar gas flux (per area): $G_M = \dot{n}/A = 754.65/2.7778 = 271.7$ kmol/(h·m^2).

3.3 Mass-transfer parameter (KGa) — Perry's representative value and conversion

- Perry's experimental table gives a representative **KGa ≈ 7.0 (lb-mol)/(h·ft^3·atm)** for SO_2/NaOH packed-tower data.
- Convert to SI: 1 (lb-mol)/(h·ft^3·atm) ≈ 16.02 kmol/(h·m^3·atm). So $\text{KGa}_{SI} \approx 7.0 \times 16.02 = 112.14$ kmol/(h·m^3·atm).

3.4 Hg and NTU → packing height

- $H_G = G_M/(KGa) = 271.7/112.14 = 2.423$ m.
- NTU for 95% removal: $\ln(y_1/y_2) = \ln(20) = 2.9957$.
- Required active packing height: $h_T = H_G \times NTU = 2.423 \times 2.9957 = 7.26$ m.

Design pick: Active packing height = 7.5 m (round up). Add internals/disengagement/sump → **overall shell ≈ 9–10 m**.

4. Hydraulic & equipment checks

4.1 Pressure drop (estimate)

- Representative ΔP for random packing at moderate velocity: ~0.3–0.4 kPa/m (conservative). Using 0.326 kPa/m: $\Delta P_{packing} \approx 0.326 \times 7.3 = 2.38$ kPa. Add losses → **total ΔP ≈ 3.0 kPa**.

4.2 Fan power

- Hydraulic power = Q·ΔP = 5.5556 m^3/s × 3,000 Pa = 16,667 W ≈ **16.7 kW**.
- Assuming overall fan+motor efficiency ≈ 60% → electrical power ≈ 16.7/0.6 = **27.8 kW** → choose **30 kW motor**.

5. Liquid system, stoichiometry & recirculation

- Total SO_2 molar inlet = $y_1 \times \dot{n}$ = 0.001 × 754.65 = **0.75465 kmol/h** = 754.65 mol/h.
- 95% removal → reacted SO_2 = 0.95×754.65 = **717.9 mol/h**.
- Reaction (SO_2 + 2 NaOH → products) → NaOH consumption = 2 × 717.9 = **1,435.8 mol/h**.
- NaOH mass makeup = 1,435.8 × 40 g/mol = **57.4 kg/h**.

Recirculation: choose **30 m^3/h** of 1.5 wt% NaOH as a starting practical recirc rate (this provides surface wetting, KGa enhancement and buffer between makeup and liquor composition).

6. Packing selection, materials & internals (recommendations)

- **Packing:** structured or random depending on cost and ΔP target. Vendor data to confirm KGa/HETP.
- **Shell & internals:** FRP-lined carbon steel or stainless steel. Include a redistributor if packing > 4 m tall
- **Instrumentation:** pH, temperature, level, NaOH dosing, flow, and pressure indicators.
- **Operation:** Maintain pH > 9 for SO_2 absorption efficiency; treat bleed for sulfite/sulfate disposal.

7. References:

- Perry's handbook experimental KGa and packing tables were used to take data.
- Section 14: *Gas Absorption and Gas–Liquid System Design* — equations (14-76), HETP/HOG relations.
- Tables 14-3 / 23-6: KGa for SO_2–NaOH systems.
- Figures 14-48 → 14-53: packing pressure-drop and capacity charts.
- Table 14-7: packing characteristics and factors.