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Heat Transfer and Fluid Flow Calculations of Industrial Shell Boilers and Evaluation of Operation Conditions

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Agenda

- ▶ Problem & objectives
- ▶ Boiler configuration (HX1–HX6)
- ▶ Modeling framework (combustion, heat transfer, hydraulics)
- ▶ Sanity checks / validation posture
- ▶ Key results: control case + parametric trends
- ▶ Conclusions, limitations

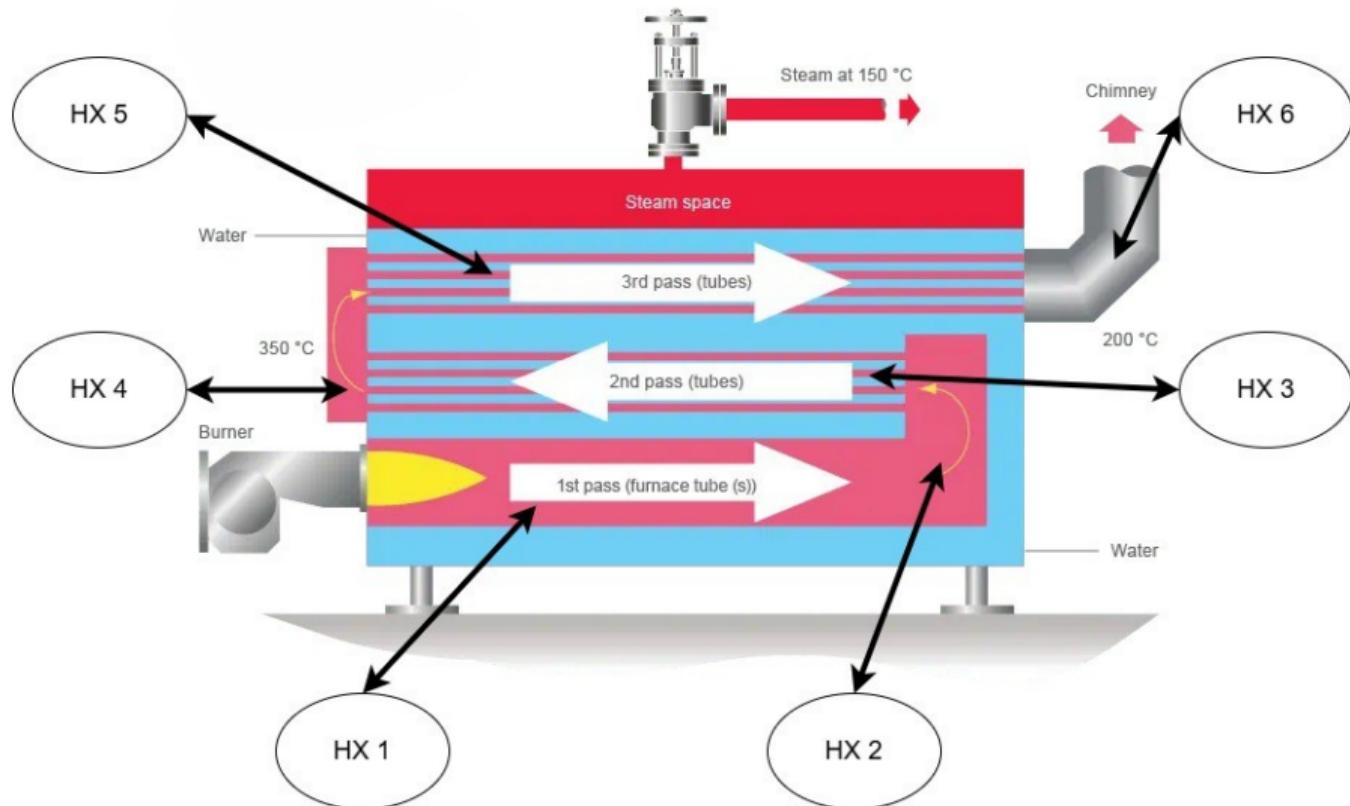
Motivation & problem statement

- ▶ Industrial shell boilers are common (6–25 bar, ~0.5–20 t/h typical)
- ▶ Performance is set by **coupled physics**:
 - ▶ combustion → flue-gas properties & heat input
 - ▶ multi-stage convection + radiation
 - ▶ geometry-driven pressure losses
- ▶ Need a **fast, physics-based tool** for:
 - ▶ efficiency/stack temperature prediction
 - ▶ steam capacity under varying operation
 - ▶ sensitivity to key parameters (λ , pressure, firing rate, fouling)

Boiler configuration: three-pass + economizer (HX1–HX6)

- ▶ Gas-side stages (sequential):
 - ▶ **HX1** furnace → **HX2** reversal → **HX3** tube-bank → **HX4** reversal → **HX5** tube-bank → **HX6** economizer → stack
- ▶ Water/steam side:
 - ▶ HX1–HX5: **pool boiling at drum saturation**
 - ▶ HX6: **single-phase feedwater heating**

Shell boiler labeled stages

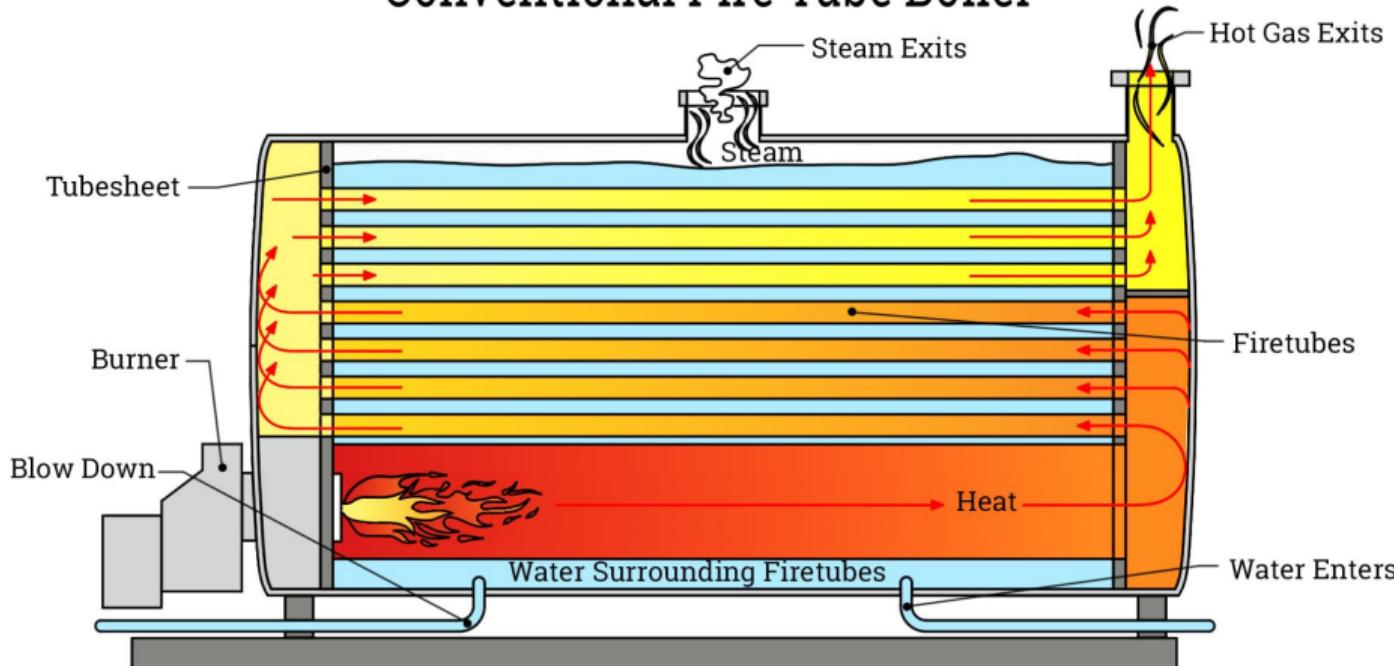


Boiler geometry context (cross-section)

- ▶ Drum: ~4.5 m ID, ~5 m length (modeled as saturated reservoir)
- ▶ Stages use geometry from config/stages.yaml (diameters, lengths, tube counts)
- ▶ Includes wall conduction + fouling layers in the thermal resistance network

Boiler cross section

Conventional Fire Tube Boiler

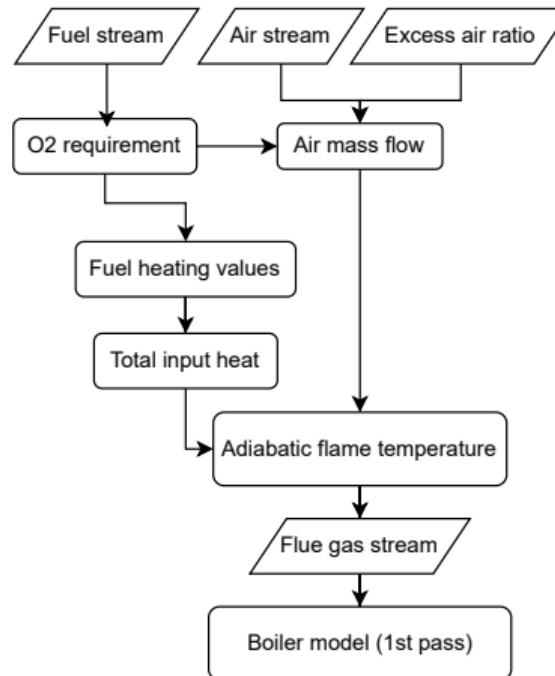


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Model architecture (Python framework)

- ▶ Inputs (YAML):
 - ▶ fuel composition + \dot{m}_{fuel} , excess air λ , drum pressure
 - ▶ stage geometries + loss coefficients + fouling factor
- ▶ Main modules:
 - ▶ **Combustion** (Cantera): T_{ad} , flue-gas c_p , μ , k , composition, Q_{in}
 - ▶ **HX solver**: 1D marching, resistance network, radiation+convection
 - ▶ **Hydraulics**: stage-wise ΔP with correlations + minor losses
 - ▶ **Postproc**: boiler KPIs + stage summaries

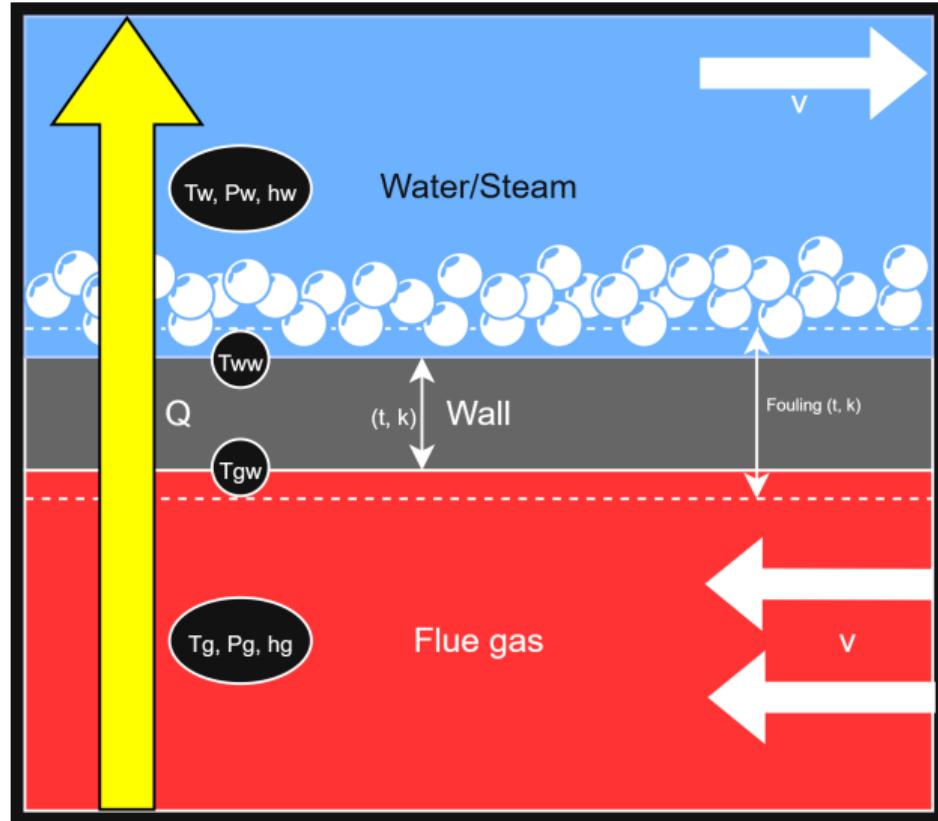
Combustion flow



Heat-transfer model: 1D marching + resistance network

- ▶ Counter-current, stage-wise 1D marching in x :
 - ▶ $q'(x) = UA'(x) [T_g(x) - T_w(x)]$
 - ▶ update h_g, h_w via $\Delta h_g = -Q/\dot{m}_g$, $\Delta h_w = +Q/\dot{m}_w$
- ▶ Overall conductance per length from series resistances:
 - ▶ gas convection + **gas radiation** + fouling + wall + water-side HTC
- ▶ Regimes:
 - ▶ gas: internal convection (HX1–HX5), crossflow bank (HX6)
 - ▶ water: pool boiling (HX1–HX5), single-phase internal flow (HX6)

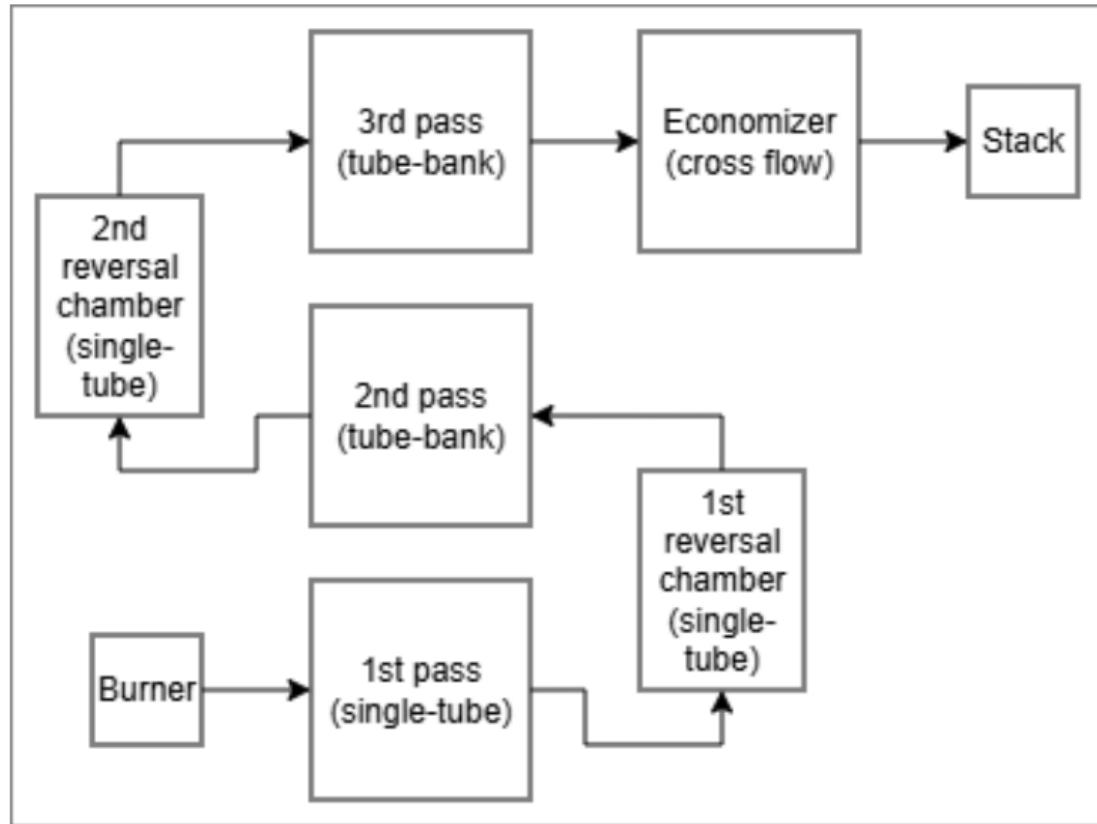
Heat transfer resistance network



Gas/water properties + radiation handling

- ▶ Gas properties: **Cantera** mixture at local T, P (c_p, μ, k, ρ)
- ▶ Water/steam properties: **IAPWS-IF97** (saturation $T_{\text{sat}}(P)$, h_f, h_g , single-phase liquid props)
- ▶ Radiation model (gray-gas bands):
 - ▶ participating media CO_2/H_2O , banded emissivity $\varepsilon_g(T, p_i, L_b)$
 - ▶ linearized: $h * g, \text{rad} = 4\sigma F \varepsilon_g T * \text{film}^3$

Gas path through stages



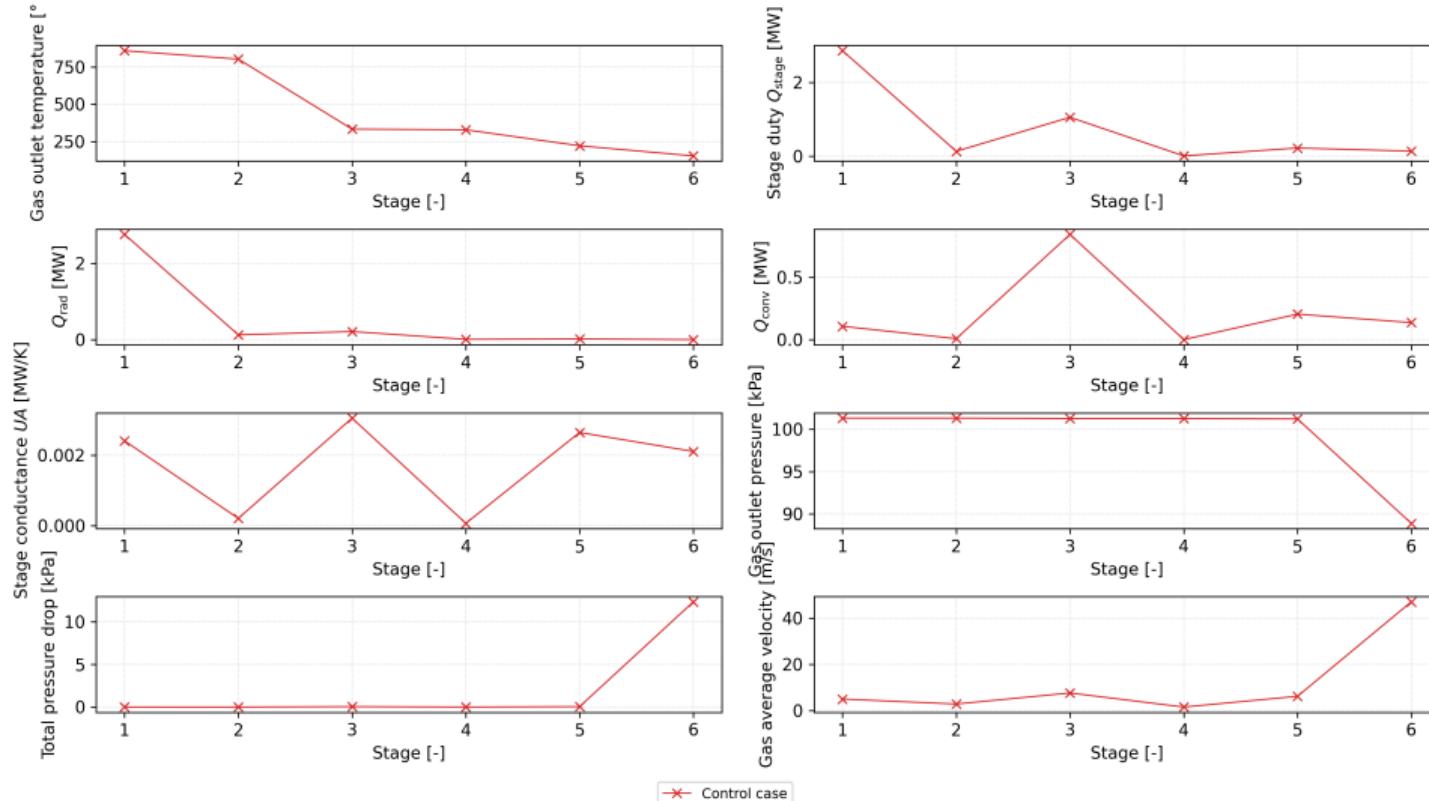
Hydraulics: pressure-drop model and coupling

- ▶ Per-step decomposition:
 - ▶ friction: $\Delta P_{\text{fric}} = -f \frac{\Delta x}{D_h} (\rho V^2 / 2)$
 - ▶ minor losses: $\Delta P_{\text{minor}} = -K(\rho V^2 / 2)$
- ▶ Friction factor:
 - ▶ laminar $64/\text{Re}$, turbulent **Colebrook–White** (seeded by Swamee–Jain)
- ▶ Economizer gas side: **tube-bank bundle loss** (drag-based), distributed along L
- ▶ Coupled update: $P_{i+1} = P_i + \Delta P_{\text{total}} \rightarrow$ affects $\rho, \mu, V, \text{Re}, \text{HTCs}$

Sanity checks / validation posture (no dedicated experiment)

- ▶ Numerical consistency:
 - ▶ converged outer loop on η and \dot{m}_w (fixed-point iteration)
 - ▶ global energy balance error ~ 0 (control case table)
- ▶ Physical plausibility:
 - ▶ stack temperature and efficiency in expected industrial ranges for gas-fired fire-tube + economizer
 - ▶ monotonic gas temperature drop $HX1 \rightarrow HX6$; duties highest upstream
- ▶ Stage-wise trends:
 - ▶ radiation fraction highest in $HX1$; convection more important downstream

Stage-wise heat transfer and hydraulics (control)



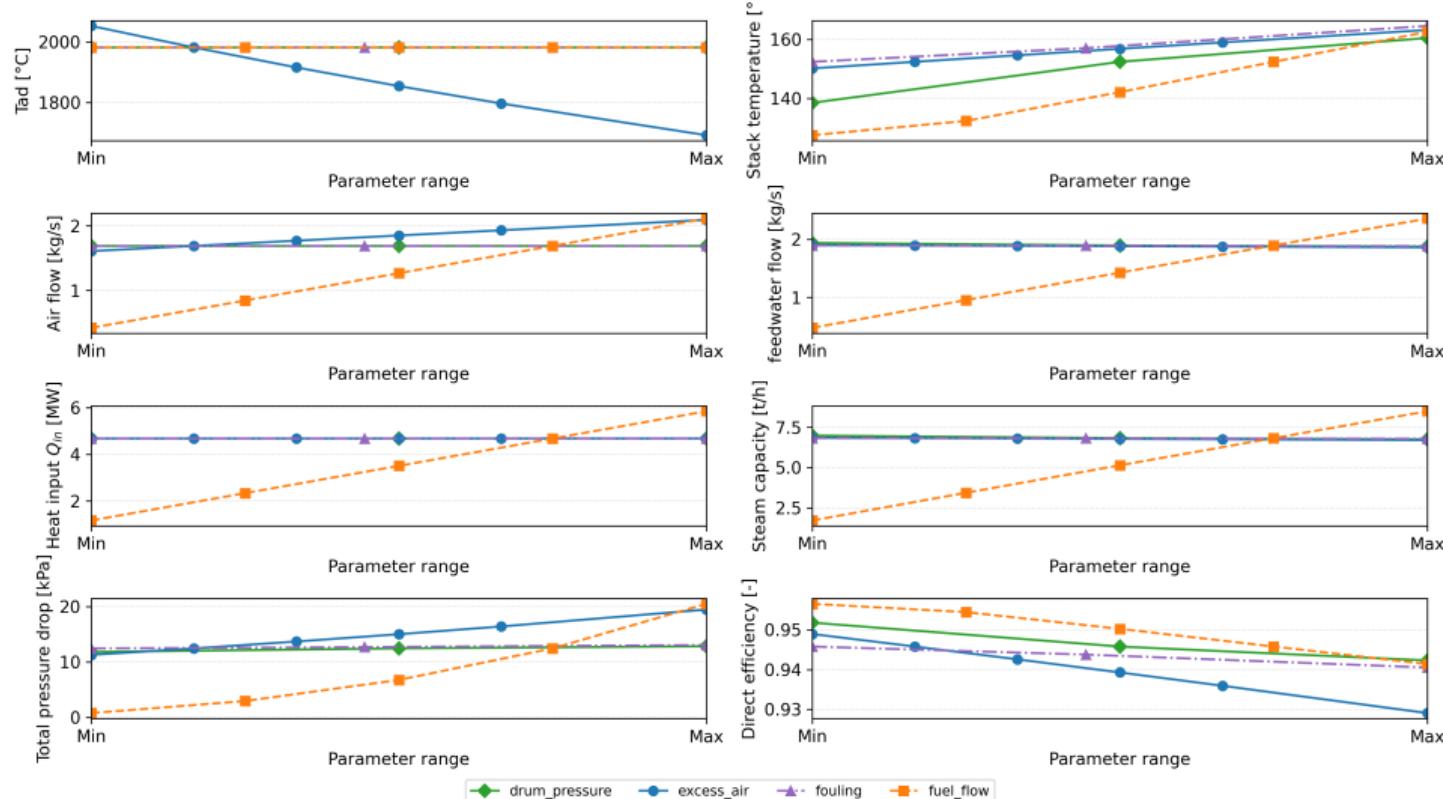
Control case: key performance numbers (reference point)

- ▶ Operating point:
 - ▶ $\dot{m}_{\text{fuel}} = 0.1 \text{ kg/s}$, $\lambda = 1.05$, $P_{\text{drum}} = 10 \text{ bar}$, fouling factor $f = 1$
- ▶ Control-case KPI label:
 - ▶ $\eta \approx 0.95 \text{ (LHV)}$, $Q_{\text{useful}} \approx 4.42 \text{ MW}$, $Q_{\text{in}} \approx 4.68 \text{ MW}$
 - ▶ **Steam $\approx 6.81 \text{ t/h}$** , $T_{\text{stack}} \approx 152^\circ\text{C}$
 - ▶ $\Delta P_{\text{gas}} \approx 12.45 \text{ kPa}$ (economizer dominates)
- ▶ Heat-transfer distribution (stage totals, MW):
 - ▶ HX1: **2.86** (mostly radiative), HX3: **1.06**, HX6: **0.14**

Parametric trends (main findings)

- ▶ Excess air λ :
 - ▶ **shallow efficiency optimum near $\lambda \approx 1.05$**
 - ▶ higher $\lambda \rightarrow$ higher flue mass flow \rightarrow higher stack losses and ΔP
- ▶ Drum pressure:
 - ▶ pressure changes shift **steam quantity more than efficiency**
 - ▶ higher $P \rightarrow$ higher T_{sat} \rightarrow reduced driving $\Delta T \rightarrow$ higher T_{stack}
- ▶ Firing rate (\dot{m}_{fuel}):
 - ▶ duties and steam rate scale **approximately linearly** over practical load range
- ▶ Fouling:
 - ▶ reduces downstream convective recovery \rightarrow **raises T_{stack}** and slightly lowers η

KPI overview across parameter groups



Conclusions & limitations

- ▶ Built a coupled framework:
 - ▶ 3-pass shell boiler as **6 sequential gas-side stages**
 - ▶ combustion + heat-transfer + hydraulics
- ▶ Model reproduces physically consistent behavior:
 - ▶ realistic control case: $\eta \sim 0.95$ (LHV), $T_{\text{stack}} \sim 152^\circ\text{C}$, $\Delta P_g \sim 12.5 \text{ kPa}$
 - ▶ correct directional sensitivities for λ , P , firing rate, fouling
- ▶ Main limitations (scope choices):
 - ▶ steady-state 1D
 - ▶ pool-boiling treated via correlation at saturation; no detailed circulation/separation

Questions

- ▶ Thank you.