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

Saif-Aldain Aqel

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

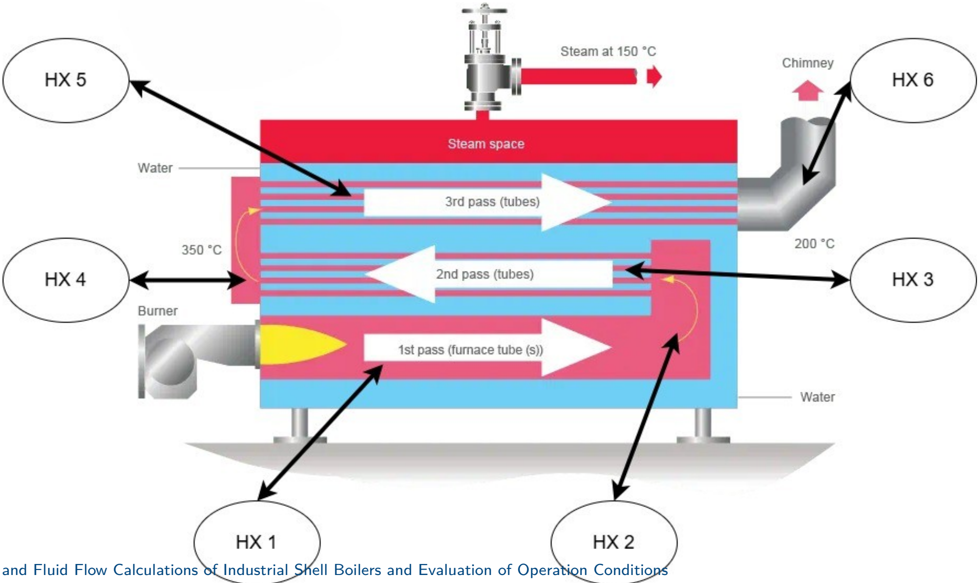
Motivation & problem statement

- Industrial shell boilers are common (6–25 bar, ~0.5–20 t/h typical)
- Performance is set by **coupled physics**:
  - combustion $\rightarrow$ 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**
- What to look at: **stage boundaries** and where the economizer sits downstream

Shell boiler labeled stages



Boiler geometry context (cross-section)

- Drum: $\sim$4.5 m ID, $\sim$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
- What to look at: **furnace tube + tube banks + reversal chambers** locations

Boiler cross section

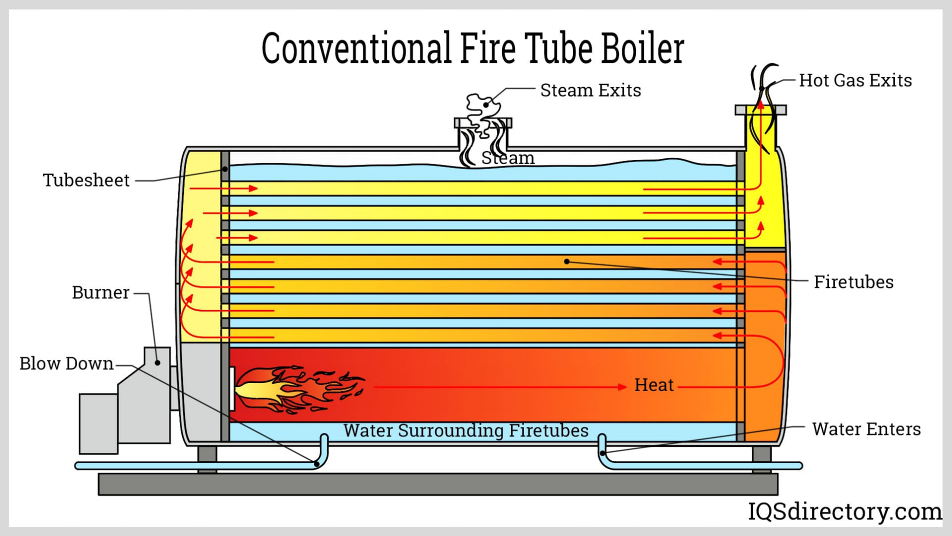
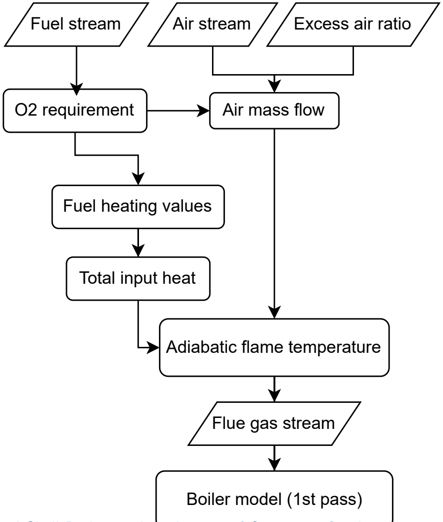


Figure 2: Boiler cross section

Model architecture (Python framework)

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

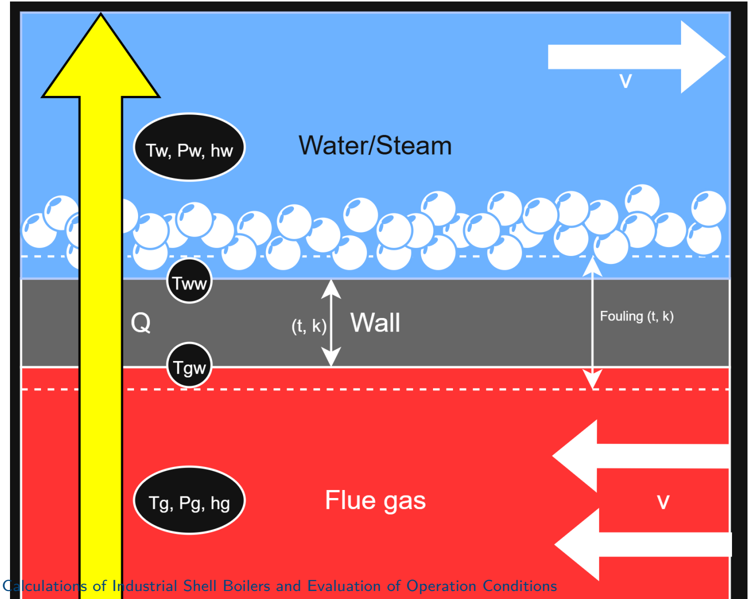
Combustion flow



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)
- What to look at: the **series resistance path** gas $\rightarrow$ wall $\rightarrow$ water

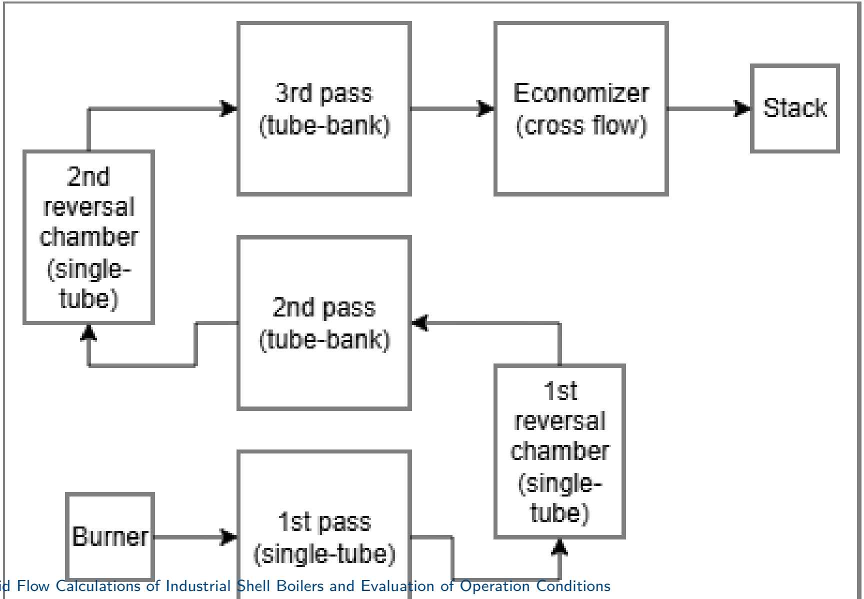
Heat transfer resistance network



Gas/water properties + radiation handling

- Gas properties: **Cantera** mixture at local T, P (c_p, μ, k, ρ)
- Water/steam properties: **IAPWS-IF97** (saturation $T\_\mathrm{sat}(P)$, 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: $h * g, \mathrm{rad} = 4\sigma F \varepsilon_g T * \mathrm{film}^3$
- What to look at: upstream stages are **radiation-dominated**, downstream mostly convection

Gas path through stages



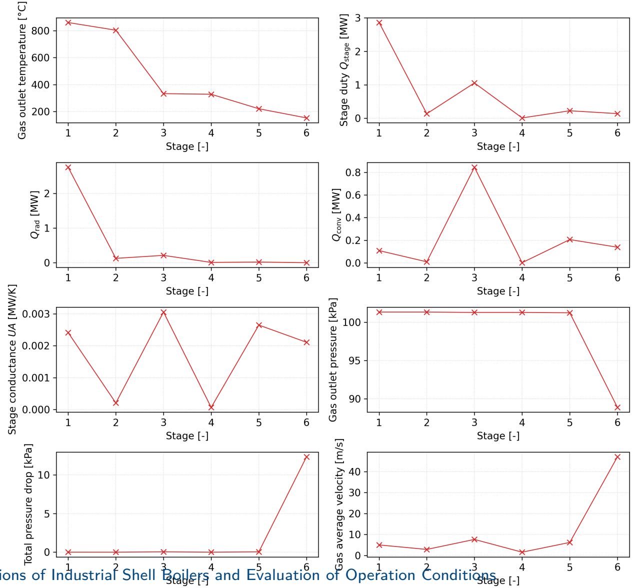
Hydraulics: pressure-drop model and coupling

- Per-step decomposition:
  - friction: $\Delta P\_\mathrm{fric} = -f \frac{\Delta x}{D_h} \left(\rho V^2/2\right)$
  - minor losses: $\Delta P\_\mathrm{minor} = -K(\rho V^2/2)$
- Friction factor:
  - laminar $64/\mathrm{Re}$, turbulent **Colebrook–White** (seeded by Swamee–Jain)
- Economizer gas side: **tube-bank bundle loss** (drag-based), distributed along L
- Coupled update: $P * i + 1 = P_i + \Delta P * \mathrm{total} \rightarrow$ affects ρ, μ, V, Re, 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
- What to look at: stage-wise profiles are smooth and ordered across stages

Stage-wise heat transfer and hydraulics (control)



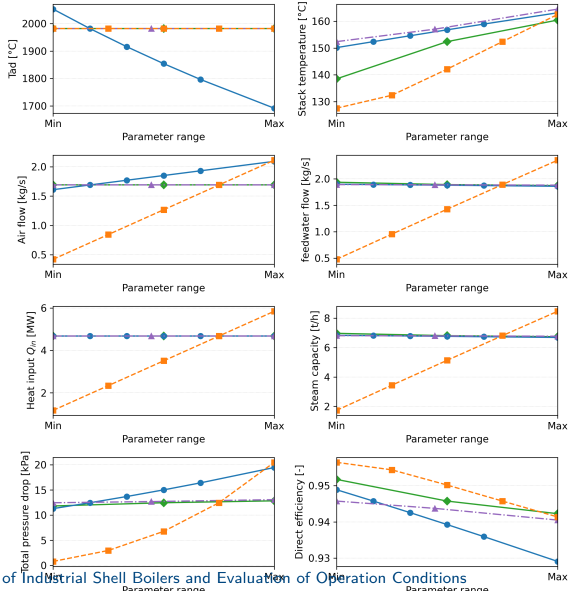
Control case: key performance numbers (reference point)

- Operating point:
  - $\dot{m} * \mathrm{fuel} = 0.1$ kg/s, $\lambda = 1.05$, $P * \mathrm{drum} = 10$ bar, fouling factor $f = 1$
- Control-case KPI label:
  - $\eta \approx 0.95$ **(LHV)**, $Q * \mathrm{useful} \approx 4.42$ MW, $Q * \mathrm{in} \approx 4.68$ MW
  - **Steam** $\approx$ **6.81 t/h**, $T\_\mathrm{stack} \approx 152°\mathrm{C}$
  - $\Delta P\_\mathrm{gas} \approx 12.45$ **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 $T * \mathrm{sat} \rightarrow$ reduced driving $\Delta T \rightarrow$ higher $T * \mathrm{stack}$
- 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 (Cantera) + HT (resistance network + gray-gas radiation) + hydraulics
- Model reproduces physically consistent behavior:
  - realistic control case: $\eta \sim 0.95$ (LHV), $T\_\mathrm{stack} \sim 152^\circ\mathrm{C}$, $\Delta P_g \sim 12.5$ kPa
  - correct directional sensitivities for λ, P, firing rate, fouling
- Main limitations (scope choices):
  - steady-state 1D; simplified radiation (gray bands, no soot)
  - pool-boiling treated via correlation at saturation; no detailed circulation/separation
  - validation is consistency/range-based (no matched experiment)

Questions

- Thank you.