



Budapest University of Technology and Economics  
Faculty of Mechanical Engineering  
Department of Energy Engineering

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

By: Saif-Aldain Aqel

Supervisor: Dr. Lezsovits Ferenc

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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

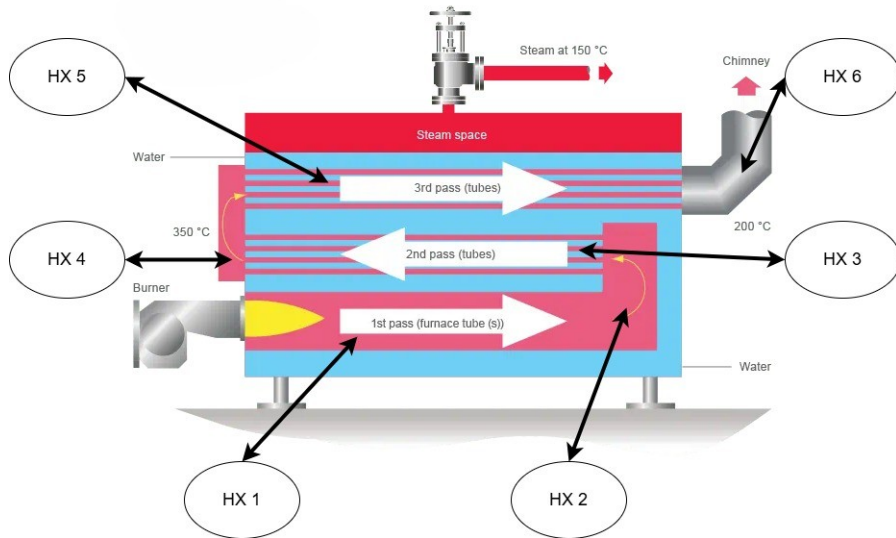
# Motivation & problem statement

- ▶ 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 ( $\lambda$ , 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**

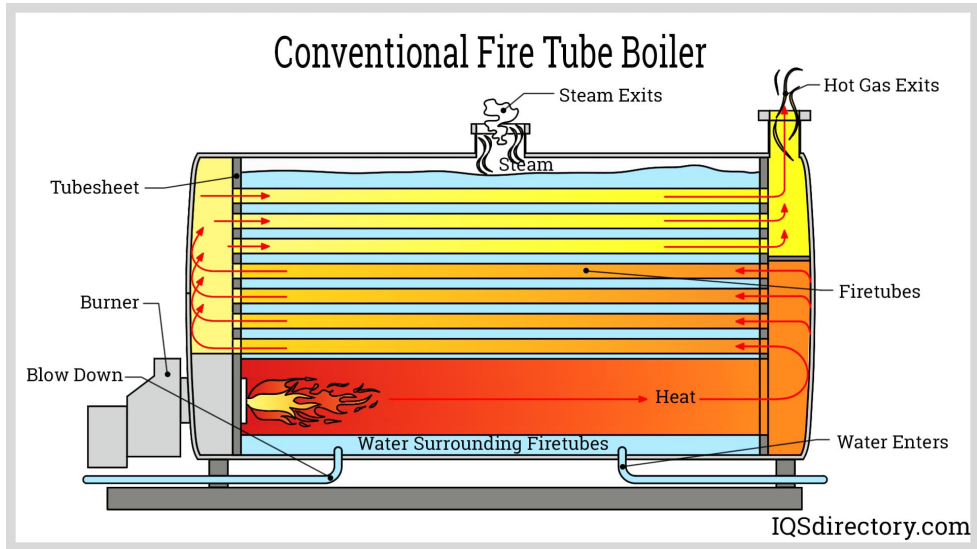
# Shell boiler labeled stages



## Boiler geometry context (cross-section)

- ▶ Drum:  $\sim 4.5$  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

# Boiler cross section

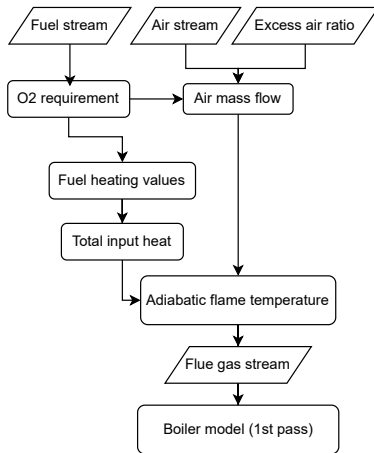


# Model architecture (Python framework)

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



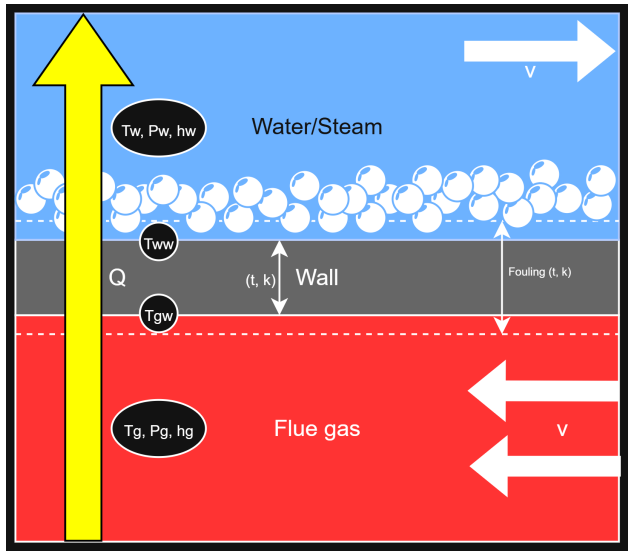
# Combustion flow



# 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)

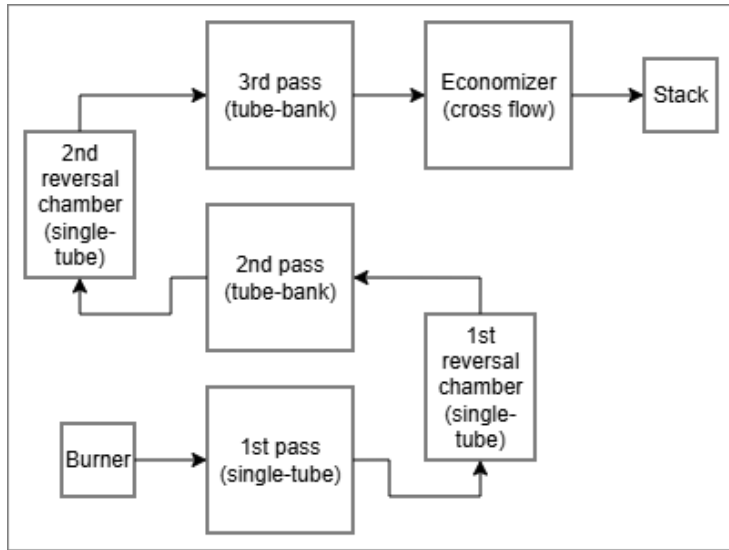
# Heat transfer resistance network



# Gas/water properties + radiation handling

- ▶ Gas properties: **Cantera** mixture at local  $T, P$  (  $c_p, \mu, k, \rho$  )
- ▶ 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  $\text{CO}_2/\text{H}_2\text{O}$ , 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



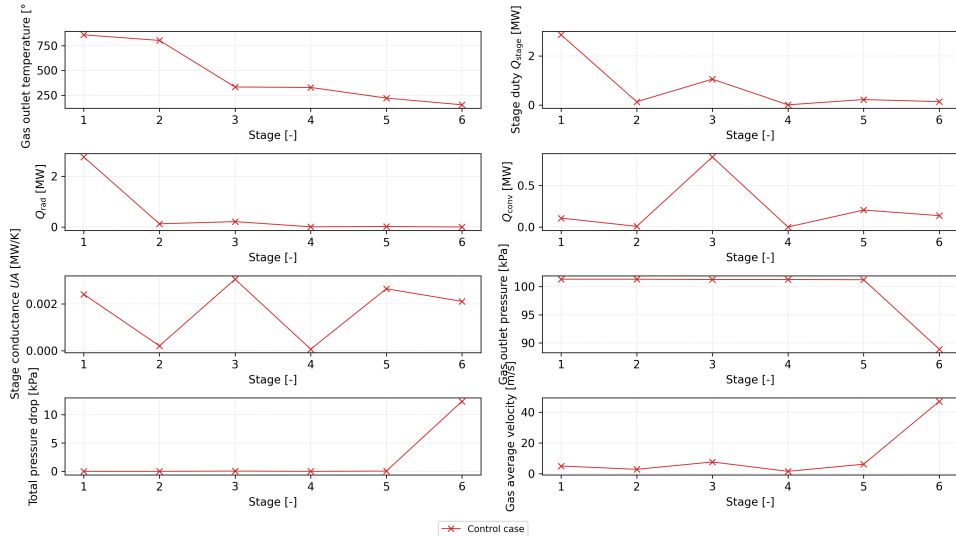
# Hydraulics: pressure-drop model and coupling

- ▶ 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  $\eta$  and  $\dot{m}_w$  (fixed-point iteration)
  - ▶ global energy balance error  $\sim 0$  (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)





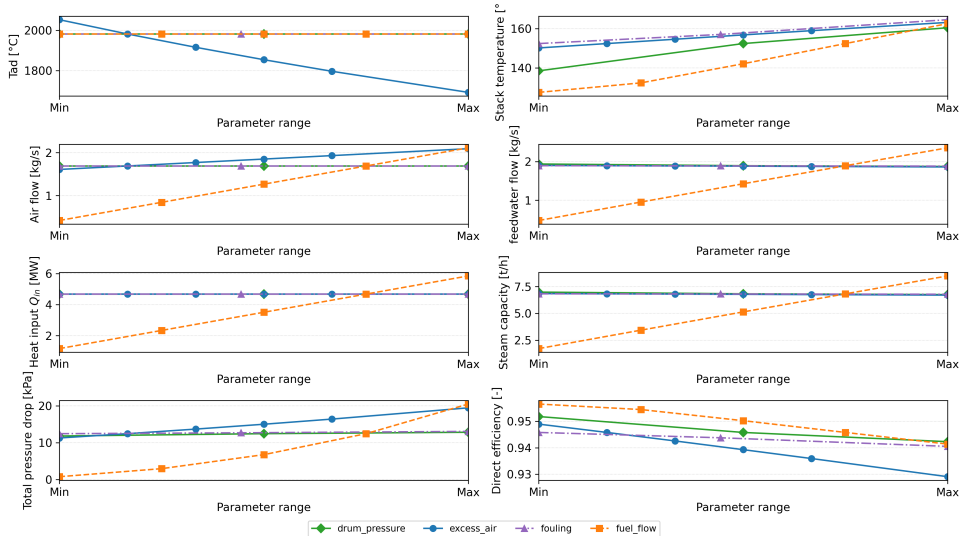
## Control case: key performance numbers (reference point)

- ▶ 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:
  - ▶  $\eta \approx 0.95$  (**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  $\lambda$ :
  - ▶ **shallow efficiency optimum near**  $\lambda \approx 1.05$
  - ▶ higher  $\lambda \rightarrow$  higher flue mass flow  $\rightarrow$  higher stack losses and  $\Delta P$
- ▶ Drum pressure:
  - ▶ pressure changes shift **steam quantity more than efficiency**
  - ▶ higher  $P \rightarrow$  higher  $T_{\text{sat}} \rightarrow$  reduced driving  $\Delta T \rightarrow$  higher  $T_{\text{stack}}$
- ▶ Firing rate ( $\dot{m}_{\text{fuel}}$ ):
  - ▶ duties and steam rate scale **approximately linearly** over practical load range
- ▶ Fouling:
  - ▶ reduces downstream convective recovery  $\rightarrow$  **raises**  $T_{\text{stack}}$  and slightly lowers  $\eta$

# 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),  $T_{\text{stack}} \sim 152^{\circ}\text{C}$ ,  $\Delta P_g \sim 12.5$  kPa
  - ▶ correct directional sensitivities for  $\lambda$ ,  $P$ , firing rate, fouling
- ▶ Main limitations (scope choices):
  - ▶ steady-state 1D
  - ▶ pool-boiling treated via correlation at saturation; no detailed circulation/separation

# Questions

► Thank you.