DTU Compute
Department of Applied Mathematics and Computer Science

OPTIVERSE 2-control

Model-Based Control for the Cement Industry

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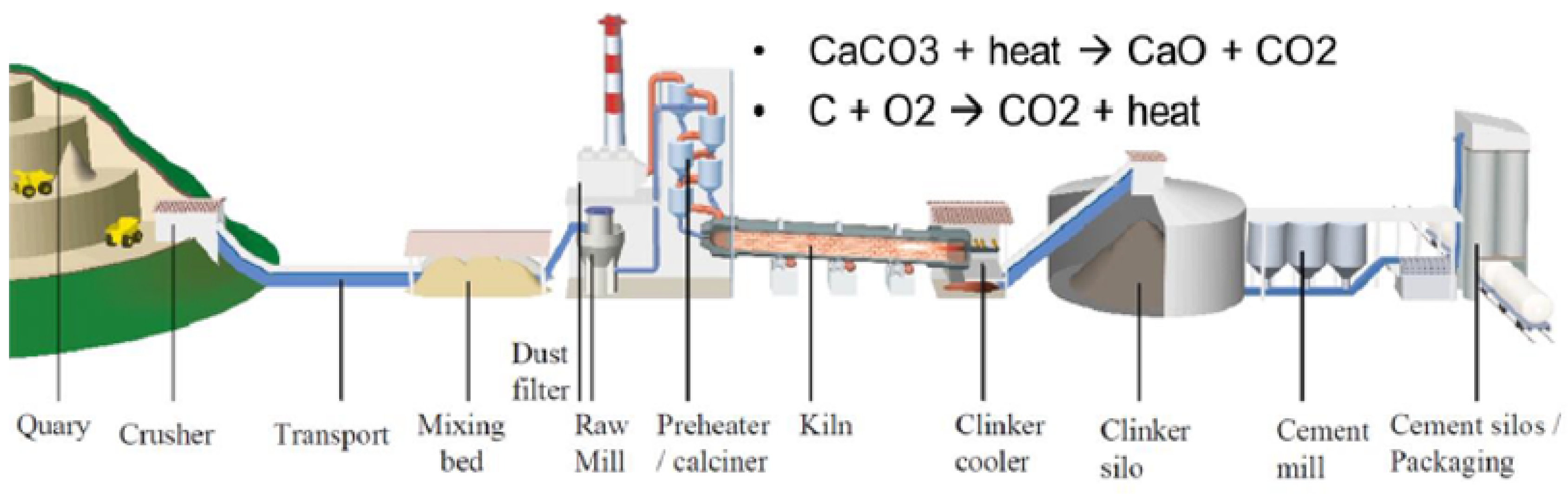
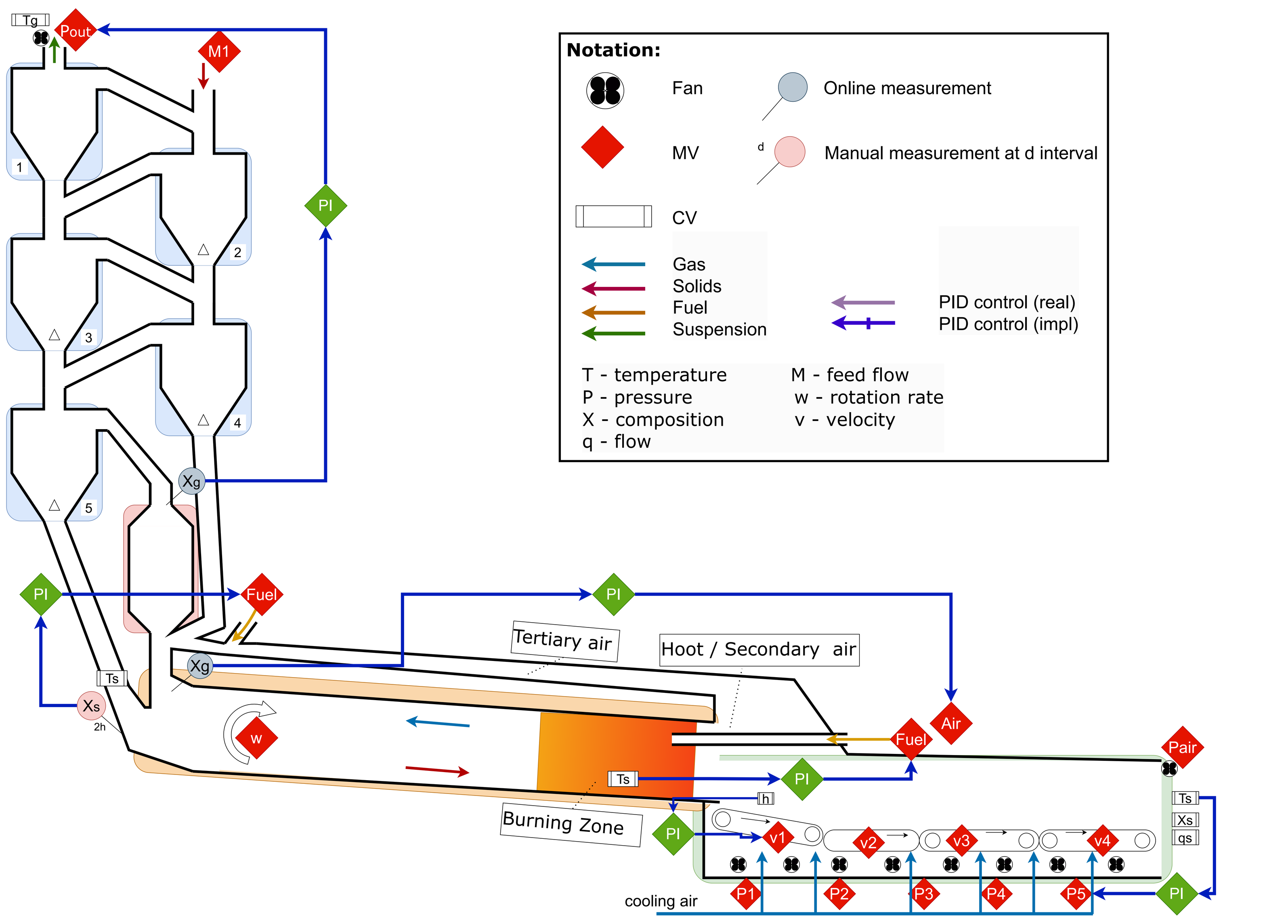
1. Cement manufacturing and the pyro-section





2. DAE of the pyro-section

▶ DAE structure

$$\begin{aligned} \dot{x} &= f(x,y,u) \\ 0 &= g(x,y,u) \\ z &= h(x,y,u) \end{aligned}$$

▶ Mass and energy balances

$$\begin{aligned} \partial_t c &= -\nabla \cdot N + R \\ \partial_t \hat{U} &= -\nabla \cdot \tilde{H} + Q \end{aligned}$$

▶ Algebraic relations

$$\begin{aligned} U(T,P,c) - \hat{U} &= 0 \\ V(T,P,c) - 1 &= 0 \end{aligned}$$

▶ Thermo-physical properties

$$\begin{aligned} V &= V(T,P,n) \\ H &= H(T,P,n) \\ U &= H(T,P,n) - PV(T,P,n) \\ C_p &= C_p(T,n) \\ \rho &= M'c \\ \mu &= \mu(T,n,\hat{V}) \\ k &= k(T,n,\hat{V}) \\ D &= D(T,P,c) \end{aligned}$$

▶ Transport phenomena

$$\begin{aligned} N &= cv - D\nabla c \\ \tilde{H} &= H(T,P,N) - k\nabla T \\ v &= v(\nabla P, \mu, \rho) \\ Q &= Q(T,P,n,k,\mu,\rho,C_p) \end{aligned}$$

▶ Reaction and production rates

$$R = \nu' r(T,P,c)$$

▶ Clinker formation reactions

$$\begin{aligned} CaCO_3 &\rightarrow CO_2 + CaO \\ 2CaO + SiO_2 &\rightarrow C_2S \\ CaO + C_2S &\rightleftharpoons C_3S \\ 3CaO + Al_2O_3 &\rightarrow C_3A \\ 4CaO + Al_2O_3 + Fe_2O_3 &\rightarrow C_4AF \end{aligned}$$

▶ Combustion reactions

$$\begin{aligned} 2C + O_2 &\rightarrow 2CO \\ C + H_2O &\rightarrow CO + H_2 \\ C + CO_2 &\rightarrow 2CO \\ 2CO + O_2 &\rightarrow 2CO_2 \\ CO + H_2O &\rightarrow CO_2 + H_2 \\ 2H_2 + O_2 &\rightarrow 2H_2O \end{aligned}$$

▶ Radical reactions

$$\begin{aligned} O_2 + Ar &\rightleftharpoons 2O + Ar \\ H_2 + N_2 &\rightleftharpoons 2H + N_2 \\ H + O_2 + N_2 &\rightleftharpoons HO_2 + N_2 \\ H + O_2 &\rightleftharpoons OH + O \\ H_2 + O &\rightleftharpoons OH + H \\ H_2 + OH &\rightleftharpoons H_2O + H \\ 2OH &\rightleftharpoons H_2O + O \end{aligned}$$

▶ NOx reactions

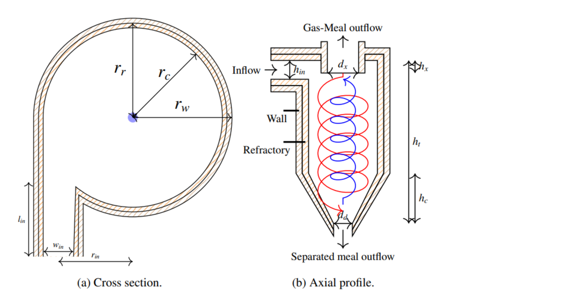
$$\begin{aligned} N + NO &\rightleftharpoons N_2 + O \\ O_2 + N &\rightleftharpoons NO + O \\ N + OH &\rightleftharpoons NO + H \end{aligned}$$

▶ SOx reactions

$$\begin{aligned} S + O_2 &\rightleftharpoons SO + O \\ SO + O &\rightleftharpoons SO_2 \\ SO_2 + O &\rightleftharpoons SO_3 \\ CaO + SO_2 + \frac{1}{2}O_2 &\rightleftharpoons CaSO_4 \\ CaO + SO_2 &\rightleftharpoons CaSO_3 \\ CaO + SO_3 &\rightleftharpoons CaSO_4 \\ CaSO_3 + 0.5O_2 &\rightleftharpoons CaSO_4 \\ FeS_2 + \frac{11}{4}O_2 &\rightarrow \frac{1}{2}Fe_2O_3 + 2SO_2 \end{aligned}$$

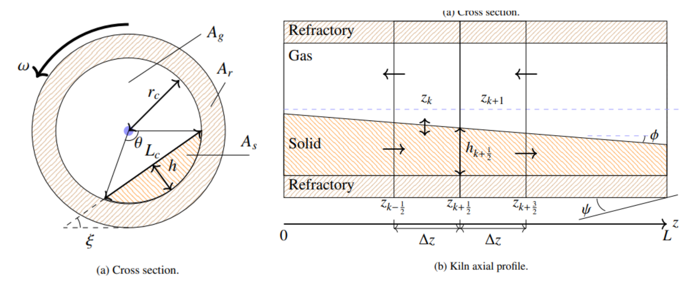
▶ Cyclone specific model formulas

$$v_{sep} = \frac{d_m^2 \Delta\rho\, v_{\theta,r_{eq}}(v_{in})^2}{18\mu_m\, r_{eq}}, \quad r_{eq} = \sqrt{\frac{V_\Delta}{\pi h_t}}$$



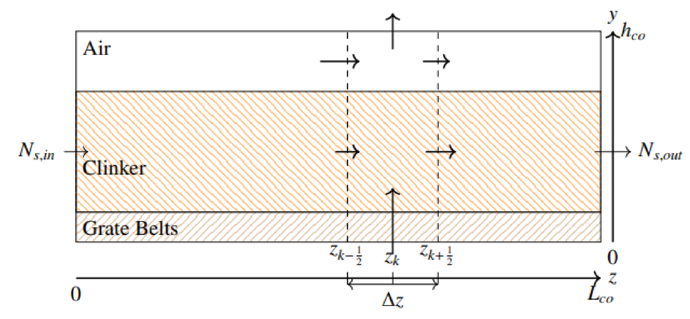
▶ Kiln specific model formula

$$v_s(z) = \omega \frac{\psi + \phi(z)\cos(\xi)}{\sin(\xi)} \frac{\pi L_c(z)}{\operatorname{asin}(\frac{L_c(z)}{2r_c})}$$



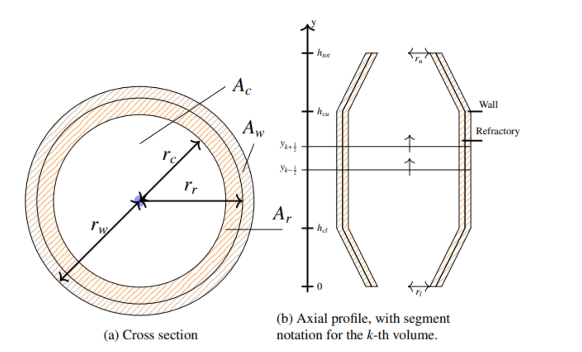
▶ Cooler specific model formulas

$$\begin{aligned} Q_{ij}^{cv} &= A_{ij}\beta_{ij}(T_i - T_j) \\ \beta &= \frac{k_s Nu}{D_p + 0.5\phi D_p Nu} \\ Nu &= 2 + 1.8 Pr^{\frac{1}{3}} Re^{\frac{1}{2}} \end{aligned}$$



▶ Calciner specific model formulas

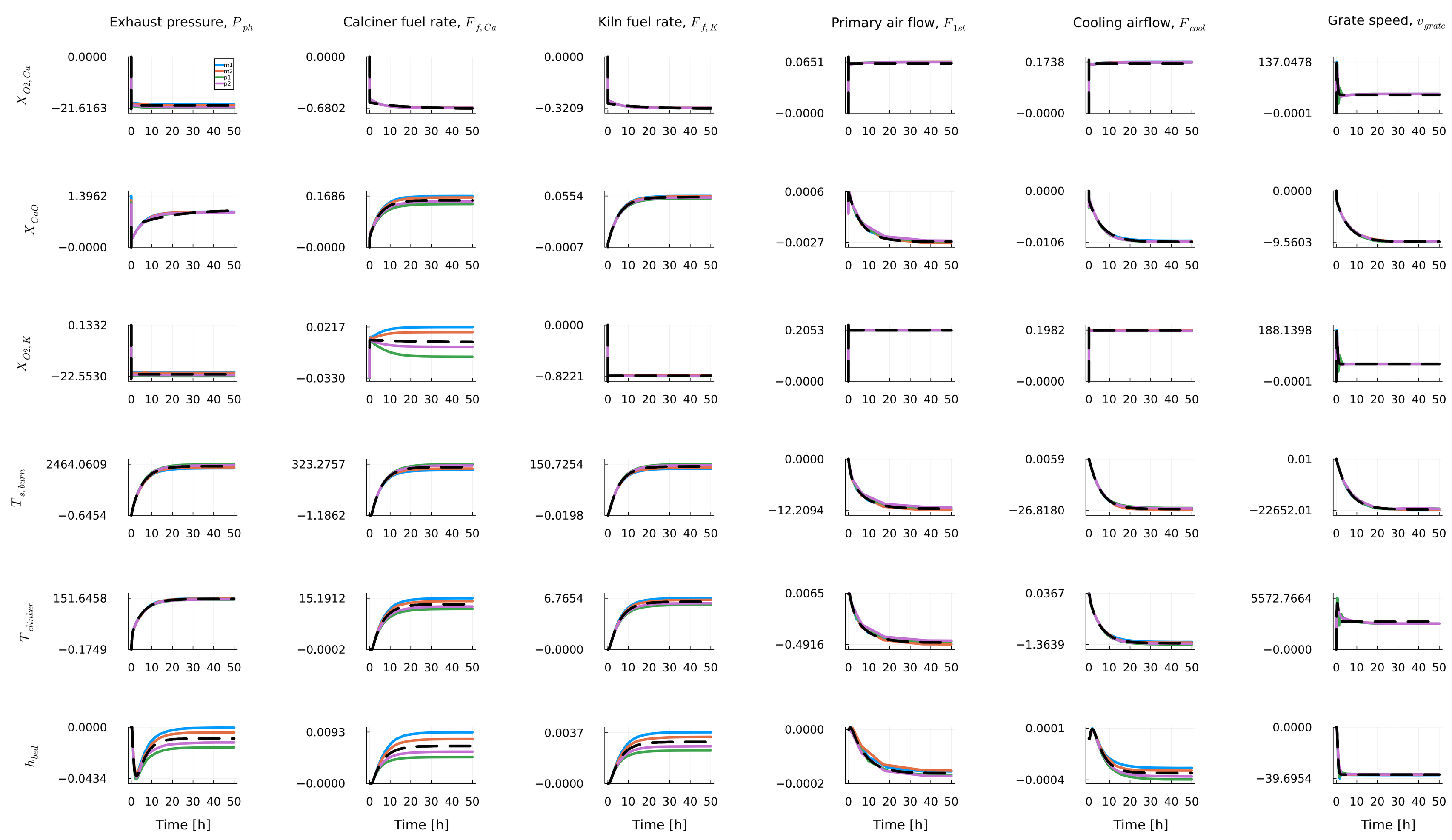
$$\begin{aligned} \beta_m &= \frac{k_m}{D_H} Nu \\ Nu &= \frac{\frac{f}{8}(Re_D - 1000)Pr}{1 + 12.7(\frac{f(Re_D)}{8})^{\frac{1}{2}}(Pr^{\frac{2}{3}} - 1)} \end{aligned}$$



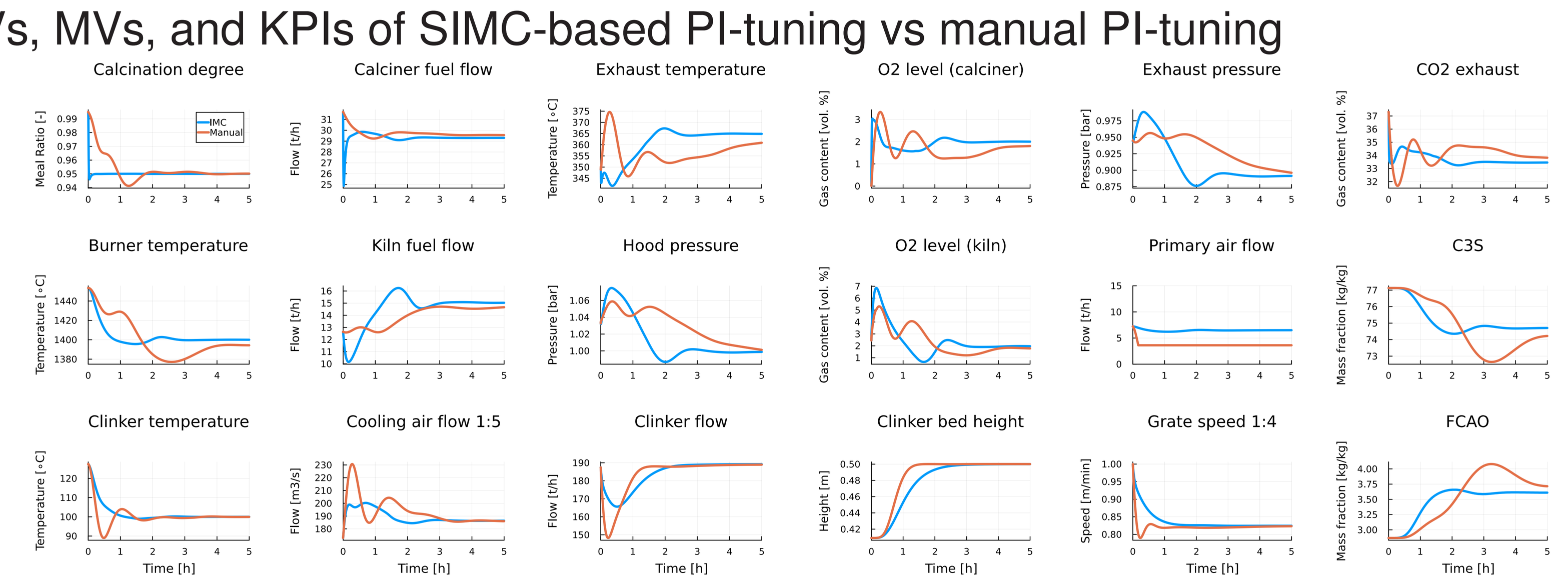
3. Model-based step repsonse & IMC-based tuning

▶ Normalized step response from the model and the estimated linear transfer function

$$\hat{g}(s) = K_0 \frac{\tau_z s + 1}{(\tau_1 s + 1)(\tau_2 s + 1)} e^{-\tau_d s}$$



▶ CVs, MVs, and KPIs of SIMC-based PI-tuning vs manual PI-tuning



4. RGA

▶ Linearized system

$$\begin{aligned} G(s) &= C(sI - A)^{-1}B + D \\ A &= \partial_x f - \partial_y f\,[\partial_y g]^{-1}\,\partial_x g \\ B &= \partial_u f - \partial_y f\,[\partial_y g]^{-1}\,\partial_u g \\ C &= \partial_x h - \partial_y h\,[\partial_y g]^{-1}\,\partial_x g \\ D &= \partial_u h - \partial_y h\,[\partial_y g]^{-1}\,\partial_u g \end{aligned}$$

▶ CV-MV pairing evaluation based on RGA

$$\Lambda_\omega(G) = G(i\omega) \circ (G(i\omega)^{-1})^T$$

$$[\Phi_\omega]_{ij} = \frac{1}{[\Lambda_\omega(G)]_{ij}} - 1$$

Table 1: RGA matrix.
Intuitive pairs (blue,orange).
RGA-based pairs (red,orange).

CV\MV	v_{grate}	P_{ph}	F_{feed}	$F_{f,Ca}$	$F_{f,K}$	F_{1st}	F_{cool}
$X_{O2,Ca}$	-7e-6	5.20	-0.08	-1.13	1.61	-2.17	-2.43
X_{CaO}	1e-5	-6.62	1.30	13.4	-14.4	3.87	3.51
$X_{O2,K}$	8e-5	-3.56	-0.02	-0.01	-4.23	7.14	1.69
$T_{s,burn}$	-0.01	8.54	-1.38	-11.7	19.4	-8.35	-5.51
F_{clink}	1e-3	-0.17	1.04	2e-3	0.01	0.04	0.08
$T_{clinker}$	-2e-6	-2.41	0.18	0.42	-1.26	0.45	3.61
h_{bed}	1.01	0.02	-0.04	0.02	-0.08	0.02	0.05

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