Steady state process optimization of an electric flash clay calcination plant

Nicola Cantisani [*] **Jan Lorenz Svensen** [*]
Shanmugam Perumal [**] **John Bagterp Jørgensen** [*]

[*] *Department of Applied Mathematics and Computer Science, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark*
[**] *FLSmidth Cement, India, Chennai*

Abstract: This paper presents a study on the determination of the optimal steady states of an industrial electric flash clay calcination plant. Such a process is relevant in the context of sustainable cement production. By deploying electrical heating, CO_2-free calcined clay can be produced, which can substitute some of the traditional limestone-based cement clinker. By using a nonlinear model of the plant, the optimization problem is formulated to minimize energy consumption, while maximizing the production rate of calcined clay and ensuring a specified quality requirement. The optimal manipulated variables, for each clay feed or power set-point, are computed as solution of the problem, and presented in the results. The numerical solution of the problem is obtained using a hybrid approach, that combines global optimization with gradient-based methods. Steady state optimization enables the development of process control and real-time optimization.

Keywords: Chemical process control, Optimization, Steady state, Green cement, Clay calcination, Process optimization

1. INTRODUCTION

Cement manufacturing is a major source of carbon dioxide emissions, contributing to 8-9% of the global total. Moreover, its annual production is expected to grow by 50% by 2050 (Monteiro et al., 2017). Accordingly, there is high interest in developing alternative production methods that can reduce emissions. Clinker is the main component of cement, and it is produced by calcining limestone in a kiln, which releases CO_2. Approximately 40% of the CO_2 emissions are due to the burning of fossil fuel in the kiln. 50% of the CO_2 emissions are related to the chemical process of calcination of limestone, and the remaining 10% of the CO_2 emissions are indirect (Cantisani et al., 2024). Emissions reduction can be achieved in three different ways: 1) by lowering the clinker-to-cement ratio, 2) by substituting fossil fuel with renewable energy, 3) by capturing and storing the CO_2 generated by the process and fossil fuel combustion. The calcined clay production falls under the first strategy. In the recent years, calcined kaolinite-rich clay (CC) as a clinker substitute has gained attention, because of its natural abundance and its CO_2-free calcination process. Substitution of up to 50% clinker with CC in cement blends is viable, achieving similar mechanical properties and even improving some aspects of durability (Scrivener et al., 2018; Hanein et al., 2021). The calcination process of clay is achieved by thermally releasing the water bounded in the molecules. The electrification of this process using renewable energy and the partial substitution of clinker with CC can reduce emissions by up to 50% in the final product. Additionally, the use of electricity instead of fuel allows for better temperature control, and thus higher product quality.

The need to run the process using electricity coming from renewable energy introduces new challenges. Because of the intermittent nature of these sources, it is expected that the process may need to run dynamically at different conditions and operating points. A dynamic model of the process is therefore useful to be able to simulate these scenarios. Cantisani et al. (2024) present a dynamic model of a flash clay calciner, and Cantisani et al. (2025) present a plant-wide model of a flash clay calcination plant. The model unlocks the development of advanced control technologies, such as model predictive control (MPC). Before developing any plant controller, it is relevant to perform a steady state optimization (SSO) of the process. This in not only relevant from a control perspective, but it is useful to analyze and understand the process, including its stability. The optimization procedure consists in determining the economic optimal steady states (SS) of the process, given a fixed parameter, like feed of clay or input power. These steady states are achieved by determining the optimal position of the system's manipulated variables, such that the overall economic profit is maximized and the product respects quality requirements. The problem can be solved iteratively by sweeping the parameter in a given interval. This procedure generates an optimal mapping between the parameter and the manipulated variables. This information can, first of all, be used to discuss or motivate the development of a certain control strategy for the plant. Secondly, the SSO problem can be implemented online in a real time optimization layer, that communicates with an MPC algorithm (Marchetti et al., 2014; Krishnamoorthy

[⋆] The project has been funded by EUDP in the ECoClay project 64021-7009.

et al., 2018; Petersen et al., 2017). Moreover, Laurini et al. (2024) present the vision on the electrification of clay calcination, and its integration into sustainable power grids. This is achieved with an energy management system (EMS) that solves the cement plant's power scheduling problem. This set-point should then be used by the clay plant's RTO layer to determine the optimal steady state to follow.

This paper formulates and solves the SSO problem for an electric flash clay calcination plant. Two different formulations are presented: when the clay feed is a disturbance and when the input power is a disturbance. The numerical solution of such problems is obtained with a hybrid optimization approach, which is presented and discussed in the paper. The results are presented and discussed, and a stability analysis of the steady states is also performed. The work is entirely novel on this kind of process.

The paper is structured as follows. Section 2 introduces the general steady state optimization problem of a system modeled by nonlinear differential algebraic equations. Section 3 provides an overview of the clay calcination process and the configuration of the plant. Here we outline the main equations and parts of the plant-wide model. The steady state optimization problem of the clay calcination plant is formulated in Section 4. Section 5 discusses the numerical approach to solve the problem. Section 6 shows and discusses the results. Section 7 concludes the paper and introduces future research goals based on this work.

2. STEADY STATE OPTIMIZATION

In the context of physical first principle modeling, chemical plants are often naturally modeled as systems of nonlinear differential algebraic equations (DAEs). We can indicate these in the general form

$$\frac{dx}{dt} = f(x, y, u, d, p), \tag{1a}$$

$$0 = g(x, y, u, d, p). \tag{1b}$$

x are the differential variables, y are the algebraic variables, u are the manipulated variables (MVs), or inputs, d are the disturbance variables, and p the model parameters. The time dependency is not included explicitly, as we consider time invariant models. The control variables (CVs), or outputs, of the system are indicated as

$$z = h(x, y, u, d, p). \tag{2}$$

These usually represent some relevant key performance indicators of the process that we want to control. The steady state optimization problem can be formulated as

$$\begin{aligned}
\min_{x,y,u} \quad & \phi = \phi(x, y, u) && (3a)\\
s.t. \quad & 0 = f(x, y, u, d, p) && (3b)\\
& 0 = g(x, y, u, d, p) && (3c)\\
& z = h(x, y, u, d, p) && (3d)\\
& z \in \mathcal{Z} && (3e)\\
& u \in \mathcal{U} && (3f)
\end{aligned}$$

Constraints (3b) and (3c) impose the steady state condition on the DAE model. Constraint (3d) introduces the output equations, while (3e) imposes requirements on them. Constraint (3f) introduces bounds on the inputs.

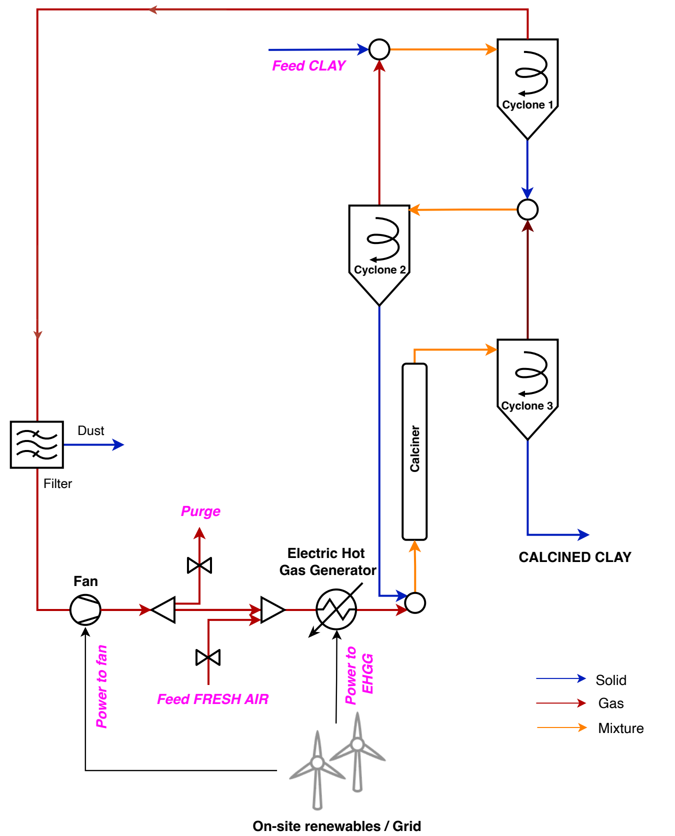

Fig. 1. Process diagram of the electric flash clay calcination plant. The system inputs (MVs) are highlighted in magenta. Notice that either the power or the clay feed can be a disturbance instead.

If the process model (1) or outputs (2) is nonlinear, the optimization problem (3) is also nonlinear. The solution to the problem determines the optimal MVs, and, hence, the corresponding system steady state, such that the cost function, ϕ, is minimized.

3. CLAY CALCINATION PROCESS

Figure 1 shows a diagram of the clay calcination process. In this section, we provide a short description of the process and give an overview of the mathematical model. The thermal activation of the clay is performed in a loop. The fresh clay is introduced in the loop after being crushed, at the inlet of cyclone 1 (see Figure 1). The material undergoes pre-heating through two cyclones (cyclone 1 and cyclone 2), where a part of the clay already gets calcined because of the high temperature. The pre-heated solid is then directed to the calciner. The calciner is a long plug-flow reactor, where the solid material stream is mixed with the hot gas stream coming from the electric hot gas generator. The hot gas transfers heat to the solid particles, ensuring that all the clay gets calcined. Cyclone 3 separates the solid product from the gas before leaving the process. The gas is recirculated in a loop, in order to recover energy. A circulating fan holds a certain pressure difference in the whole loop. A ceramic filter removes any unseparated solid particle residue (dust) from the gas before being recycled. Some of the gas is purged to remove water and ensure that water does not accumulate in the loop. Fresh air is mixed to the recycled stream. The gas flow undergoes heating by going through the electric hot gas generator (EHGG), which transfers heat to the gas by resistive heating. This could, alternatively, be replaced by a thermal storage, that works as a buffer when electricity is intermittent. The process is CO_2 free, as the hot gas generator runs on renewable energy and the clay does not release any carbon dioxide.

3.1 Process model

The plant-wide model consists of several building blocks: stoichiometry and kinetics of the reaction, thermophysics of the solid and gas phases, model of the calciner, model of the cyclones, model of the other components, and connection of the units. The model of the calciner, along with the chemical and thermophysical models, has been published by Cantisani et al. (2024). Cantisani et al. (2025) present the entire plant-wide model. We give a brief overview of the model here, but we refer to the previous publications for a detailed description.

We consider clay that is composed of kaolinite and quartz. The main reaction occurring when calcinating clay is dehydroxylation of kaolinite. The reaction leads to the formation of metakaolin and water vapor, according to the following reaction

$$\mathrm{Al_2O_2 \cdot 2SiO_2 \cdot 2H_2O(s) \rightarrow Al_2O_2 \cdot 2SiO_2(s) + 2H_2O(g)}. \tag{4}$$

We indicate it as $\mathrm{AB_2} \rightarrow \mathrm{A} + 2\mathrm{B}$. The chemical model is given by the reaction rate, r, and the production rate vector, R.

$$r = r(T_s, c) = k\, c_{AB_2}^3, \tag{5a}$$
$$k = k(T_s) = k_0 \exp\left(-\frac{E_A}{R_{gas} T_s}\right), \tag{5b}$$
$$R = R(T_s, c) = \nu' r(T_s, c). \tag{5c}$$

We use the indices s and g to indicate solid and gas phase. c indicates concentrations. The thermophysical model are a set of functions that evaluate the volume, V, the enthalpy, H, and, consequently, the internal energy, U, as a function of temperature, T, pressure, P, and number of moles, n.

$$V = V(T, P, n), \tag{6a}$$
$$H = H(T, P, n), \tag{6b}$$
$$U = H - PV. \tag{6c}$$

Given the molar flux N, the enthalpy flux may also be computed

$$\tilde{H} = H(T, P, N). \tag{7}$$

The calciner model consists of the the mass and energy balances in space, z, and time, t,

$$\partial_t c = -\partial_z N + R, \tag{8a}$$
$$\partial_t \hat{u}_s = -\partial_z \tilde{H}_s + \hat{J}_{gs}, \tag{8b}$$
$$\partial_t \hat{u}_g = -\partial_z \tilde{H}_g - \hat{J}_{gs}, \tag{8c}$$

and the algebraic relations

$$V_s(T_s, P, c_s) + V_g(T_g, P, c_g) - 1 = 0, \tag{9a}$$
$$U_s(T_s, P, c) - \hat{u}_s = 0, \tag{9b}$$
$$U_g(T_g, P, c) - \hat{u}_g = 0. \tag{9c}$$

The transport model includes advection and diffusion, i.e.

$$N = N_a + N_d = v \cdot c - D \odot \partial_z c. \tag{10}$$

The velocity is modeled explicitly such that $v = v(T, \partial_z P, c)$. The solid-to-gas heat transfer is

$$\hat{J}_{gs} = \alpha_{gs}(T_g - T_s), \qquad \alpha_{gs} = 6\, k_{gs} \frac{V_s(T_s, P, c)}{d_{med}}. \tag{11}$$

The cyclones are modeled with a lumped approach. For one cyclone, the mass and energy balances read

$$d_t c = \frac{1}{V}(A_1 N_1 - A_2 N_2 - A_3 N_3) + R, \tag{12a}$$
$$d_t \hat{u}_s = \frac{1}{V}(A_1 \tilde{H}_{1,s} - A_2 \tilde{H}_{2,s} - A_3 \tilde{H}_{3,s}) + \hat{J}_{gs}, \tag{12b}$$
$$d_t \hat{u}_g = \frac{1}{V}(A_1 \tilde{H}_{1,g} - A_2 \tilde{H}_{2,g} - A_3 \tilde{H}_{3,g}) - \hat{J}_{gs}. \tag{12c}$$

The indices $1, 2, 3$ indicate inlet, gas outlet and separation outlet, respectively. A indicates a cross-sectional area. The material fluxes are

$$N_{1,s} = v_1 c_{s,in}, \qquad N_{1,g} = v_1 c_{g,in}, \tag{13a}$$
$$N_{2,s} = v_2(1-\eta) c_s, \qquad N_{2,g} = v_2 c_g, \tag{13b}$$
$$N_{3,s} = v_3\, \eta\, c_s, \qquad N_{3,g} = 0. \tag{13c}$$

The separation efficiency, η, is modeled explicitly, and the velocities are related to the pressure drop via algebraic equations. The volume and internal energy algebraic equations (9) are also imposed.

The other components of the system, i.e. fan, gas purge, fresh air mixer, and electric hot gas generator, are modeled via static balances (algebraic equations), with no accumulation. For example, the EHGG is modeled by

$$H(T_{in}, P, f) - H(T_{out}, P, f) + P_{EHGG} = 0, \tag{14}$$

where $T_{in}, T_{out}, P, f, P_{EHGG}$ are the inlet and outlet temperature, the pressure and the molar flow rate of the gas, and the electrical power. Finally, the units are connected by assuming that the pressure at the outlet of one unit is the same as the pressure at the inlet of the next one. The number of variables of the full model is 151, when using 10 finite volume cells in the calciner for discretizing the PDEs. The inputs of the system, u, are the clay and fresh air feeds, the opening of the purge valve, the power to the fan and the power to the EHGG. The disturbances of the system, d, are the temperature of the fresh clay and the temperature of the fresh air. That is

$$u = \begin{bmatrix} F_{clay} \\ F_{fresh} \\ \alpha_{purge} \\ P_{fan} \\ P_{EHGG} \end{bmatrix}, \qquad d = \begin{bmatrix} T_{clay} \\ T_{fresh} \end{bmatrix}. \tag{15}$$

Notice that, depending on the setup, either the power, P_{EHGG}, or the clay feed, F_{clay}, can be a disturbance instead. The outputs of the system are the calcined clay production rate and its degree of calcination. These can be computed from the separation outlet flow of cyclone 3, that is

$$z = \begin{bmatrix} CC \\ CD \end{bmatrix} = \begin{bmatrix} A_3\, N_{3,s}^{Cyc3} \cdot M_s \\ (c_{s,A}^{Cyc3} M_A) / \sum_{i=\{AB_2, A\}} (c_{s,i}^{Cyc3} M_i) \end{bmatrix}. \tag{16}$$

M indicates molar mass.

4. PROBLEM FORMULATION

We now formulate the steady state optimization problem for the clay calcination plant. As explained before, the

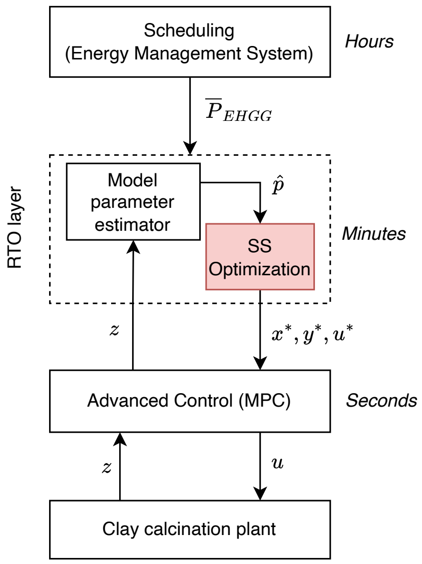

Fig. 2. Proposed multi-layer control hierarchy. In the case of an EMS pre-determining the available power, the SS optimization problem determines the optimal SS and MVs to run the plant. This set-point is sent to the MPC that controls the clay plant.

objective of the optimization problem is to maximize profit. This means to minimize energy consumption and maximize production at the same time, while ensuring product quality.

A simple way to formulate the problem would be to assume that a certain output of calcined clay is requested to satisfy the demand from the next processing plants in the cement line. In this case, the fresh clay feed is specified as a disturbance, and we aim to minimizing the use of energy that ensures the minimum calcination degree requirement.

Depending on the overall control setup, the power sent to the clay plant might instead be predetermined by a scheduling algorithm (EMS), from the upper control layer. In this case, the power is regarded as a disturbance rather than an MV, and we would like to produce as much calcined clay as possible with the available power. Figure 2 presents the proposed multi-layer control hierarchy. The EMS calculates and schedules the optimal distribution of power among the units in the cement plant, after trading energy in the day-ahead market. The information is passed to the RTO layer, that computes the optimal set-point for the controller to follow (SSO). The advanced controller, for example a linear MPC, optimizes the MVs in order to bring the system at the desired optimal SS, using the measurements obtained in real time from the plant. A feedback loop with a model parameters estimator should be implemented from the MPC to the RTO optimization layer, to account for model-plant mismatch (Marchetti et al., 2014; Roberts and Williams, 1981).

We propose and solve the problem for both the formulations.

4.1 Clay feed as a disturbance

If the the clay feed set-point, $\overline{F}_{clay}$, is known, the profit is maximized by minimizing the use of power. The optimization problem reads

$$\begin{aligned}
\min_{x,y,u} \quad & \phi = P_{EHGG} && \text{(17a)}\\
s.t. \quad & F_{clay} = \overline{F}_{clay}, && \text{(17b)}\\
& 0 = f(x,y,u,d,p), && \text{(17c)}\\
& 0 = g(x,y,u,d,p), && \text{(17d)}\\
& CD \geq 94\%, && \text{(17e)}\\
& 100 \leq F_{fresh} \leq 300 \text{ [kg/h]}, && \text{(17f)}\\
& 0.7 \leq P_{fan} \leq 1.5 \text{ [kW]}, && \text{(17g)}\\
& 0.2 \leq \alpha_{purge} \leq 1, && \text{(17h)}\\
& 10 \leq P_{EHGG} \leq 60 \text{ [kW]}. && \text{(17i)}
\end{aligned}$$

Constraint (17e) ensures that the calcination degree at the output is at least 94 %. It is expected that, at the minimizer, this constraint is active. This is because a CD higher than the lower limit would imply using more resources than necessary. The numerical values for the constraints are chosen as an example for this work, but they may be changed according to the real plant constraints.

4.2 Power as a disturbance

If the power set-point, $\overline{P}_{EHGG}$, is provided from the upper control later (EMS), the profit is maximized by producing as much calcined clay as possible that satisfies the quality requirement. The optimization problem now reads

$$\begin{aligned}
\min_{x,y,u} \quad & \phi = -F_{clay} && \text{(18a)}\\
s.t. \quad & P_{EHGG} = \overline{P}_{EHGG}, && \text{(18b)}\\
& \text{Constraints (17c)} - \text{(17h)} && \\
& 50 \leq F_{clay} \leq 600 \text{ [kg/h]}. && \text{(18c)}
\end{aligned}$$

Notice that, in both the problems, the power used by the fan, P_{fan}, is not counted in the "total" power. This is done to keep the formulation simple and because $P_{fan} \ll P_{EHGG}$. The problems could be easily modified though.

5. NUMERICAL SOLUTION

The optimization problems (17) and (18) may appear easy at a first glance, but getting a numerical solution is not trivial. This is due to the considerable amount of nonlinear constraints, that is the nonlinear dynamics (equality constraints) and the CD output inequality constraint. Because of this, starting from any feasible point might not be enough to locate the global minimizer or just a local minimizer, by using a gradient-based nonlinear optimization algorithm. We therefore propose a hybrid optimization approach. A good estimate of the global minimizer may be found by using a gradient-free evolutionary global optimization algorithm, like particle swarm optimization (PSO) (Wang et al., 2018). This class of algorithm is particularly preferred in the presence of multiple local minimizers. PSO can minimize any type of function, and requires bound constraints on the decision variables. Unfortunately, any other type of constraint is not allowed. A way to circumvent this problem is to reformulate the optimization problem, such that the constraints are eliminated, i.e.

$$\begin{aligned}
\min_{u} \quad & \phi^\star(u), && \text{(19a)}\\
s.t. \quad & u_{min} \leq u \leq u_{max}. && \text{(19b)}
\end{aligned}$$

Algorithm 1 Evaluate modified objective function $\phi^\star(u)$ for PSO optimization.

Require: u, d, p, x_0, y_0

Find the corresponding system steady state by solving the nonlinear system

$$\begin{cases} f(x,y,u,d,p) = 0, \\ g(x,y,u,d,p) = 0, \end{cases}$$

for (x, y) using Newton's scheme, given an initial point (x_0, y_0).

if converged **then**

Compute the system outputs

$$z = h(x,y,u,d,p).$$

Return objective function evaluation

$$\phi^\star = \begin{cases} \phi(x,y,u), & \text{if } z \in \mathcal{Z} \\ +\infty, & \text{otherwise} \end{cases}$$

else

Return

$$\phi^\star = +\infty$$

end if

The modified objective function $\phi^\star(u)$ can be evaluated following Algorithm 1. Subsequently, the solution obtained via PSO can be used as an initial guess for a gradient based algorithm (like interior point or sequential quadratic programming), for the original nonlinear optimization problem. Moreover, because of the model dimension, it is crucial that the analytical Jacobians of the nonlinear constraints are provided to the solver, to avoid estimating them via finite difference, that would lead to increased convergence time. Therefore, for a problem in the form (3), the model Jacobians $\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial u}, \frac{\partial g}{\partial x}, \frac{\partial g}{\partial y}, \frac{\partial g}{\partial u}$ and $\frac{\partial h}{\partial x}, \frac{\partial h}{\partial y}, \frac{\partial h}{\partial u}$ are required.

6. RESULTS

The optimization problem (17) is solved for $\overline{F}_{clay} \in [50, 600]$ kg/h. The step size in the interval is 1 kg/h, resulting in 551 grid points. The first solution is obtained with the hybrid optimization approach explained in the previous section. As we sweep the clay feed interval, the previous solution is used as initial guess for the nonlinear optimization solver in the next problem. We use Matlab's `fmincon` for the gradient based solver and `particleswarm` for PSO. The solution is plotted in Figure 3, displaying the optimal MVs and the CD constraint, as a function of the clay feed. As expected, the CD constraint is active at every optimum. We also see that the fresh air intake and the power to the fan are always kept at the minimum. We see that the relationship between clay feed and power to EHGG exhibits an almost linear behavior. The opening of the purge valve shows instead a non-trivial behavior. The minimum operating cost is achieved by purging all the gas when $F_{clay} < 350$ kg/h, while after that, the effect of the recycling starts to become beneficial and the solution jumps quickly to the lower bound of α_{purge}. We further investigate the solution, to understand why the optimum is achieved in this way. Therefore, we extract and plot some relevant information from the optimal steady states in Figure 4. We inspect the thermodynamics around the EHGG, specifically the gas temperature and enthalpy flow before and after getting heated by the EHGG, and their difference. The total gas flow rate (which is made by fresh and recycled air) and its water content is also plotted. Moreover, we also solve problem (17) fixing $\alpha_{purge} = 0.2$ and $\alpha_{purge} = 1$ and plot these solutions together, in

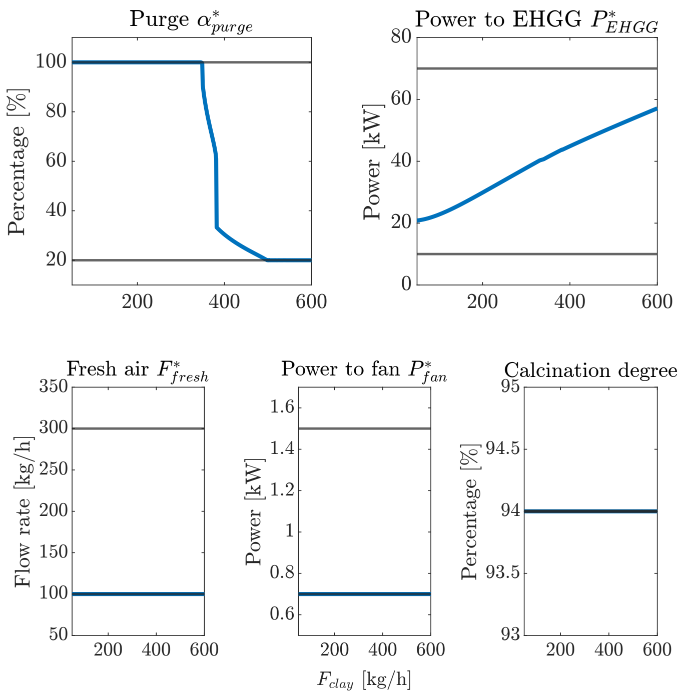

Fig. 3. Solution of the SS optimization problem (17).

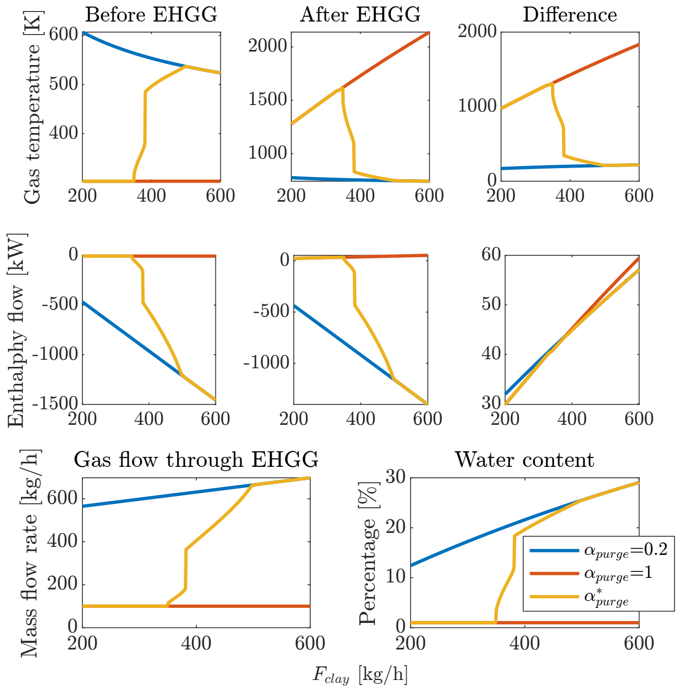

Fig. 4. SS temperature, enthalpy flow rate and mass flow rate of the gas stream through the EHGG, as a function of F_{clay}. The temperature and enthalpy difference before and after the EHGG are also plotted. The optimal solution with α^*_{purge} from problem (17) is shown, as well as the solutions when fixing $\alpha_{purge} = 0.2$ and $\alpha_{purge} = 1$.

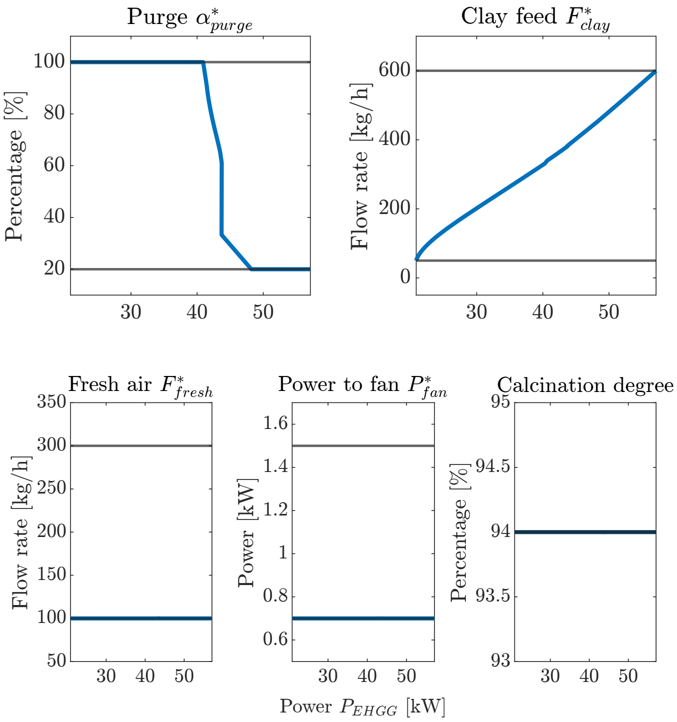

Fig. 5. Solution of the SS optimization problem (18).

order to understand why the optimal solution jumps from one bound to the other. Notice that the enthalpy flow difference is equal to the power being used by the EHGG, see (14). It is now clear that the shifting solution is due to an enthalpy effect. After the cut-off, using more air with a higher moisture content at a lower temperature is cheaper to achieve the same calcination degree. This is because heating up more air with a higher water content, but with a lower temperature gradient requires less power after the cut-off.

The optimization problem (18) is now also solved. We use the solution of problem (17) as initial guess, by exchanging the clay feed with the corresponding power to EHGG. The solution is plotted in Figure (5), as a function of the power to EHGG. As expected, the solution seems the same as the one obtained from problem (17), with the curve $F_{clay} - P_{EHGG}$ being inverted. This shows that problem (17) and (18) are inherently the same.

6.1 Stability analysis

A stability analysis is also performed on the steady states found via the optimization problems. This is done by linearizing the nonlinear model around each steady state (x_s, y_s, u_s), i.e.

$$\frac{dX}{dt}(t) = A_c X(t) + B_c U(t), \tag{20}$$

where

$$A_c = \left(\frac{\partial f}{\partial x} - \frac{\partial f}{\partial y} \left(\frac{\partial g}{\partial y} \right)^{-1} \frac{\partial g}{\partial x} \right) \Big|_{(x_s, y_s, u_s)}, \tag{21a}$$

$$B_c = \left(\frac{\partial f}{\partial u} - \frac{\partial f}{\partial y} \left(\frac{\partial g}{\partial y} \right)^{-1} \frac{\partial g}{\partial u} \right) \Big|_{(x_s, y_s, u_s)}. \tag{21b}$$

and $X(t) = x(t) - x_s$ $U(t) = u(t) - u_s$. The disturbances are assumed constant. By analyzing the eigenvalues of A_c, we observe that all the steady states are stable.

7. CONCLUSIONS

This paper formulates and solves the steady state optimization problem for an electric flash clay calcination plant. The problem is formulated such that either the clay feed or the power input is given. The solutions are presented and discussed. Future work involves developing a control strategy for the clay calcination plant, based on this work. The results in this paper suggest that the control problem of the plant can be solved by developing a simple SISO controller (PID or Linear MPC), between the clay feed and the CD, while the other inputs are held constant. This conclusion could have never been reached without the analysis carried out in this work.

REFERENCES

Cantisani, N., Svensen, J.L., Hansen, O.F., and Jørgensen, J.B. (2024). Dynamic modeling and simulation of a flash clay calciner. *IFAC-PapersOnLine*, 58(14), 283–288. 12th IFAC Symposium on Advanced Control of Chemical Processes ADCHEM 2024.

Cantisani, N., Svensen, J.L., and Jørgensen, J.B. (2025). Dynamic modeling and simulation of an electric flash clay calcination plant for green cement production.

Hanein, T., Thienel, K.C., Zunino, F., Marsh, A.T.M., Maier, M., Wang, B., Canut, M., Juenger, M.C.G., Haha, M.B., Avet, F., Parashar, A., Al-Jaberi, L.A., Almenares-Reyes, R.S., Alujas-Diaz, A., Scrivener, K.L., Bernal, S.A., Provis, J.L., Sui, T., Bishnoi, S., and Martirena-Hernández, F. (2021). Clay calcination technology: state-of-the-art review by the RILEM TC 282-CCL. *Materials and Structures*, 55(1), 3.

Krishnamoorthy, D., Foss, B., and Skogestad, S. (2018). Steady-state real-time optimization using transient measurements. *Computers & Chemical Engineering*, 115, 34–45.

Laurini, B., Cantisani, N., da Silva, W.R.L., Zong, Y., and Jørgensen, J.B. (2024). Electrification of clay calcination: A first look into dynamic modeling and energy management for integration with sustainable power grids.

Marchetti, A., Ferramosca, A., and González, A. (2014). Steady-state target optimization designs for integrating real-time optimization and model predictive control. *Journal of Process Control*, 24(1), 129–145.

Monteiro, P., Miller, S., and Horvath, A. (2017). Towards sustainable concrete. *Nature Materials*, 16(207), 698–699.

Petersen, L.N., Poulsen, N.K., Niemann, H.H., Utzen, C., and Jørgensen, J.B. (2017). Comparison of three control strategies for optimization of spray dryer operation. *Journal of Process Control*, 57, 1–14.

Roberts, P. and Williams, T. (1981). On an algorithm for combined system optimisation and parameter estimation. *Automatica*, 17(1), 199–209.

Scrivener, K., Martirena, F., Bishnoi, S., and Maity, S. (2018). Calcined clay limestone cements (LC^3). *Cement and Concrete Research*, 114, 49–56.

Wang, D., Tan, D., and Liu, L. (2018). Particle swarm optimization algorithm: an overview. *Soft Computing*, 22(2), 387–408.