Nonlinear model predictive control “MPC” for slab reheating furnace based on transient numerical model

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Summary
In steel industry, without consideration of blast furnaces, reheating furnaces are classified the biggest energy consumers. The research of efficient control algorithms permitting less energy consumption has become an important issue for those furnaces. In this paper, a nonlinear Model Predictive Controller (MPC) is designed for a steel slab walking-beam reheating furnace. A numerical nonlinear model is utilized to predict the furnace thermal behaviour and to optimize zone temperature set points. The MPC control strategy uses this transient model to solve at each time step a dynamic optimization problem under constraints, in order to obtain the best zone temperature set points. This optimization problem is solved using “Nelder-Mead simplex” method that allows having fast minimization of objective function. The controller is able to deal with transient operating situations of the furnace. Simulation on industrial data shows an energy reduction of 5%, and a significant improvement of heating performances.

Key Words
MPC, predictive, control, reheating, furnace, nonlinear, transient, optimization.

Introduction
Reheating furnace is the first step in a hot rolling process; it consists in heating steel slabs (0.24m x 1.5m x 10m) from ambient temperature to around 1250°C with a usual production rate of 350tons/hour. To achieve this task, the furnace dimensions are quite significant (60m x 12m x 6m). The annual energy consumption of the considered furnace in this paper is equivalent to the consumption of 10e5 houses (one house consumption is 1toe/year = 42 GJ/year (toe: tonne of oil equivalent) [9], and steel production of the considered furnace is 3 x10e6 ton/year, with consumption of 1.4GJ/ton, corresponding to 4.2 x 10e6 GJ/year). Thus, energy efficiency is a great challenge in furnace control.

Figure 1: Walking beam reheating furnace

A walking-beam reheating furnace is usually divided into several control zones: recuperation zone, preheating zone, one or more heating zones and soaking zone as shown in Figure 1. Recuperation zone is not equipped with burners so that steel slabs can retrieve heat from exhaust fumes. Slabs are mainly heated in preheating and heating zones where burners are installed. In soaking zone, homogeneity of temperature inside slabs is enhanced to meet the requirement of hot rolling step. The furnace is a complex system with strong thermal coupling between zones, high thermal inertia in walls and roofs, strong sensitivity to combustion parameters (air and gas ratio, variable LCV: Lower Calorific Value, oxygen rate).

Nowadays, hot rolling mills demand an increasing range of slabs in terms of dimensions, steel grade, desired discharged temperature, and reheating time [11]. Therefore, the furnace is frequently in transient operation. Moreover, the slab temperatures cannot not be measured directly which make control task more difficult. Temperature control concerns safety, product quality, the achievable production rate, and the energy consumption of the slab furnace. The discharged temperatures of slabs are controlled by adapting zone temperature set points. The temperature of each zone is subsequently regulated by adjusting air and gas flow rates injected to it. Thus, in common design, the temperature control of a reheating furnace is mainly divided into 2 different levels, as shown in Figure 2. At each time instant, the level 2 determines the temperature set points for each zone of furnace accordingly to the scheduling of slabs, their desired discharged temperature and the instantaneous thermal state of the furnace. At this level, slab temperatures are estimated by a heat transfer model to avoid costly measurements. The level 1 calculates required power injected to each zone to reach the set points given by level 2.
MPC is an advanced control method which handles process constraints, deals with multivariable processes and transforms a control problem into an online optimization under constraints problem [10]. The application of MPC in reheating furnace has been recently subject of several studies. Application of MPC for the level 1 of the furnace is carried out in [6]. Simulation result shows interesting improvement in terms of energy consumption and heating quality. In [1], MPC is designed for level 2 of the control based on a linear adaptive model. Experimental measurement shows 3% of energy gain, and improved accuracy of slab discharged temperature. The MPC method was also implemented for a pusher-type reheating furnace which is a different from the walking-beam furnace considered in this study [13]. The work brings enhancement in accuracy of slab temperature control, yet the energy consumption aspect is not mentioned. A numerical of furnace model is utilized to determine zone temperature set points in [7].

A model-based control is implemented in industrial furnaces, the rejection rate of slab towards changes of slab thickness, slab residence time, and furnace halts is lower than the results of manual mode. At the same time, better heating quality is obtained, yet the energy efficiency is not considered. In [11], an analytical switched steady-state model of pusher-type reheating furnace is developed, and then is used in MPC design. The algorithm used in optimization problem is quasi-newton method. Industrial results show significant improvement of heating quality and reduction of energy consumption. In this paper, a numerical transient model of walking-beam reheating furnace is presented. This model takes into account the transient effects on furnace operations (which are mandatory due to variation of client demands). A MPC controller for the level 2 of reheating furnace is then designed and solved using Nelder-Mead simplex algorithm.

1. Existing furnace control system

1.1. Steady state heat transfer modelling

At level 2 of the considered furnace control, a steady-state model is utilized. This model is constructed based on the radiation effect of furnace walls, furnace fumes, on slabs, and conductive heat transfer inside slabs. In order to estimate temperature of a slab, the steady-state model makes assumption that at each time instant, there is only one type of slab inside the furnace, and thermal transfer happens between zone walls, fumes and the considered slab. Therefore, interactions between slabs are ignored. A temperature profile of the slab is established, and the average temperature of slab is used as the controlled output. The radiative heat transfer inside furnace follows the Stefan-Boltzmann law. Heat radiation between two surfaces is described by:

$$Q = F \sigma (T_1^4 - T_2^4),$$  \hspace{1cm} (1)

Where $Q$ (W.m$^{-2}$) is the power radiated from surface 1 to surface 2, $\sigma$ (W.m$^{-2}$.K$^{-4}$) is Stefan Boltzmann constant, $T_1$ and $T_2$ are absolute temperature of two surfaces, $F$ is a form factor.

Inside slabs, the conductive heat transfer is described by unsteady one-dimensional heat conduction equation [8]:

$$\rho c \frac{dT}{dt} = \frac{d}{dx} \left( k \frac{dT}{dx} \right).$$  \hspace{1cm} (2)

Where $\rho$ is mass density of steel (kg.m$^{-3}$), $c$ is the specific heat capacity of steel (J.kg$^{-1}$.K$^{-1}$), $T$ is temperature inside slab, and $k$ is material conductivity (W.m$^{-1}$.K$^{-1}$).

Because of the fact that steady-state model does not take into account the interactions between slabs, it performs poorly in transient operations. In order to overcome the low reliability of steady-state model, transients are actually handled manually based on experiences of the furnace operator.

1.2. Existing controller

Each slab entering to the furnace has a different temperature target at the exit of furnace. This target depends on slab dimensions, materials and product requirements. To obtain desired final slab temperatures, two extreme heating tendencies may happen: early heating and late heating, as illustrated in Figure 3. In the early heating strategy, slabs are heated mainly in the front zones: preheating zone, and the first half of heating zone. This strategy often leads to high homogeneity of temperature inside slabs, but the furnace consumes great amount of energy. On the other hand, late heating strategy heats slabs mainly in the second half of heating zone and soaking zone. The furnace consumes less
energy, but temperature homogeneity of slabs may not reach the requirements of the hot rolling mill.

Figure 3: Predetermined temperature trajectory of a slab inside the furnace

In the existing level 2 of considered furnace, a steady-state model of reheating furnace is used to estimate slab temperatures at each position inside the furnace. A heating curve is calculated for each slab before entering into the furnace. Based on the predetermined curve, desired temperature for each slab at the end of each zone is imposed.

Temperature set points of zones are calculated so that slab temperatures reach their targets at the end of each zone, see Figure 3. In practice, due to high variation of production and the error of the steady-state model, the heating curve of slabs cannot be tracked properly. This causes energy waste which leads to overheated slabs as shown in Figure 4. Therefore, the lack of energy efficiency and heating quality is to be considered.

2. MPC design

2.1. Transient heat transfer modelling

A numerical dynamic model has been developed based on three-dimensional radiative heat transfer, one-dimensional convective heat transfer, one-dimensional conductive heat transfer in the slab and two-dimensional on the walls (one-dimensional in length and one-dimensional in thickness). Skid and door losses, variable excess air, charging and discharging plan of slabs, characteristic of different industrial gases used in furnace are taken into account, which is not the case in steady-state model. The numerical model takes as inputs the current temperature of slabs and the future set points of zone temperature to predict the future behavior of the furnace. The prediction model is able to predict the furnace variables like: Necessary gas and air flow rates to reach the desired zone temperatures, temperature profile of slabs, temperature of walls and roof, and exhaust fumes temperature.

The instantaneous slab temperatures are not directly measured. They are estimated by another numerical model which is based on the same method as the prediction model and runs in a faster sample time. Inputs of the model are the measured gas and air flow rates. The output estimations are temperature profile of slabs, temperature of walls and roof, exhaust fumes temperature, and zone temperatures.

Figure 5: Experimental calibration trial of the transient model by means of instrumented slab

This transient model is able to describe the dynamic of furnace in transients, has a reasonable computational requirement and therefore, can be used for online implementation. It is validated with industrial data as shown in Figure 5.

2.3. Formulation of optimization problem

The MPC consists in optimization of furnace zone temperature set points to achieve heating objectives such as:

- Accurate tracking of desired slab temperatures
- High homogeneity of discharged slabs
- Minimum loss of material through scale formation
- Energy efficiency

On the other hand, furnace constraints on zone temperature, zone heating power, heating constraints on homogeneity, and discharged temperature of slabs are also considered in the optimization problem. As shown in Figure 2, the control variables of level 2 are the temperature set points for each zone of the furnace. Prediction horizon should not be
higher than the average residence time of a slab inside the furnace. When a slab is discharged and/or another slab is loaded into the furnace, furnace structure and dynamic change. Therefore, sample time should correspond to charging and discharging periods. The online optimization leads to a flexibility of heating curve for slabs which may reduce energy consumption and improve heating quality depending on furnace situation at one given time. Therefore, there is no more one reference heating curve for each slab that is fixed once before charging the product, the target strategy is adapted at each calculation step regarding furnace state. Global objective function takes into account control objectives, furnace inertia and heating constraints:

\[
J = \alpha \times J_{\text{tracking}} + \beta \times J_{\text{energy}} + \mu \times (C_{\text{gradient}} - C_{\text{zone_temp}})
\]

Where \(J_{\text{tracking}}\) is the criterion on error of discharged temperature. \(J_{\text{energy}}\) is the criterion on consumed energy. \(J_{\text{gradient}}\) is the criterion on temperature homogeneity of discharged slab. \(C_{\text{gradient}}\) is constraint on temperature homogeneity of discharged slab. \(C_{\text{tracking}}\) is constraint on final discharged temperature of slab. \(C_{\text{zone_temp}}\) is constraint on zone temperature. Each criterion is calculated regarding all the considered slabs and heating zones. The details of these criterions are described in [14]. The weighting coefficients \((\alpha, \beta, \gamma)\) determine the compromise or the strategy between heating requirements and energy consumption, while \(\mu\) is a penalty coefficient having usually great value.

2.4. Dynamic optimization

An important part of MPC is the optimization algorithm. Among optimization methods, direct search methods use only function values to find the minimum. Other methods use either explicit partial derivatives or approximated ones. Due to the fact that furnace model is a numerical model; there is no explicit formulation of partial derivatives. Therefore, reasonable choice of optimization algorithm for the considered problem is a direct search method. In this work, we use Nelder-Mead simplex method for minimization problem of the objective function provided in Equation 3. More details on the algorithm are described in [14] with focus on algorithm steps and convergence study.

In practice, the algorithm tends to be able to satisfy control purpose by producing rapid initial declines of function value. In [12], Nelder-Mead algorithm is practically shown to be faster than other direct search methods in case of less than four-dimension variable. But, with a problem of more than eight-dimension variable, the algorithm is not guaranteed to be robust. It is not the case here as we are in a four-dimension problem (optimization of temperature set-points of four zones).

3. Simulation results

The simulation is developed in Intel Fortran environment. Computational power assures real-time simulation. Prediction horizon \(T_p=120\) min represents average residence time of a slab inside burner zones. The sampling period \(T_s=5\) min is the average discharging gap between 2 successive slabs (note, the mill has two furnaces, so one slab is discharged to the mill every 2 or 3 minutes. Industrial data of three-day operation, in which 900 slabs are heated in one furnace, is used to simulate MPC of the considered furnace.

![Figure 6: Histogram of error of final slab temperatures: red: MPC; black: Existing control](image)

Table 1: Error of discharged temperature compared to target

<table>
<thead>
<tr>
<th></th>
<th>Average (°C)</th>
<th>Standard deviation (°C)</th>
<th>+/-20°C (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPC</td>
<td>7.4</td>
<td>8</td>
<td>92</td>
</tr>
<tr>
<td>Existing</td>
<td>13.7</td>
<td>10</td>
<td>75</td>
</tr>
</tbody>
</table>

Table 2: Temperature gradient of slab through the thickness

<table>
<thead>
<tr>
<th></th>
<th>Average (°C)</th>
<th>Standard deviation (°C)</th>
<th>+/-20°C (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPC</td>
<td>68</td>
<td>26</td>
<td>93</td>
</tr>
<tr>
<td>Existing</td>
<td>73</td>
<td>26</td>
<td>90</td>
</tr>
</tbody>
</table>

In Table 1 and Figure 6: it is noticed that MPC achieves higher temperature success (+/- 20°C) without overheating the products. This gain of performance is obtained by reducing the scattering and reducing the average overheating, which can be considered as the margin. The more heating model is accurate; the lower can be the margin.

In Table 2 it is noticed that MPC achieves higher homogeneity of products. The obtained gradient of slab temperature is lower meaning more homogeneous temperature inside the slab. Figure 8 shows that MPC in average leads to late heating strategy. It commonly known that late heating leads to high gradient. Nevertheless, in this case the gradient is lower because it is taken in consideration in the optimization criterion.
Table 3: Energy consumption per ton of heated slab (divided by a reference average consumption in GJ/ton)

<table>
<thead>
<tr>
<th>Day</th>
<th>MPC</th>
<th>Existing controller</th>
<th>Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day1</td>
<td>0.9852</td>
<td>1.0444</td>
<td>5.7</td>
</tr>
<tr>
<td>Day2</td>
<td>1.0148</td>
<td>1.0667</td>
<td>4.9</td>
</tr>
<tr>
<td>Day3</td>
<td>0.9111</td>
<td>0.963</td>
<td>5.4</td>
</tr>
<tr>
<td>Total</td>
<td>0.9704</td>
<td>1.0247</td>
<td>5.3</td>
</tr>
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</table>

Table 3 shows that MPC can improve energy consumption in average by 5%, for a furnace equipped with standard level 2 with steady state modelling.

Figure 7: Average heating curve of a representative slab with respect to its position inside furnace: red: MPC; blue: Existing controller.

A general observation for 900 heated slabs is given in Figure 7 & 8. These figures illustrate that in average the MPC heats more smoothly which confirms energy reduction shown in Table 3. Figure 8 shows the evolution of the gradient of a slab inside the furnace. As can be observed the existing controller gave generally higher gradient values which leads to waste of energy comparing to MPC controller. In Figure 8 we see that MPC controller achieves a late heating strategy in order to have less energy consumption.

Figure 8: Gradient average of slab with respect to its position inside furnace: red: MPC; blue: Existing controller

In case of bottleneck furnace, the optimization with transient modelling makes possible to increase productivity without risk of having “cold” slab for rolling. In fact, transient modelling is able to calculate the instantaneous maximum capacity of the furnace at each time step. The productivity is added the optimization criterion (through variable discharging times) and simulations in table 4 shows an productivity increase of up to 7%. Note that in this case, energy consumption per ton is higher.

Table 4: Productivity increase in case of furnace bottleneck situation.

<table>
<thead>
<tr>
<th></th>
<th>MPC</th>
<th>Existing Level 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average scattering temperature</td>
<td>1°C</td>
<td>5°C</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>10°C</td>
<td>17°C</td>
</tr>
<tr>
<td>Average residence time</td>
<td>164min</td>
<td>179min</td>
</tr>
<tr>
<td>Production rate</td>
<td>304 ton/h</td>
<td>282 ton/h</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>4% more</td>
<td></td>
</tr>
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</table>

Conclusion

This study presents the design procedure of MPC for the reheating furnace based on a numerical dynamic model. Quadratic criteria based on predicted behavior of the furnace and furnace constraints are used to solve online optimization problem. Simulations illustrate that MPC provides better heating quality, and a reduction of energy consumption of 5%. An implementation campaign is in progress to apply the new model and control strategy for the industrial furnace.

Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>MPC</td>
<td>Model predictive control: advanced control algorithm</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional, Derivative and Integral control: conventional/basic control algorithm.</td>
</tr>
<tr>
<td>LCV</td>
<td>Lower calorific Value of combustion gas, expressed in MJ/Kg or Kcal/Kg</td>
</tr>
<tr>
<td>Toe</td>
<td>Ton of oil equivalent : is a unit of energy, the amount of energy released by burning one ton of crude oil</td>
</tr>
<tr>
<td>GJ</td>
<td>Giga Joule: energy unit 1cal = 4.1855 J 1KWh = 3600 KJ</td>
</tr>
<tr>
<td>ton</td>
<td>Ton of heated slab (before rolling)</td>
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</table>
References


