Abstract— Continuous reheating furnaces are commonly used in the steel industry for annealing strips of steel coils that were laminated in the cold rolling mills process for reconstitution of the grains. These strips must be uniformly reheated following an appropriate profile so that they have the required mechanical and metallurgical properties. In addition, an optimal control of the fuel gases used in the reheating furnaces is desirable in order to reduce the costs of this production input, since it is responsible for one of the most costly portions of this kind of process. This work aims to present an optimal control strategy of the fuel gases used in continuous reheating furnaces of Aperam South America, which initially computes the furnaces energy efficiency, after performs the constraints’ analysis, and finally obtains the optimal control input in order to reduce the natural gas consumption. Experimental results are presented to corroborate the proposed optimal control, highlighting its efficiency.

Keywords— Process control, Optimal control, Energy efficiency, Continuous reheating furnaces.

Resumo— Fornos contínuos de reaquecimento são comumente utilizados na indústria siderúrgica para recobrimento das tiras das bobinas de aço que passam pelo processo de laminação para reconstituição dos grãos. Essas tiras devem ser reaquecidas uniformemente, seguindo um perfil apropriado, de forma que tenham as propriedades mecânicas e metalúrgicas requeridas. Além disso, é desejável um controle ótimo dos gases combustíveis utilizados nos fornos de reaquecimento a fim de se reduzir os gastos com este insumo, já que o tal é responsável por uma das parcelas mais onerosas dos custos de operação do processo. O presente trabalho tem por finalidade apresentar uma estratégia de controle ótimo dos gases combustíveis utilizados nos fornos de reaquecimento contínuo da Aperam South America, que calcula inicialmente a eficiência energética dos fornos, realiza a análise das restrições, para então obter a entrada de controle ótimo calculada para reduzir o consumo de gás natural. Resultados experimentais são apresentados para corroborar o controle ótimo proposto, destacando sua eficiência.

Palavras-chave— Controle de processos, Controle ótimo, Eficiência energética, Fornos contínuos de reaquecimento.

1 Introduction

Continuous combustion reheating furnaces are widely used in cold rolling areas in the steel industry. In them, the strip shaped coils are annealed in such a way that they have the required mechanical and metallurgical properties. To achieve that a proper temperature control of the strip, by controlling the furnace, is necessary. Since the 1970s, the modeling and control problems of continuous reheating furnace have received considerable attention (Yang and Lu, 1988). Two main reasons can be raised for the interest in the study of this type of furnace, one of them is that the temperature control problem of the strip is not trivial due to the complexity of the process (Yang and Lu, 1986). The second one is that reheating furnaces are responsible for a significant amount of energy consumption in integrated steel industries (McBrien et al., 2016).

Considering that the heating of the strip is obtained by the absorption of the energy supplied by the atmosphere of the furnace, control problems of temperature and the air, besides burned fuel flows in each zone, arise. Added to these problems, the irregularities of the processed materials must be considered, which are due to the continuous process of annealing different types of steel with different widths and thicknesses. In addition, each type of steel has a temperature profile that must be guaranteed throughout the annealing process, which requires the control of different temperature levels in each zone of the furnace.

Therefore, designing effective controllers and implementing advanced control techniques, such as optimal control in reheat furnaces, is a challenging task, considering the process complexity, its nonlinear characteristics, significant time delays, high time constants, disturbances and several other factors of uncertainty (Zhang et al., 2002).

Additionally, as mentioned before, the reheating furnace is one of the main energy consuming equipment in the iron and steel industries. Its energy consumption accounts for 15–20% of the total energy consumed, and 70% of the energy consumption of the rolling process (Hua-Li et al., 2014; Guangjun, 2008). Consequently, the energy consumption reduction of the reheat-
The research on energy saving of reheating furnace mainly includes combustion process control, mechanism analysis of heat transfer process and optimization dispatch model (Lu et al., 2017).

This work presents improvements obtained in the dynamic control of the fuel gases used in continuous reheating furnaces of stainless steel of the company Aperam South America. In order to achieve that, a methodology that consists in the energy efficiency identification of furnaces, study and control design to increase this efficiency, and implementation of optimal control of the fuel gases is used.

The rest of this paper is organized as follows. Section 2 describes the process of stainless steel reheating furnace. Section 3 presents the optimal control problem of fuel gases and its solution. Section 4 presents experimental results obtained in a continuous reheating furnaces of Aperam South America. Finally, some conclusion remarks are presented in Section 5.

2 Process description

This section describes the process of the stainless steel continuous reheating furnace, from Aperam South America, to be optimized in this work. In Figure 1 it is presented the zones of the furnaces, which in total are distributed in 3 furnaces. Zones 1 and 2 belong to the furnace 1, zones 3 to 5 to the furnace 2 and zones 6 to 8 to the furnace 3. These furnaces are used to perform heat treatment in steel coils which were previously laminated. In order to perform that, the temperature of the steel strip measured in the outlet of furnace, indicated in Figure 1 by “PIR-3.2”, must be controlled through the temperature of each zone.

A temperature profile for the strip is required for its annealing, making it necessary to expose that to different temperature levels in each zone. As it is a combustion furnace, gas burners are used to heat their zones, where each one has eight burners. The gas used is a mixture of NG (Natural Gas) and BFG (Blast Furnace Gas). A mixing station, showed in Figure 2, controls the ratio of these gases according to the LCV (Lower Calorific Value) specified in an operational practice. The gases mixing station of NG and BFG with re-heating zones of the furnaces. In this diagram illustrates the interaction between the combustible gases mixing station of NG and BFG with reheating zones of the furnaces. In this diagram block, $LCV_{Opt}$ represents the optimized computation of the LCV setpoint ($lcv_{setpoint}$) according to the flows of each zone ($q_{ng}$); $NG\_Model(s)$ is the dynamic model of the NG flow in the mixing station; $Gl_{zi}(s)$ is the temperature dynamics model of the zone $i$; and $Gv_{zi}(s)$ is the gas flow dynamics model of zone $i$, which controls the flow through the NG network. In order to prevent disturbances, we adjust the $LCV\_Opt$ dynamics to be slower than $Gl_{zi}(s)$. On the other hand, $NG\_Model(s)$ and $Gv_{zi}(s)$ dynamics are faster than $Gl_{zi}(s)$ and $LCV\_Opt$.

This adjustment is performed by controlling the ratio of the BFG to NG blend. The BFG’s LCV ranges from 700 to 1.100 $Kcal/Nm^3$ depending of chemical composition. For LCV 1.000 $Kcal/Nm^3$, the approximated composition is 30% CO, 14% CO$_2$, 1% CH$_4$, 2% H$_2$, 49% N$_2$ and 4% H$_2$O. The NG’s LCV is approximately 10.000 $Kcal/Nm^3$. The set-point (SP) for the LCV is adjusted by the operator, which takes into account the energy demand of the furnace according to the production rate. The values are tabulated and made available to the operator through a document called standard practice. The LCV set-point can be adjusted from 900 to 4500 $Kcal/Nm^3$, but the minimum LCV is related to the current value of the BFG, while the maximum value is given by the pipe limit. A block diagram is presented in Figure 3, in which the BFG flow ($q_{bfg}$) with the LCV setpoint ($lcv_{setpoint}$) are used to generate the NG reference ($q_{ng\_ref}$), which is achieved considering the gas flow dynamics.

In this process there are still variations of strip velocity within the furnace, which causes variations in the flow of incoming cold material, generating disturbances in the temperature. Besides, there are disturbances generated by variations in the internal pressure and the coupling between zones into the furnace. This coupling occurs due to the physical connection between the zones and the internal pressure control system, which causes a displacement of the generated heat in each zone (Silveira and Raffo, 2016).

3 Optimal Control Design

In order to increase the energy efficiency of annealing furnaces and, consequently, produce at the lowest possible cost, this work proposes an optimal control strategy of the fuel gases. Figure 4 illustrates the interaction between the combustible gases mixing station of NG and BFG with reheating zones of the furnaces. In this diagram block, $LCV\_Opt$ represents the optimized computation of the LCV setpoint ($lcv_{opt}$) according to the flows of each zone ($q_{ng}$); $NG\_Model(s)$ is the dynamic model of the NG flow in the mixing station; $Gl_{zi}(s)$ is the temperature dynamics model of the zone $i$, and $Gv_{zi}(s)$ is the gas flow dynamics model of zone $i$, which is achieved considering the gas flow dynamics.

2124
3.1 Problem statement

Consider that the flow of the fuel gas mixture (NG plus BFG) \( q_{mg} \), in \( \text{Nm}^3/\text{h} \), combined with the lower calorific value \( lcv_{mg} \), in \( \text{Kcal/Nm}^3 \), produces the heat transfer rate in \( \text{Kcal/h} \) according to:

\[
e = q_{mg} \times lcv_{mg}.
\]

By expanding equation (1), it can be rewritten in function of the NG flow \( q_{gn} \), BFG flow \( q_{bfg} \) and their respective LCVs:

\[
e = q_{gn} \times lcv_{gn} + q_{bfg} \times lcv_{bfg}.
\]

From equation (2), note that the heat transfer rate necessary for the reheating process can be produced in order to optimize the use of the fuel gases, that is, by maximizing BFG, which does not have significant cost, and minimizing the NG consumption. Therefore, the proposed optimization problem is given by:

\[
\begin{align*}
\text{Minimize :} & & \delta e_{\text{min}}(q_{mg}, lcv_{mg}) = \\
& & |(\gamma \times q_{\text{max}_i}) - q_{mg_i}) \times lcv_{mg}|.
\end{align*}
\]

where \( \delta e_{\text{min}} \) is the function which represents the minimum increment of heat transfer rate among zones to be minimized, taking into account the established percentage of the maximum zone flow \( \gamma \), the maximum flow rate \( q_{\text{max}_i} \) of zone \( i \), the gas flow of the current mixture of zone \( i \) \( q_{mg_i} \), and the lower calorific value of the mixed gas \( lcv_{mg} \).

In order to solve this optimization problem in an iterative way, the cost function (3), assuming
constraints (4), is rewritten as:
\[
\Lambda(q_{mg}, lcv_{mg}, p_{grt}, q_{bfg}) = \\
\delta e_{min} - \left| \delta e_{min} \cdot \frac{P_{g} \cdot P_{max}}{P_{max}} \right| - \\
\left| \delta e_{min} \cdot \frac{q_{bfg}}{q_{max}} \frac{P_{max}}{P_{grt}} \right| - \left| \delta e_{min} \cdot \frac{q_{bfg}}{q_{max}} \right|,
\]
(5)
where different weights \( \lambda_p \) and \( \lambda_q \) are considered for the constraints. The cost function \( \Lambda \) is associated with the constraints, \( P_{max} \) is the maximum furnace pressure, \( p_{grt} \) is the greatest internal pressure among the furnaces, \( \lambda_p \) is the weight for furnace pressure constraint, \( q_{max} \) is the maximum total flow rate of the BFG, \( q_{bfg} \) is its actual total flow and \( \lambda_q \) is the weight for BFG flow constraint. In order, to solve this problem one must consider that there is only one gas mixture control station that feeds all the zones. Therefore, the calculation of the \( \delta e_{min} \) is performed for the pilot zone chosen among other zones, \( \delta e_{zn_i} \), which is at its flow limit. Another consideration should be due to the furnaces pressure, in which the greatest internal pressure value is the one that must be considered as constraints.

3.2 Algorithm

In order to apply the optimization problem of fuel gases, the algorithm was implemented in the process controller (PLC-5 Allen Bradley) with the following steps:

1. Calculate the heat transfer rate increment for each zone \( i \):
\[
\delta e_{zn_i} = ((\gamma \cdot q_{max}) - q_{mg}) \cdot lcv_{mg};
\]
(6)
2. Define the priority zone:
\[
\delta e_{min} = MIN(\delta e_{zn_i}),
\]
with \( i=1,...,8 \);
3. Define the furnace \( j \) with the greatest internal pressure:
\[
p_{grt} = MAX(p_{fn_j}),
\]
with \( j=1,...,3 \);
4. Compute the cost function (5):
\[
\Lambda(q_{mg}, lcv_{mg}, p_{grt}, q_{bfg}) = \\
\delta e_{min} - \left| \delta e_{min} \cdot \frac{P_{g} \cdot P_{max}}{P_{max}} \right| - \\
\left| \delta e_{min} \cdot \frac{q_{bfg}}{q_{max}} \frac{P_{max}}{P_{grt}} \right| - \left| \delta e_{min} \cdot \frac{q_{bfg}}{q_{max}} \right|;
\]
(9)
5. Compute the optimal LCV blend:
\[
lcv_{opt} = lcv_{mg} - \frac{\Lambda}{q_{gn} + q_{bfg}},
\]
(10)
6. Compute the optimal NG flow:
\[
q_{gn} = q_{bfg} \frac{lcv_{opt} - lcv_{bfg}}{lcv_{gn} - lcv_{opt}}
\]
(12)
About the task rate, considering the interaction of combustible gases’s blend with the furnace
temperature control, it was necessary adjust the maximum increase of optimum blend (LCV) to 1 Kcal/Nm$^3$ per second and maximum decrease 0.5 Kcal/Nm$^3$ per second to prevent disturbances on the temperature control. The time constants of temperature controls are around 45 seconds and for flow controls are 5 seconds. The weights $\lambda_p$ and $\lambda_q$ were adjusting considering the influence of each variables on process, in which a good adjustment was achieved with $\lambda_p = 10$ and $\lambda_q = 0.1$.

4 Experimental Results

Several tests have been performed in the continuous reheating furnaces of stainless steel of the company Aperam South America, from which 640 tons of material have been produced using the optimal control of fuel gases proposed in this work.

Figure 5 to 10 show the process variables behavior, which corroborate the improvement of gases consumption efficiency. The evolution of the objective function associated with the constraints can be seen in Figure 5. When the optimal approach is turned on, the value of the cost function converges to zero, as it is expected. In some moments the cost function value increases or becomes negative due to process variations, but often the optimal control works to achieve the minimum cost function (5). On the other hand, when it is turned off the fuel gases system returns to work from away the optimal region.

![Figure 5: Behavior of the objective function associated to constraints.](image)

From Figure 6, note that when the optimal approach is turned on, no changes on the material temperature is observed. Some disturbances has occurred on the material temperature, which was due to the exchange of the type of material. This was only possible because the heat transfer rate was maintained approximately constant, which can be observed through the compensation between the flow of NG (Figure 8) and BFG (Figure 9). This enabled the reduction of NG consumption. In addition, it is possible to note that the constraints on the furnace internal pressure (Figure 7), the BFG flow (Figure 9), and the LCV (Figure 10) were respected.

In the production of 640 tonnes of several materials, a significant decrease in NG consumption (Figure 11) and a significant increase in BFG consumption (Figure 12) were achieved. However, for each processed material the NG consumed reduction was different (see Figure 11) due to the LCV parameter obtained from the operational practices, which was not set in an optimal sense.
With the development of this work, according to the presented experimental results obtained by annealing several types of produced steel, a reduction in the consumption of fuel gas was achieved, maintaining the same thermal efficiency of the furnaces. This reduction was possible by using the gas mixing station, minimizing the natural gas, which is one of the most costly inputs of this process, and maximizing the usage of BFG that is produced in the plant. The NG consumed reduction obtained was different for each annealed material. However, the lowest reduction was 9.4 %, which represents an average monthly savings of approximately 66 thousand m$^3$ of gas.

During the experimental results, LCV parameters have been obtained from the operational practices, which are not set in optimal values. This procedure is understandable since there was nothing beyond the operator sensitivity and parameter standardization documents in order to control the gas mixture. Future works goal in designing an adaptive optimal control in order to improve the energy consumed reduction and counterattack the operational issues.

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