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Research Article

Monitoring and adjustments of combustion parameters in reheating furnaces using a digital tool

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Abstract

Improving the energy efficiency of a reheating furnace is not a simple task because it involves a large number of parameters that, most of the time, are connected in a complex way. To be feasible, the evaluation of such a vast number of variables must be supported by digital tools that are embedded with artificial intelligence. The SMS group has developed a digital tool that effectively supports operators and engineers in enhancing energy efficiency within the reheating furnaces of hot rolling mills. This paper presents a quick study case of the use of *Viridis Performance*, an application of *Viridis Energy & Sustainability Suite*, in the analysis and correction of the deviations in the air-gas ratio of a reheating furnace. In this study, a production period of 8 hours was evaluated, during which the air-gas ratio presented a significant deviation. Analysis showed that the probable cause of the deviation was a production stoppage where the furnace control was set to manual mode. A reduction potential of 0.26 Gcal/h and a 13 kg/h decrease in CO_2 emissions were identified. *Viridis Performance* would support the process by guiding the decisions of the operator in a way that energy losses would be avoided or minimized. The potential economic savings were also quantified. This task is performed in the system by *Viridis Moneybox*, which is another application of *Viridis Energy & Sustainability Suite*. The results showed potential savings of 13 US $/h. In addition to the gains and savings outlined in this study, the utilization of *Viridis Performance* encompasses numerous other advantages, such as enhanced operational standardization and improved process capability, to name just a few.

Keywords

Digital tool, Reheating furnace, Combustion, Energy efficiency

1. Introduction

World energy consumption has been increasing continuously in recent decades, showing an increase of 11% in 2020 compared to 2019. Industrial energy consumption increased by 8% in the same period, representing 62% of world energy consumption [1]. Steel production is one of the most energy-intensive industrial processes, with a consumption equivalent to 18% of the world's energy [2]. Although the most significant consumers in the steel production chain are concentrated in upstream processes, such as blast furnaces, basic oxygen furnaces, and electric arc furnaces, energy consumption in downstream processes is far from insignificant. Among downstream processes, hot rolling is one of the largest sources of energy consumption [3].

In this context, due to their wide applicability, the reheating furnaces' energy consumption and efficiency is a topic of interest for several reasons, including:

- Important cost driver;
- An important emission source;
- Indirect influence on product quality.

The increase in energy efficiency of heating furnaces has been the subject of study in several papers in the literature:

Chen, Chung, and Liu [6] evaluated the energy consumption and performance of reheating furnaces in a hot strip mill through numerical predictions and practical measurements. The results showed that heat recovery systems correspond to 15% of the furnace's energy input, highlighting the importance of maintenance and correct management of this equipment. Khalid et al. [7] evaluated combustion with oxygen enrichment for reheating furnaces to reduce natural gas consumption in pusher furnaces. The results suggest that oxygen enrichment in the reheat furnace can significantly impact the environmental performance of the hot mill and contribute to the transition to steelmaking with a lower carbon footprint. Schmitz et al. [8] compared a state-of-the-art natural gas-fired reheating furnace to an electric heating furnace, a hydrogen-air heating furnace, and finally to a heating furnace, hydrogen-oxygen heating. The results showed significant potential for reducing CO_2 emissions, depending on the country's specific electricity production mix and future expansion of renewable energy sources. Furthermore, increasing H_2 production efficiency will reduce primary energy consumption and CO_2 emissions for reheating furnaces.

Digitalization is a keyword within the concept of Industry 4.0, along with the continuous search for increased energy efficiency and productivity. Digital tools, through real-time systems integration, provide increased productivity and cost reduction, greater process consistency, continuous quality monitoring, reduced breakdowns through monitoring of critical parameters, greater understanding of processes and equipment, and increased operational standardization through constant tracking of specific goals, among other things.

The present work will use a digital tool, *Viridis Performance*, to perform an exploratory analysis of the main reheating furnace process parameters, such as air-gas ratio during transient periods, to identify deviations, increase energy efficiency, and reduce energy consumption.

Viridis Performance is a digital tool from the SMS group embedded with state-of-the-art methodologies based on artificial intelligence and mathematical models. It ensures that energy efficiency actions are applied daily, reducing energy costs without equipment modification or production disruption.

2. Methodology

The methodology proposed in this work consists of performing an energy balance on a real operating scenario of a reheating furnace and a subsequent analysis of deviations that could be avoided using Viridis Performance. The reheating furnace is of the walking beam type and operates with coke furnace gas (COG). The methodology was divided into the following subsections: “Energy Balance” and “Analyses,” as shown below.

2.1. Energy Balance

The energy balance used in this study follows the first law of thermodynamics [9]. The control volume is given in Figure 1, and the energy balance is defined by equations 1 to 7.

$$\dot{E}_{in} = Cs_{air} + Cs_{fuel} + \Delta Hc_{fuel} \quad (1)$$

$$\dot{E}_{out} = Cs_{fumes} \quad (2)$$

$$\Delta E = \dot{E}_{in} - \dot{E}_{out} \quad (3)$$

$$\Delta Hc_{fuel} = \sum_{i=1}^{k} fuel\ (i) + O_2 \xrightarrow{\Delta h0} CO_2 + H_2O \quad (4)$$

$$Cs_{air} = \sum_{i=1}^{k} Cs_{air}(i)_{@Tair\ [°C]} - Cs_{air}(i)_{@25\ [°C]} \quad (5)$$

$$Cs_{fuel} = \sum_{i=1}^{k} Cs_{fuel}(i)_{@T_{fuel}\ [°C]} - Cs_{fuel}(i)_{@25\ [°C]} \quad (6)$$

$$Cs_{fume} = \sum_{i=1}^{k} Cs_{fumes}(i)_{@Tfumes\ [°C]} - Cs_{fumes}(i)_{@25\ [°C]} \quad (7)$$

In which $\dot{E}_{in}$ is the input energy defined by Eq. (1), in (kcal/h); $\dot{E}_{out}$ is the output energy defined by defined by Eq.(2), in (kcal/h); ΔE is the available energy balance defined by Eq.(3), in (kcal/h); Cs_{air} is the sensible heat from air defined by Eq.(5), in (kcal/h), whose components are listed Table 2; Cs_{fume} is the sensible heat from the fumes defined by Eq.(7), in (kcal/h), whose components are listed in Table 3; Cs_{fuel} and ΔHc_{fuel} are the sensible heat and the fuel combustion energy defined by Eq. (6) and Eq. (4), respectively, and whose components are listed in Table 1.

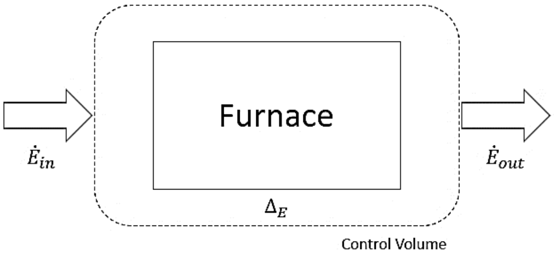

Figure 1. Energy balance control volume

Table 1. Fuel gas composition

		% Volumetric
1	CO_2	2.9
2	N_2	6.5
3	H_2	57.9
4	CO	7.5
5	CH_4	23.2
6	C_2H_6	2.2

Table 2. Air gas composition

		% Volumetric
1	O_2	21
2	N_2	79

Table 3. Fumes composition

CO_2
H_2
N_2
O_2
H_2O

2.2. Analyses

Subsequent analyses are made for a billet reheating furnace of the walking beam type that operates with coke furnace gas (COG). Such analyses are based on a typical production day.

As shown in Figure 2, the air-gas ratio remains at the same level most of the time. However, a significant deviation is evident between 4 am and 12 pm. The native resources of *Viridis Performance* were used to conduct an exploratory analysis for the period and determine the cause of this deviation.

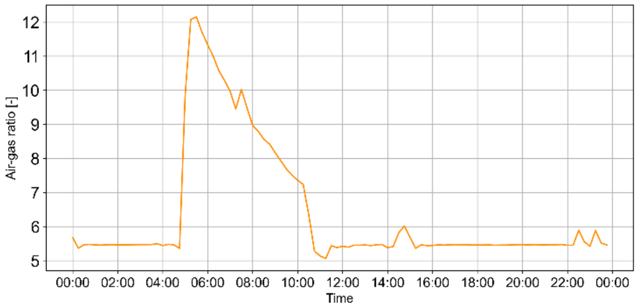

Figure 2. The air-gas ratio for one production day

The reheating furnace operates with COG, which is a by-product gas and, as such, may have its availability affected by process events. In case of unavailability and/or low availability of this gas, it is possible to use natural gas to supply the energy demand of the furnace, which changes the air-gas ratio. To evaluate if the air-gas ratio was changed due to a change in the fuel, the variation of the lower heating value (LHV) was plotted for the analyzed period, as shown in Figure 3. As can be seen, the maximum LHV variation was less than 5%, which does not indicate a fuel change.

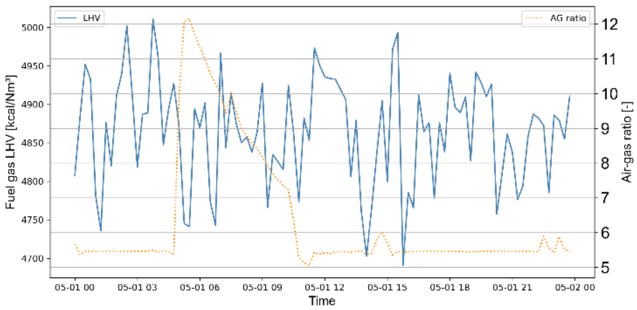

Figure 3. COG LHV variation

The next point to be checked is the production rate of the furnace. As seen in the graph of Figure 4, there is a stoppage in the furnace charge when the air-gas ratio presents a deviation. The curve in blue refers to an incremental scale that records the mass of the billets loaded into the furnace. Thus, the flat levels indicate periods when the billet charge was not recorded. The sudden drop in the graph shows the shift change period when the incremental counter is reset. The usage of *Viridis Performance* allowed a crosscheck of this hypothesis with production management data to confirm this assumption.

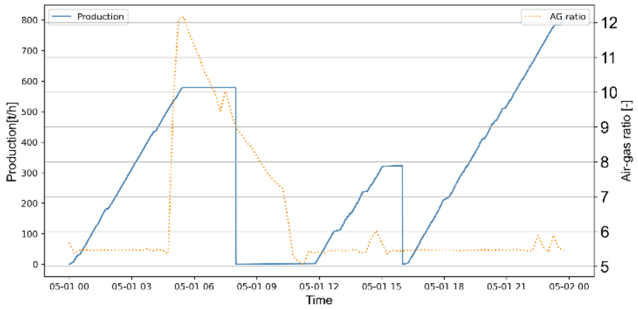

Figure 4. Reheating furnace production rate

Figure 5 shows that the operator manually reduced the furnace temperature during the stoppage. This hypothesis is validated by observing the temperatures of the control zones. The dashed line shows the setpoint of the control zones remained constant, while the value measured by the control thermocouples indicates a drop in the temperature (solid line). The additional analysis of air and fuel flows in each control zone shows a reduction for both, but the air-gas ratio was not maintained.

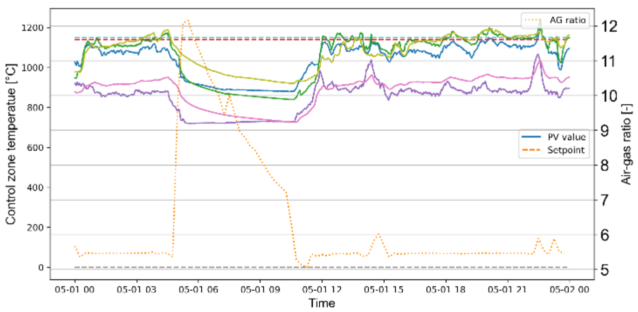

Figure 5. Control zones temperature

It is unclear whether the standard operational procedure requires a change to manual operation in case of prolonged stoppages. However, the reduction in the furnace temperature could have been achieved by keeping the air-gas ratio constant with lower energy input. Using *Viridis Performance's* resources to carry out the energy balance, whose methodology was previously described, it is possible to quantify the impact of this approach. The results found in the energy balance will be discussed in the next section.

3. Results and Discussion

An energy balance was performed for two different scenarios. The first refers to the actual production period discussed in the previous section. The second aims to quantify what energy input ($\dot{E}_{in}$, Eq. (3)) is needed to maintain the same net energy (ΔE, Eq. (3)) of scenario one if the air-gas ratio were kept at the same level before the deviation.

Table 4 shows the operational parameters used in the energy balance. The actual average values shown in the previous section were used for scenario one. For scenario 2, historical data were used, whose operation took place in conditions similar to those analyzed. For this purpose, *Viridis Performance* was used to define representative values from similar scenarios. The values of free oxygen in the fumes were calculated through the stoichiometric analysis of combustion.

Table 4. Energy balance parameters

Scenario	Avg. AG ratio	Fumes O_2 level	Air temp.	Fumes temp.
1	8:1	11%	260 °C	500 °C
2	5:1	4.7%	350 °C	650 °C

Table 5 summarizes the energy balance results for the two scenarios.

Table 5. Energy balance results

Scenario	$\dot{E}_{in}$ [Gcal/h]	ΔE [Gcal/h]	$\dot{E}_{out}$ [Gcal/h]	CO2 [Kg/h]
1	6.95	4.79	2.16	1085
2	6.69	4.79	1.9	1072

Analyzing the results, it can be concluded that by reducing the air-gas ratio from 8:1 to 5:1, the energy input necessary to maintain the same net energy in the furnace (ΔE = 4.79 Gcal/h) is decreased by 3.74% (0.26 Gcal/h). This occurs because, although the temperature of the fumes is higher in scenario two compared to scenario 1, the flue gas flow rate is significantly lower, which results in a decrease of 12% in energy loss through the fumes. The higher fumes temperature also results in a higher combustion air temperature, contributing to lower fuel demand.

Reducing energy consumption is a direct benefit of better control of combustion parameters. In addition to reducing gas consumption, lower CO_2 emissions are a secondary benefit. Performing the stoichiometric combustion analysis, scenario 2 emits 1.2% (13 kg/h) less CO_2 than scenario 1. Figure 6 and Figure 7 show the energy balance results.

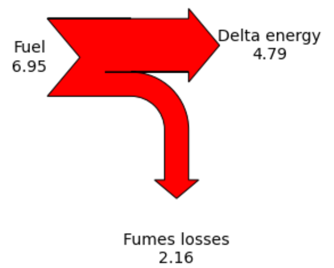

Figure 6. Energy balance results for scenario one

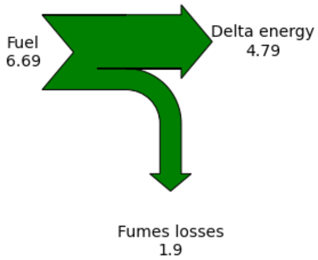

Figure 7. Energy balance results for scenario two.

4. Conclusion

The present work used *Viridis Performance* to identify deviations in the combustion parameters of a billet reheating furnace. *Viridis Performance* is an application of the *Viridis Energy & Sustainability Suite* that allows the real-time monitoring of hundreds of parameters through artificial intelligence resources and machine learning techniques. It enables the calculation and control of several indicators applied to different contexts, such as production levels, product mixes, etc.

A period of 8 hours was identified in which the air-gas ratio of the reheating furnace showed a significant deviation. Using native resources of *Viridis Performance*, an exploratory analysis was performed indicating that the probable cause of this deviation was a production stoppage where the operator placed the furnace control system in manual mode, and the adopted procedure to reduce the energy input did not keep constant the air-gas ratio. Through an energy balance, a potential energy saving of up to 3.7% was identified only by controlling the AG ratio. In addition, a reduction of 1.2 in the amount of CO_2 emitted would be possible.

Viridis Performance can continuously monitor hundreds of parameters, triggering alerts and checklists for the operator in case of deviations. In the case presented here, for example, when detecting a deviation in the air-gas ratio, the system would have triggered an alert and a checklist of corrective measures, guiding the operator to follow the operating standard. In cases where the deviation persists, new alerts are triggered, which can, for example, be configured so that alerts can be forwarded to the operation supervisor and/or to the operation management.

Another feature of the *Viridis Energy & Sustainability Suite* is the *Viridis Moneybox*. *Viridis Moneybox* prices the cost of each deviation from the operating standard. For example, taking a cost of 51 US $/Gcal as a reference, the potential reduction would be 13 US $/h only by controlling the AG ratio. Continuously pricing deviations are especially useful in defining the company's strategic plan and can be used as a benchmark for prioritizing projects and maintenance activities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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