





# Analysis of the influence of moisture in steelmaking gases on the lower heating value and thermal performance

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## Abstract

Steelmaking gases are key energy sources in integrated coke-based steel plants, but their high moisture content—introduced during wet gas cleaning—can significantly reduce combustion efficiency. This study quantifies the impact of residual moisture on the lower heating value (LHV) of blast furnace gas (BFG) and its effect on boiler thermal performance. A thermodynamic model was developed to calculate dry, wet, and useful LHV, incorporating psychrometric principles and process conditions. Results show that moisture can reduce the effective LHV by up to 12%, leading to higher specific fuel consumption and financial losses, especially on hot days when condensation is limited. The findings emphasize the need to adjust control systems and performance indicators to account for moisture, ensuring accurate energy management and improved operational efficiency.

**Keywords:** Blast furnace gas; Moisture; Lower heating value; Boiler efficiency.

## 1 Introduction

Integrated cokebased steel plants are highly energyintensive facilities, in which steelmaking gases—blast furnace gas (BFG), coke oven gas (COG), and LinzDonawitz gas (LDG)—constitute the primary fuel streams for stationary combustion processes. As unavoidable byproducts of metallurgical operations, these gases exhibit physicochemical and thermodynamic properties that fundamentally shape the performance of thermal equipment such as boilers and industrial furnaces. Their inherently low and highly variable calorific values, large volumetric flow rates, and fluctuating chemical compositions pose significant challenges to combustion stability, thermal efficiency, and process control. Consequently, understanding and properly managing the behavior of these gases is essential for ensuring reliable operation, maximizing energy recovery, and maintaining optimal efficiency in integrated steelmaking systems [1,2].

One of the defining characteristics of steelmaking gases is their high concentration of inert species — primarily nitrogen and carbon dioxide — which dilute the combustible components and consequently reduce the lower heating value (LHV). This dilution effect not only limits the energy available for combustion but also contributes to less efficient heat transfer, uneven gas flow distribution, and overall reductions in thermal efficiency across stationary combustion systems in integrated steel plants [3-7]. Furthermore, the wet gascleaning systems used to remove particulates and impurities introduce substantial moisture into the gas stream.

Although a portion of this moisture condenses along the distribution network, the extent of condensation is highly sensitive to environmental conditions, particularly ambient temperature, which can significantly alter the moisture content reaching enduse equipment [8].

On hotter days, the reduction or even the interruption of water vapor condensation can result in a higher moisture fraction in the gas feeding combustion systems, negatively affecting the thermal performance and efficiency of the processes. Despite the relevance of this phenomenon, its impact on the energy management of steel plants is still scarcely discussed in technical literature. In this context, the present study carries out a detailed simulation on the effect of residual moisture in the BFG, analyzing its influence on the LHV and, consequently, on the thermal performance of boilers. The obtained results highlight the importance of considering the dry LHV in the evaluation and management of the energy indicators of steel mills, contributing to a more efficient and safer operation.

## 2 Development

This section will present definitions of some important concepts for the development of the work, as well as the methodology for compensating the moisture content of compound gases based on psychrometric concepts and the implementation of moisture compensation in control loops and Key Performance Indicators (KPI) calculations.

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## 2.1 Higher heating value (HHV) and lower heating value (LHV)

The Higher Heating Value (HHV) is defined as the total amount of heat released by the complete combustion of a unit mass or volume of a fuel, assuming that all combustion products, including water (both from the initial moisture and that generated by the reaction), are cooled down to the reference temperature, allowing the condensation of water vapor.

During this condensation process, the latent heat of vaporization of water is released and, therefore, included in the HHV value. Essentially, the HHV accounts for all recoverable thermal energy from the combustion, representing the maximum energy available in the fuel [9].

On the other hand, the LHV adopts a more practical perspective, considering that the water formed during combustion remains in the gaseous state in the combustion products, and its latent heat of vaporization is not recovered. This approach reflects scenarios where the exhaust gases are released at high temperatures, preventing water condensation [8].

## 2.2 Gas washing and cleaning process

The gases generated in steelmaking processes leave their sources at high temperature and with a large amount of solid particles. Therefore, gas washing systems typically involve a process of cooling, washing the gas to remove particulate matter (if the cleaning is wet), followed by the removal of part of the moisture. This study focuses primarily on blast furnace gas (BFG); thus, the typical operation of the cleaning and washing process for this fuel will be described below.

The gas leaving the blast furnace carries solid particles, therefore the gas must undergo two cleaning stages: dry and wet, as shown in Figure 1 [11].

As observed in Figure 1, a typical BFG cleaning system initially subjects the gas to a dry process, generally a dust collector and cyclone, where a large quantity of the coarser dust particles is removed. Subsequently, the gas undergoes a wet process, where water spraying provides the final gas cleaning stage, removing finer dust particles [12].

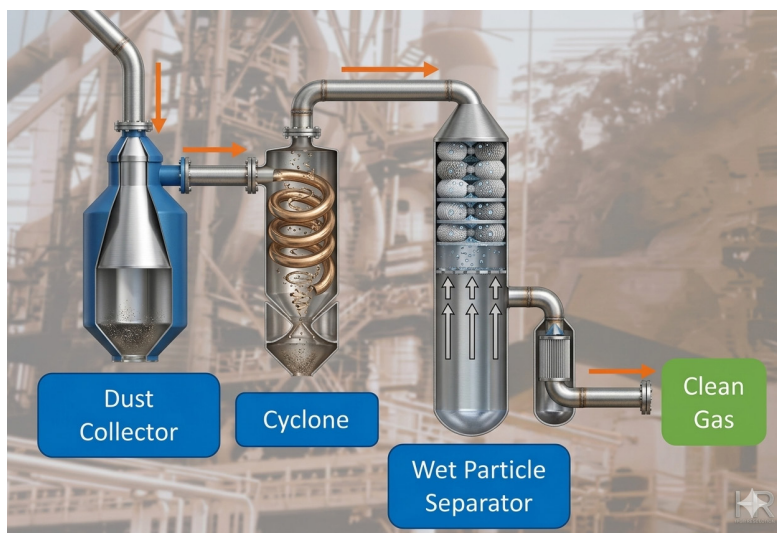
As previously noted, during the steel gas production and washing processes, moisture is added to the gas, which is partially removed by condensation along the distribution pipelines due to pressure and temperature. The presence of this moisture in the fuel influences the LHV; however, as will be seen next, calorimeters, for example, remove the moisture before analysis. Thus, throughout this work, when the term dry LHV is used, it should be understood as the result of the measurement or calculation with the moisture present in the gas removed, and the wet LHV refers to the result with the moisture still present. The useful LHV is the wet LHV minus the energy required for vaporizing the moisture during combustion.

## 2.3 LHV Measurement and analysis systems

In industrial fuelgas measurement systems (e.g., calorimeters and process gas chromatographs), the reported LHV typically reflects the dry gas basis, because the sampling system conditions the sample by removing moisture prior to analysis. This conditioning improves repeatability and comparability across operating conditions but does not represent the LHV of the moist gas actually delivered to consumers.

It is important to distinguish the roles of sensible and latent heat in the presence of water in steelmaking gases:

- Water vapor (gas phase): When water is present as vapor, it does not require vaporization; instead, part of the available combustion energy is spent as sensible heat to raise the vapor temperature from the line/inlet temperature to the exhaust/flame temperature.



**Figure 1.** Schematic of a blast furnace gas (BFG) cleaning system [10].

This reduces the useful energy available for steam generation and directly affects performance indicators (e.g., specific fuel consumption and boiler efficiency).

- Liquid water (condensed phase): If the gas temperature falls below the dew point during cooling, some water condenses and is transported as liquid droplets or films. In this case, during combustion the system must first supply latent heat of evaporation to reevaporate liquid water, in addition to sensible heating of the resulting vapor. This extra energy demand further reduces the useful LHV available to the process.

The flowchart (Figure 2) below better illustrates the process of gas withdrawal and analysis.

### 2.4 Methodology for moisture compensation based on thermodynamic concepts related to gas and vapor mixtures

In thermodynamics, the term ‘vapor’ refers to the gaseous phase of a substance at temperatures below its critical temperature, where condensation is possible if the pressure approaches the saturation pressure. This means that water in blast furnace gas behaves as vapor because it is below its critical temperature and near the saturation region, making condensation likely when the gas cools or pressure changes. This characteristic is essential for modeling moisture behavior in BFG distribution systems [13,14].

This is precisely what occurs with the mixture of blast furnace gas and water vapor, originating from the gas scrubbing process previously explained.

To model this phenomenon, thermodynamic concepts related to gas and vapor mixtures will be used. As previously mentioned, for the sake of simplicity, this study will focus

only on blast furnace gas (BFG), since it is the primary fuel for the boilers and also the gas most affected by moisture.

Table 1 presents the volumetric and mass compositions of dry BFG, as well as some important characteristics that will be used in the following calculations to calibrate the model [15-17].

In addition to the table above, it is important to explain that this modeling is being performed considering the Gerdau Ouro Branco plant, where there are two blast furnaces located approximately 1000 m from the boilers of the power plant, and together they supply about 460,000 Nm<sup>3</sup>/h of BFG to the distribution system. All calculations are performed for three representative points in the system:

- immediately after the wet gas scrubbing process, where the gas is assumed to be saturated with moisture at the measured temperature and pressure;
- after the Top Pressure Recovery Turbine (TRT), assuming isothermal expansion and conservation of water content unless condensation occurs [18,19]; and
- at the boiler inlets, where the actual conditions of temperature and pressure are applied.

This approach allows the model to capture the effect of moisture throughout the distribution system and its impact on the lower heating value (LHV) and thermal performance.

Table 2 presents the temperature and pressure of the gas at each point.

For tractability, BFG is treated as an ideal gas mixture of noncondensable species (CO, CO<sub>2</sub>, N<sub>2</sub> and H<sub>2</sub>), while water is handled explicitly as vapor and, when the dew point is exceeded, as liquid.

After this definition, the absolute humidity of the BFG must be calculated using Equation (1), derived from the ideal gas equation of state:

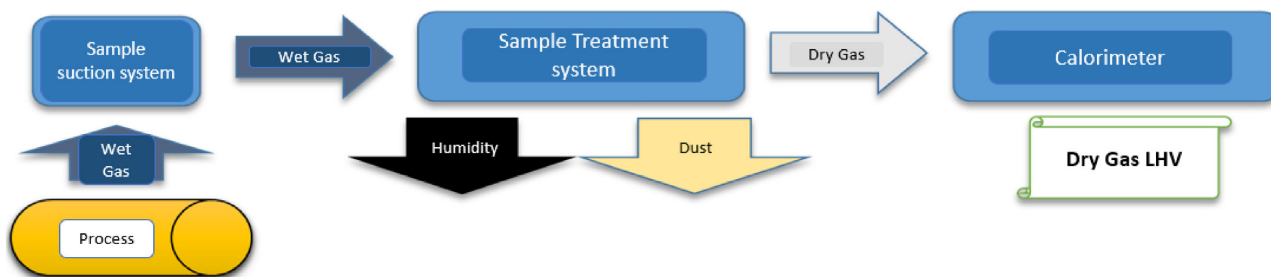


Figure 2. Flowchart of the gas withdrawal and analysis process.

Table 1. Composition and characteristics of dry Blast Furnace Gas

Element	% vol	Molar Mass (g/mol)	% mass	LHV (kcal/Nm <sup>3</sup> )
CO	24.40%	28.01	22.09%	12,625
H <sub>2</sub>	3.10%	2.02	0.20%	10,792
CO <sub>2</sub>	23.30%	44.01	33.15%	0
N <sub>2</sub>	49.20%	28.01	44.56%	0
Blast Furnace Gas	100.00%	30.93	100.00%	3,416

**Table 2.** Temperature and pressure of BFG at each point in the system

Item	Unit	After gas washing	After TRT	In the boilers
BFG Temperature	°C	60	60	to be determined
Gauge pressure	kPa	160.00	5.88	5.88
Atmospheric pressure	kPa	101.33	101.33	101.33
Absolute pressure	kPa	261.33	107.21	107.21

$$\omega = \frac{M_v}{M_{BFG}} \times \frac{P_v}{P_{BFG} + P_v} \quad (1)$$

Where  $M_v$  and  $M_{BFG}$  (g/mol) are the molar masses of the vapor and the BFG, respectively, and  $P_v$  and  $P_{BFG}$  are the vapor pressure and the BFG pressure (kPa).

The vapor pressure can be considered equal to the saturation pressure at the fluid temperature  $P = P(T_{sat})$ , since the vapor pressure cannot exceed the saturation pressure; if this occurs, the excess water will condense. Furthermore, in some locations where absolute humidity is conserved (after passing through the Top Turbine), the vapor pressure may be calculated by equation (1).

The wet LHV is then determined of the BFG according to Equation (2):

$$LHV_{wet} = (1 - y_{H_2O}) \times LHV_{dry} \quad (2)$$

Where ( $y_{H_2O}$ ) is the molar fraction of vapor (%) which is determined via Equation (3):

$$y_{H_2O} = \frac{P_v}{P_{total}} \quad (3)$$

Next, the density of the BFG and the vapor density at STP (standard temperature and pressure) are calculated using Equations (4) and (5):

$$\rho_{BFG} = \frac{M_{BFG}}{V_{MSTP}} \quad (4)$$

$$\rho_{steam} = \frac{M_{H_2O}}{V_{MSTP}} \quad (5)$$

Where ( $V_{MSTP}$ ) is the molar volume at STP (22.414 Nm<sup>3</sup>/kmol).

The next step is to calculate the volumetric flow rates of dry gas, wet gas, and moisture in Nm<sup>3</sup>/h as well as the moisture mass flow rate using Equations (6) to (8):

$$V_{wetBFG} = V_{BFGtotal} \times (1 - y_{H_2O}) \quad (6)$$

$$V_{moisture} = V_{BFGtotal} \times (y_{H_2O}) \quad (7)$$

$$\dot{m}_{moisture} = V_{moisture} \times \rho_{steam} \quad (8)$$

Once the moisture mass flow rate is obtained, it is possible to quantify the energy consumed during combustion to raise the temperature of the vapor up to the temperature reached during combustion, through Equation (9):

$$q_{H_2O} = \dot{m}_{H_2O} \times \left( \int_{T_1}^{T_2} c_{p, mass}(T) dT \right) \quad (9)$$

Where T1 is the BFG temperature at the boiler inlet and T2 is the flame temperature of the BFG, (1,333 °C) [20]. And to calculate the cp was used the Cp(T) model of Shomate/Nasa.

Then, the useful LHV can be obtained, i.e., the LHV subtracting the energy required to raise the temperature of the moisture present in the BFG, by Equation (10):

$$LHV_{useful} = LHV_{wet} - \frac{q_{H_2O}}{V_{totalBFG}} \quad (10)$$

The next step is to determine the possible steam production using the three LHVs (dry, wet, and useful) and then calculate the specific consumption of the boiler.

In this case, the specific consumption will be calculated with and without the effect of moisture correction on the LHV, meaning it will be calculated using the LHV of dry BFG and then using the LHV of wet BFG, both determined with the actual steam production obtained earlier using the useful LHV. To calculate the steam production, Equation (11) [21], 2022 will be used:

$$\Pi_{steam} = \frac{V_{BFG} \times LHV_{useful}}{cons. esp_{BFG}} \quad (11)$$

Table 3 presents the results of some parameters previously formulated for a single ambient temperature point in order to demonstrate that the model was calibrated.

It can be observed that the obtained results were satisfactory and relatively close to real data, which will be presented in the next chapter.

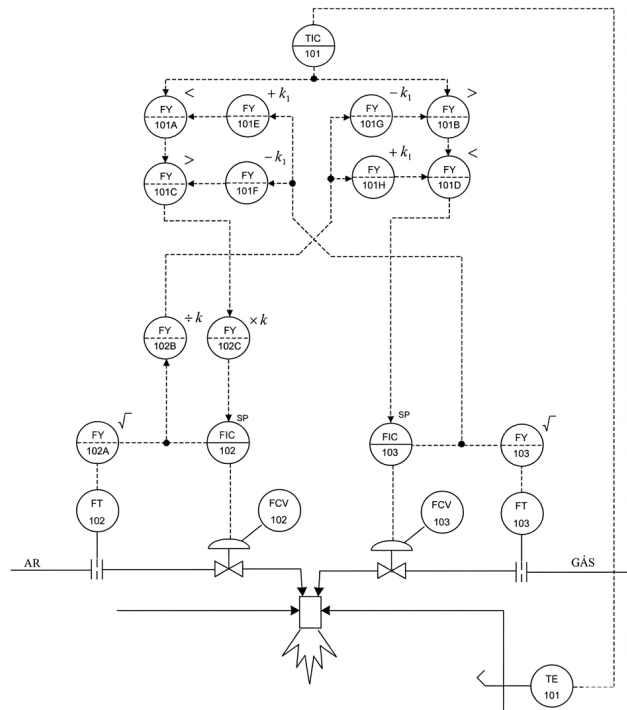
## 2.5 Necessary changes in process control systems and performance analysis systems

Based on the calculations presented above and the behavior observed in industrial processes, it becomes necessary to implement changes in the control systems of the consumption unit aiming to optimize combustion processes and make performance indicators more accurate. These adjustments are desirable in basically all consuming processes, such as boilers, reheating furnaces, and regenerators.

In these processes, there are control loops responsible for optimal combustion adjustment, which aim to maintain the air/gas ratio in the region of highest efficiency. These loops, usually of the cross-limit type, use a factor to adjust the stoichiometric air-to-fuel ratio.

**Table 3.** Results of the parameters formulated above

Item	Unit	After Gas Washing	After TRT	In Boilers
Ambient temperature	°C	25.00	25.00	25.00
Absolute humidity	kg/kg	0.0481	0.0481	0.0167
Total heat loss	W	6.03E+06	6.03E+06	6.03E+06
Out BFG temperature	°C	60.00	60.00	24.05
Steam pressure	kPa	19.95	8.18	2.99
Molar fraction of vapor	%	7.63%	7.63%	2.79%
Dry BFG density	kg/Nm <sup>3</sup>	1.38	1.38	1.38
Wet BFG density	kg/Nm <sup>3</sup>	1.34	1.34	1.36
Steam density	kg/Nm <sup>3</sup>	0.80	0.80	0.80
Total BFG flow rate	Nm <sup>3</sup> /h	460,000	460,000	460,000
Dry BFG flow rate	Nm <sup>3</sup> /h	424,890	424,890	447,153
Moisture flow rate	Nm <sup>3</sup> /h	35,110	35,110	12,847
Moisture mass flow rate	kg/h	28,227	28,227	10,328
Dry LHV	kcal/Nm <sup>3</sup>	815.81	815.81	815.81
Wet LHV	kcal/Nm <sup>3</sup>	753.54	753.54	793.02
Useful LHV	kcal/Nm <sup>3</sup>	713.36	713.36	778.32



**Figure 3.** Example of a double cross-limit combustion control loop.

Therefore, it becomes necessary to apply a correction in the air/gas ratio based on the fuel moisture content, which would allow for a more accurate combustion adjustment. This correction becomes more important in systems where no O<sub>2</sub> or CO gas analysis system exists in the exhaust gases.

The correction of the air/gas ratio correction factor can be obtained similarly to the wet LHV, as shown in Equation (12):

$$AirGas_{wet} = (1 - y_{H_2O}) \times AirGas_{dry} \quad (12)$$

Figure 3 presents, as an example, a combustion control loop of the double cross-limit type, where the variable K represents the air-to-fuel ratio setpoint, which should be adjusted according to Equation (12).

Another situation in which it is beneficial to compensate for moisture in the LHV of gases is in gas mixing stations, such as in the reheating furnaces of rolling mills. In these cases, the LHV of the mixed wet gas can be calculated based on the wet LHV of the incoming gases to the mixer, rather than from the dry LHV, as is normally implemented in control loops.

In various processes, an energy efficiency indicator (specific fuel consumption) is calculated based on the ratio between the total input energy and the production of the respective process.

Since the input energy is obtained by multiplying the fuel flow rates by their respective LHVs, this figure is directly influenced by the gas moisture throughout the day, which could suggest a false indication of performance loss during hot days. Therefore, it is also necessary to perform the specific fuel consumption calculations based on the useful LHV of the gases. Next, we will conduct a more detailed study of the impact of moisture on the specific consumption of boilers.

### 3 Results and discussion

This section presents the results obtained from the previously developed model applied to hourly data for days with milder temperatures and days with higher

temperatures in order to compare the results with real data from some boilers.

Figure 4 shows the results obtained with the model for specific consumption with and without moisture correction on a day with higher ambient temperature (01/21/2025). As can be seen, specific consumption increases with ambient temperature because the higher the ambient temperature, the lower the heat loss from the BFG to the boiler, and consequently, the lower the steam condensation. Under extreme conditions, when the ambient temperature is very high, the BFG temperature can remain above the dew point temperature, causing no condensation to occur, thereby intensifying the impact on the boiler.

Figure 5 shows the specific consumption with and without moisture correction for a day with milder temperatures (04/14/2025). As can be seen, specific consumption also increases with ambient temperature; however, the increase is much milder since the variation in ambient temperature was smaller than on day 1, as shown in the previous graph.

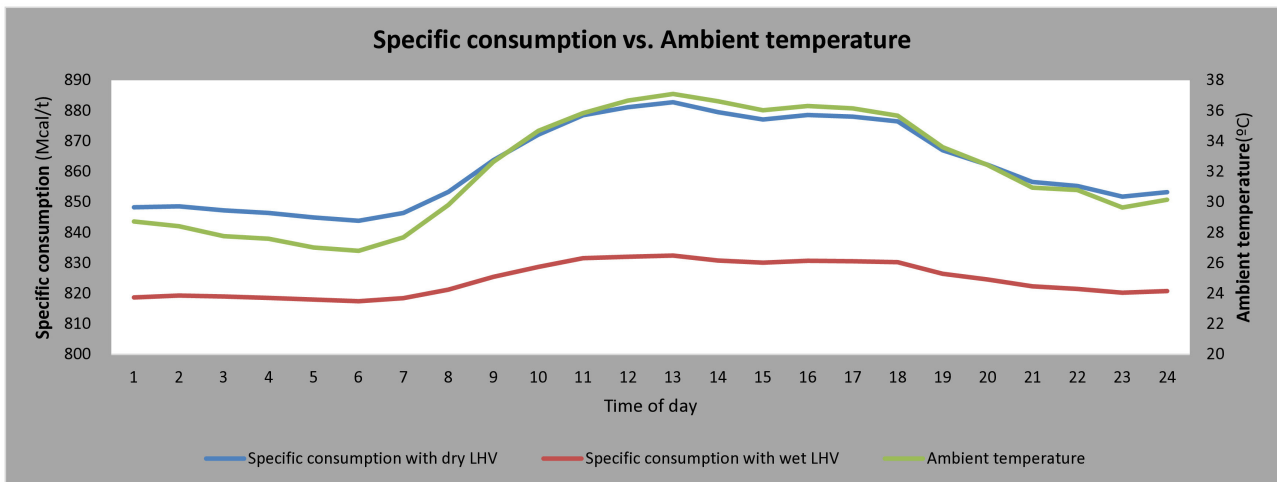


Figure 4. Variation of specific consumption with higher ambient temperature.

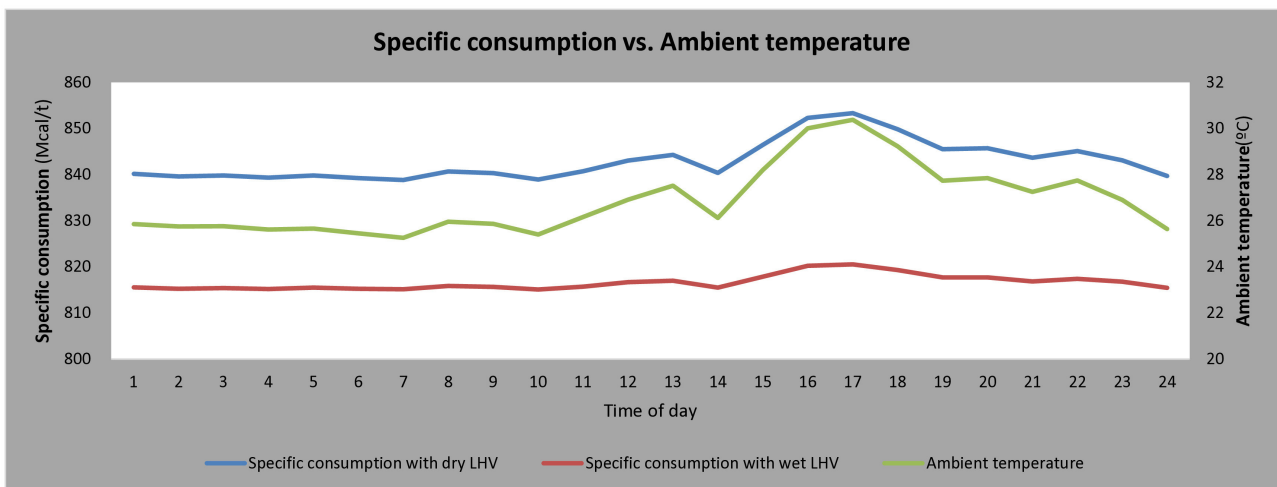


Figure 5. Variation of specific consumption with milder ambient temperature.

Next, Figures 6 to 9 will present real results obtained from boilers 1 and 4 with the ambient temperature and with the calculated specific consumption. As can be seen,

the profile of the real specific consumption of the boilers is identical to the profile obtained from the modeling, demonstrating the consistency of the theoretical model.

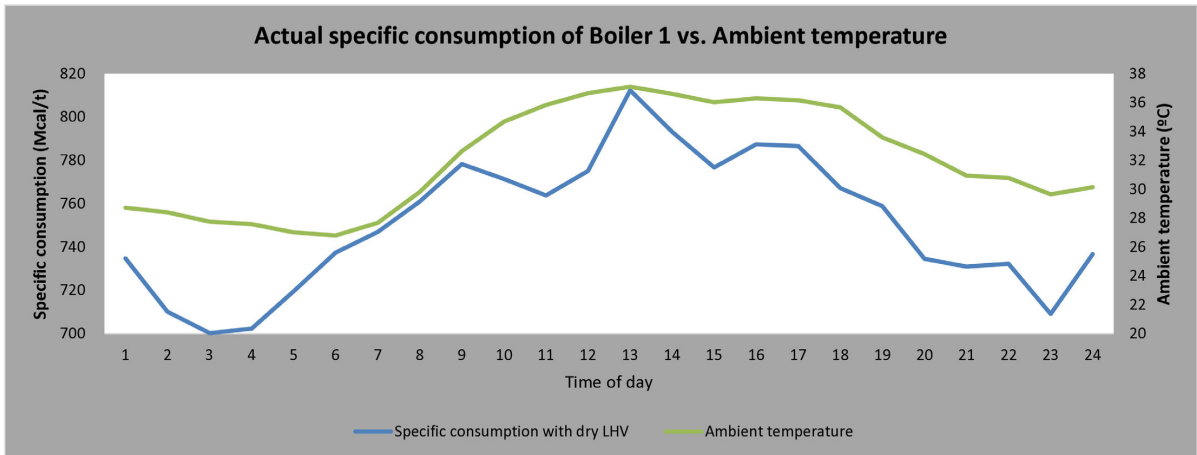


Figure 6. Variation of actual specific consumption of Boiler 1 with ambient temperature.

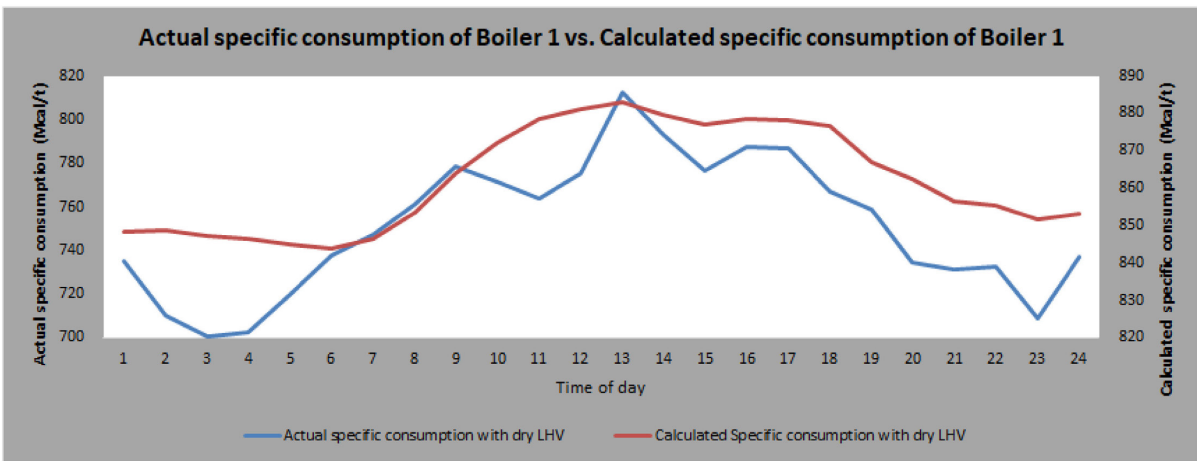


Figure 7. Variation of actual specific consumption with calculated specific consumption.

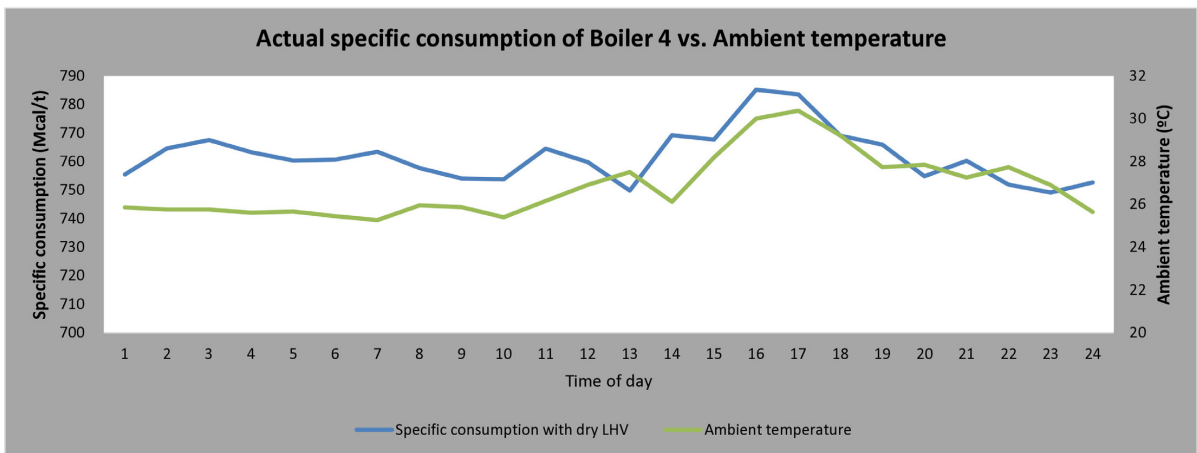


Figure 8. Variation of the actual specific consumption of Boiler 4 with ambient temperature.

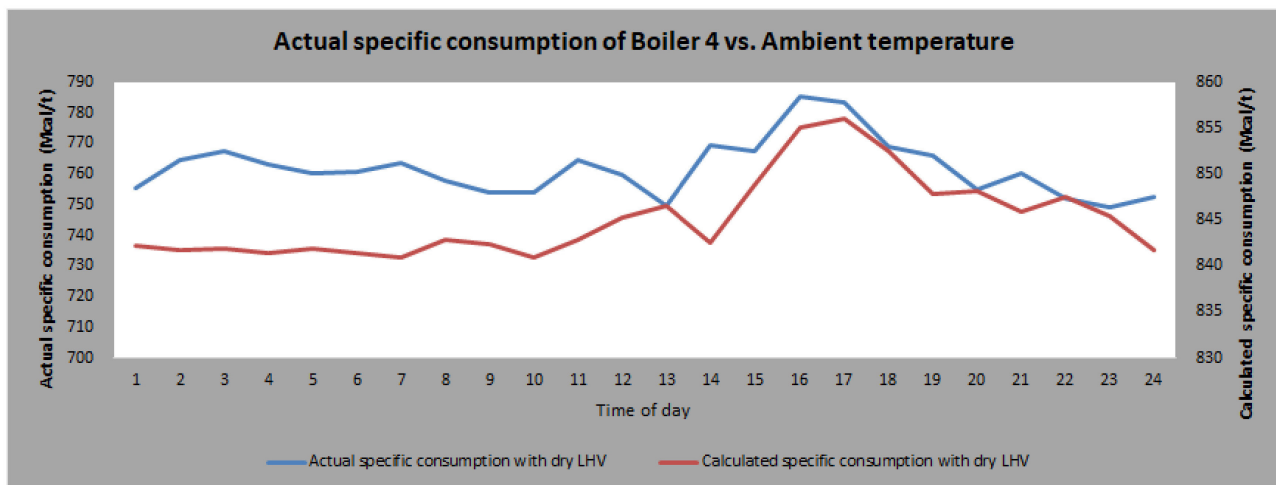


Figure 9. Variation of actual specific consumption with calculated specific consumption.

However, the actual values of specific consumption are not equal and represent a difference on the order of 80 to 100 Mcal/t. This difference is due to the simplification made by considering only the effect on the BFG and assuming the boiler burns pure BFG, which differs from the real situation.

As discussed above, the purpose of this study is to develop a thermodynamic model to calculate the wet LHV and the useful LHV, thereby isolating the effect of moisture and its temperature-dependent behavior. It is not within the scope of this work to build a boiler specific consumption model, since such an approach would necessarily require an integrated treatment of additional variables, including the fuel mix, heat exchanger efficiencies, as well as the combustion air conditions (temperature and humidity) and the fuel properties.

Modeling efforts with this objective, as well as more detailed analyses of these variables, have already been developed by the same authors in [21,22].

#### 4 Conclusion

This study has presented the process rationale for the high moisture concentration in the steelmaking gases. A theoretical model was developed to quantify the impact of moisture in the steelmaking gases on the LHV and on the specific consumption of boilers and other stationary combustion equipment.

The results showed the adherence of the theoretical model to real data. Moreover, the study highlighted the significant impact of moisture on boiler efficiency, thus making the use of wet LHV essential for monitoring performance indicators. It was found that ambient temperature significantly influences efficiencies, as it directly affects moisture condensation.

Therefore, we can state that with global warming and increased frequency of heat waves, a deterioration of thermal efficiencies is expected, a topic that is still not widely addressed and quantified.

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