MODELLING AND ANALYSIS OF AN INTEGRATED BOILER AND GASIFIER SYSTEM

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ABSTRACT
This paper shows the development of a model for an integrated gasifier and boiler unit. The feed to the gasifier is subject to composition changes that can disturb the entire operation of the system. As boilers need fuel feed with controlled composition, it is very important to develop a simulator for the system so that the operation can be investigated and a control system be further proposed. A simulator was developed based on models from the literature. Tests were performed in the system, first considering each unit separately and then integrated. The results provide a description of the behavior of the output variables of the boiler considering the presence the disturbances in the gasifier.

KEY WORDS

1. Introduction
Energy in its various forms is one of the most used resources by humanity for several applications. In the contemporary context of the 21st century, people are improving their quality of life. This statement can be verified by the growth of indexes that measure the quality of life. For instance, Figure 1 shows the growth in the Human Development Index (HDI) in the group of countries named BRICS in recent years.

Figure 1 - World and BRICS HDI [1]

The improvements in quality of life can also be associated to the growth of consumer goods and services. To meet this growing consumption, the energy industry, research and education centers and governments are looking for ways to increase the energy supply, simply by increasing production, making current processes more efficient, creating new processes, utilizing sources of alternative and/or renewable energy or from new raw materials. In this context, the gasification of biomass and other products, like industrial by-products and domestic waste, emerge with increasing interest, also due to environmental protection politics.

According to reference [2], gasification is a chemical process that converts carbonaceous materials such as biomass to gaseous fuel or raw material for industries. Previously to 2004, gasification plants produced approximately 380 MW/plant. In 2010, the production had raised to 474 MW/plant. This increase in production is indicative of the improvement in the operating efficiency and technology of these units [3,4].

The literature presents many works investigating gasification units. For example, an entire project, including design, construction and practical results, of a counterflow gasifier is found in [5]. A modelling of co-gasification of biomass is presented in reference [6]. An extensive discussion of combustion and gasification in a fluidized bed, including mathematical modelling is described in [2] and [7]. A kinetic approach to modelling fixed bed gasifier is derived in [8].

However, few works focus on the analysis of the integration of gasifiers with other processing units. For example, a plant configuration for processing power and steam generation that stands out is the one with integrated power generation cycle (IGCC or “Integrated gasification combined cycle”) [9, 10]. It can include CO₂ capture and polygeneration plants as presented in Figure 2.

The growing interest in this type of energy source from gasification and the lack of works that present the modelling of gasification units integrated with boilers are the main motivations of the present study.

Hence, the general objective of this work is the development of a dynamic simulator based on models of the literature for a unit in which the gas produced in a gasifier is used as fuel in a boiler. The behavior of the output variables is analysed under disturbances in the operation conditions, so that in a further phase of the
investigation a control system may be proposed for the integrated unit.

This paper is structured as follows. Fundamentals on gasification and boilers are reviewed in Section 2. Section 3 presents the models adopted in the development of the simulator and discusses the variables related to control of the unit. Section 4 presents the simulation results and Section 5, the conclusions.

2. Fundamentals

2.1 The Process

Reference [11] states that gasification is a thermo-chemical conversion that aims to produce a high-value gas from low value liquid or solid carbon-containing compounds, such as coal, refinery residues or biomass. The partial oxidation of these inputs requires the use of air, oxygen or water steam [12]. The gas can be used as fuel to generate heat and electricity or serve as a feedstock for the manufacture of chemicals and/or hydrogen [11].

In the process, carbon reacts with vapor water and oxygen at relatively high pressures and temperatures (typically 1500K) to produce raw synthesis gas (syngas), a mixture essentially containing carbon monoxide and hydrogen and certain by-products. The by-products are removed and the clean synthesis gas may be used as fuel to generate electricity or steam, as basic chemical building blocks for wide use in the chemical and petrochemical industry and to produce hydrogen.

Figure 3 is a simplified representation of a gasification reactor, considering coal as input [9].

The gasification process involves the following steps according to [5]:

- Drying;
- Pyrolysis;
- Partial combustion of volatiles and char;
- Gasification reactions;

Drying consists in humidity removal from the raw material if it is of vegetal origin. In Figure 4, a representation of the effect of temperature on the mass of raw material of various origins [13] is shown. It can be seen that, even though the shape of the profiles are alike, the residual amount of water changes according to the biomass origin.
The gasification reactions also depend on the origin of the raw material and on the reaction conditions and heating rate of the reactants. The main reactions in the gasification process are listed below [11, 14].

**Gas – Solid**

**Complete Combustion:**
\[ \text{C} + \text{O}_2 \leftrightarrow \text{CO}_2 \quad \Delta H = -393.5 \text{ kJ/mol} \quad \text{Eq. 1} \]

**Partial Combustion:**
\[ \text{C} + \frac{1}{2} \text{O}_2 \leftrightarrow \text{CO} \quad \Delta H = -123.1 \text{ kJ/mol} \quad \text{Eq. 2} \]

**Reaction Steam-Carbon:**
\[ \text{C} + \text{H}_2\text{O} \leftrightarrow \text{CO} + \text{H}_2 \quad \Delta H = +118.5 \text{ kJ/mol} \quad \text{Eq. 3} \]

**Boudard Reaction:**
\[ \text{C} + \text{CO}_2 \leftrightarrow 2 \text{CO} \quad \Delta H = +159.9 \text{ kJ/mol} \quad \text{Eq. 4} \]

**Methanation:**
\[ \text{C} + 2 \text{H}_2 \leftrightarrow \text{CH}_4 \quad \Delta H = -87.5 \text{ kJ/mol} \quad \text{Eq. 5} \]

**Gas – Gas**

**Water-Gas-Shift:**
\[ \text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2 \quad \Delta H = -40.9 \text{ kJ/mol} \quad \text{Eq. 6} \]

Reference [15] discusses the advantages and disadvantages of using biomass for gasification. The advantages are mostly related to the fact that biomass is a renewable and relatively low cost energy source that results in attenuation of hazardous emissions (CH\text{4}, CO\text{2}, NO\text{x}, SO\text{x}, trace elements). The disadvantages include the high cost of gathering, transportation, storage and pre-treatment. Additionally, the variety in the composition, properties and quality is pointed as a disadvantage.

Commercially, several types of gasifiers can be found increasing production scale year by year. Each reactor presents specific features and applications. A large compilation of the main types of reactors (including countercurrent packed bed, co-current fixed bed and fluidized bed) is presented in [3]. The ALSTOM gasifier adopted in the present work considers a fluidized bed reactor. This type of gasifier presents high volume capacity and high reaction rates [3].

Figure 5 exhibits a simplified scheme representing the ALSTOM gasifier [16, 17]. It is a chemical reactor where coal reacts with air and steam to produce low calorific fuel gas that can be fed to a gas turbine. This reactor also produces char. Limestone is also added to remove the sulfur present in the coal [17,18].

According to reference [19], boilers are equipment used for steam generation in various pressure and temperature ranges. They receive liquid water heat through the heat transfer system. This fuel can be gaseous, liquid or solid and can have plant, animal or mineral origin [19].

In the present work, a gasifier is integrated with a boiler. The models adopted in the development of the simulator and the selection of the variables for analyses are presented in the next section.
2.2 The Control of the Process

The gasification reactor requires that critical process variables are controlled [17]. In the case of the ALSTOM model, the variables pressure, temperature, calorific value of the bed and bed mass should be monitored and/or controlled [17]. These are the direct and desired controls. Other controls are needed, such as: sulfur and its products and NOx generation, particulates, among others [3].

The main controls of a boiler are pressure (demand) of the steam system and level in the water system. Thus, any variation in fuel supply system, air feed, water feed or steam demand, can affect the performance of the steam system of a plant. A robust steam control system is needed to ensure a good response to disturbances and changes in operating sets.

To a systematic analysis through the control point of view, boilers are usually divided into water and fuel systems. The water system contains the controls on the level of vessel, while the fuel system encompasses the pressure control, air flow, water flow to the vessel and steam flow out of the boiler. Figure 6 shows an illustration of the controls of a boiler [20].

![Figure 6 - Scheme of a boiler with steam turbine [20]](image)

A review of recent research does not indicate a large volume of work focusing on integrated control of gas generation gasifier, whether a boiler for steam generation, or a gas turbine to generate electricity. Modelling of the gasifier was focused in [6, 21]. An environmental and economic approach was made in [12]. [22] performed a comprehensive analysis of the feasibility of the integrated operation, but the issue of integrated control was not addressed. A gasification process for the production of methanol using syngas with varying load submitted to model predictive control (MPC) was investigated in [23].

3. Methodology

3.1 The models for the simulation

3.1.1 ALSTOM Gasification Model

The ALSTOM gasification model was adapted here, based on [17]. The proposed process presents high order, high degree of non-linearity and strong interactions between variables. The state-space representation of the ALSTOM gasifier is given by:

\[ \dot{X} = Ax + Bu \]

\[ Y = Cx + Du \]

Where the vectors: X: internal state of the gasifier; U: input variables and Y: output variables. A, B, C, D are appropriately dimensioned system matrices.

The studied model considers a total of 5 states, 4 input variables (u1: char flow; u2: air mass flow rate; u3: coal flow; u4: steam mass flow) and 4 output variables (y1: calorific value of the fuel gas; y2: bed weight; y3: fuel gas pressure; y4: fuel gas temperature). Disturbances in the sink pressure (P_{in}) are also considered.

The model can be represented by transfer functions matrix [24], as follows:

\[
\begin{pmatrix}
    y_1(s) \\
    y_2(s) \\
    y_3(s) \\
    y_4(s)
\end{pmatrix} =
\begin{bmatrix}
    G_{11}(s) & G_{12}(s) & G_{13}(s) & G_{14}(s) & u_1(s) \\
    G_{21}(s) & G_{22}(s) & G_{23}(s) & G_{24}(s) & u_2(s) \\
    G_{31}(s) & G_{32}(s) & G_{33}(s) & G_{34}(s) & u_3(s) \\
    G_{41}(s) & G_{42}(s) & G_{43}(s) & G_{44}(s) & u_4(s)
\end{bmatrix}
\begin{pmatrix}
    u_1(s) \\
    u_2(s) \\
    u_3(s) \\
    u_4(s)
\end{pmatrix}
\begin{pmatrix}
    G_{51}(s) \\
    G_{52}(s) \\
    G_{53}(s) \\
    G_{54}(s)
\end{pmatrix}
\begin{pmatrix}
    P_{in}(s)
\end{pmatrix}
\]

So that each G_{mn} is an output-input transfer function.

The gasifier inputs at the nominal conditions and their limits are given in Table 1 according to reference [24].

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Nominal values</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Char extraction flowrate (k/s)</td>
<td>0.90</td>
<td>3.5</td>
</tr>
<tr>
<td>Air flow rate (kg/s)</td>
<td>17.42</td>
<td>20</td>
</tr>
<tr>
<td>Coal flow rate (kg/s)</td>
<td>8.55</td>
<td>10</td>
</tr>
<tr>
<td>Steam flow rate (kg/s)</td>
<td>2.70</td>
<td>6.0</td>
</tr>
<tr>
<td>Limestone flow rate (kg/s)</td>
<td>0.85</td>
<td>1.0</td>
</tr>
</tbody>
</table>

3.1.2 Boiler Model

Åström & Bell [25] proposed a model based on mass and energy balance. The works [26] and [27] used the model proposed in [21] to simulate the behavior of industrial boilers. Reference [19] compared the influence of different types of fuels in the performance of the controls.

In the following, the model of [25] is presented, based on the equipment illustrate in Figure 7:
Figure 7 - Scheme of steam production in a boiler [25]

\[ e_i \frac{dp}{dt} = Q - q_f (h_f - h_t) - q_s h_s \]  
Eq. 10

\[ e_i = h_i V_s \left( \frac{\partial P}{\partial p} + \rho V_t \frac{\partial h_f}{\partial p} + \rho V_w \frac{\partial h_s}{\partial p} + m_t C_p \frac{\partial t_s}{\partial p} \right) \]  
Eq. 11

where: \( C_p \), metal specific heat \( (J/(kg \cdot ^\circ C)) \); \( h_f \), feedwater specific enthalpy \( (J/kg) \); \( h_s \), steam specific enthalpy \( (J/kg) \); \( h_w \), water specific enthalpy \( (J/kg) \); \( m_t \), total metal mass \( (kg) \); \( P \), pressure \( (Pa) \); \( Q \), heat rate \( (W) \); \( q_f \), feedwater flowrate \( (kg/s) \); \( q_s \), steam mass flowrate \( (kg/s) \); \( t_s \), steam temperature \( (^\circ C) \); \( t_w \), water temperature \( (^\circ C) \); \( V_s \), total volume of steam in the system \( (m^3) \); \( V_t \), total vessel volume \( (m^3) \); \( V_w \), total water volume \( (m^3) \); \( \rho_s \), steam specific mass \( (kg/m^3) \); \( \rho_w \), specific mass of water \( (kg/m^3) \).

The boiler parameter and nominal conditions are given in Table 2 according to reference [19]

Table 2 - Boiler data [19]

<table>
<thead>
<tr>
<th>Variable/Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_p(J/(kg \cdot ^\circ C)) )</td>
<td>448</td>
</tr>
<tr>
<td>( h_f(J/kg) )</td>
<td>103900</td>
</tr>
<tr>
<td>( q_f(kg/s) )</td>
<td>0.16</td>
</tr>
<tr>
<td>( m_t(kg) )</td>
<td>1000</td>
</tr>
<tr>
<td>( q_s(kg/s) )</td>
<td>0.16</td>
</tr>
<tr>
<td>( Q(W) )</td>
<td>429,776</td>
</tr>
<tr>
<td>( V_s(m^3) )</td>
<td>0.42</td>
</tr>
<tr>
<td>( V_t(m^3) )</td>
<td>2.8038</td>
</tr>
<tr>
<td>( V_w(m^3) )</td>
<td>2.38</td>
</tr>
</tbody>
</table>

3.2 Connection between the models

Figure 8 exhibits the connection between the two models (gasifier + boiler) proposed in the present work. A simulator was developed in MATLAB/SIMULINK.

An ideal gasifier would be one that received raw material from different source matrices. However, when the matrix raw material changes, variations also occur in the composition of the feedstock. Adjustments are then needed in the operation of the gasifier [17].

So, the composition of the raw material must be frequently monitored because it will cause variation in the bed composition and consequently in calorific value of the fuel gas generated. In order to solve this problem, it is necessary to vary the air ratio and steam flowrate until the desired medium properties are achieved.

Figure 8 - Connection between plants
4. Results

4.1 Initial Tests Results

Figures 9 to 12 show the results of response curves for steps in the inputs of the gasifier and of the boiler model. The input variables chosen cause dynamic and steady-state variations in the outputs. Particularly, the gas heat value behavior is of interest to the pressure boiler study. Figures 9 to 11 show that the linear model describes very well the nonlinear counterpart in the investigated regions. Both models are provided by [17].

In Figure 9, it is possible to verify that the calorific value reaches a minimum during transient due to a 10% increase in the air flowrate.

Figure 10 exhibits a smaller variation of calorific value due to a 10% decrease in the value of the \( P_{\text{sink}} \) pressure.

In Figure 11, it is possible to verify that an increase of 10% in coal flow, the calorific value increases in the order of 50kJ/kg at steady state and presents transient peaks.

Figure 12 shows the results for steps (-25%, -10%, +10% and 25% from steady-state, in open loop) in the power supply for the boiler. It is possible to see a clear influence of power supply in generated steam pressure. It is also possible to verify that this is an integrator process.
4.2 Results of Connected Models

The models integrated as suggested in Figure 8 are now analysed. Figures 13 to 16 show the response curves for several inputs. In Figure 13, it is possible to see that the step of +0.1 kg/s deviation in the char withdrawal increases the boiler pressure. According to Figure 14, the +2 kg/s step deviation in raw material also increases the boiler pressure. The flow of steam (+0.3 kg/s step) has the most significant effect on the pressure, as represented in Figure 15. It is believed that the presence of this reagent in larger amounts promotes a greater conversion of products with higher calorific value, thus affecting the pressure significantly.

![Figure 13 - Disturbance in char withdrawal at t = 250s](image1)

![Figure 14 - Disturbance raw material flow, at t = 250s](image2)

![Figure 15 - Disturbance steam flow, at t = 250s](image3)

![Figure 16 - Disturbance air flow, at t = 250s](image4)

An increase in +2 kg/s units in deviation in air flow was the only disturbance that had initially the opposite effect, i.e., increasing the air flow rate decreased the boiler pressure, as shown in Figure 16. Since air is a mixture of N2 + O2, predominantly, it is believed that an increase in N2, the calorific value degrade, thereby lowering the pressure.

5. Conclusion

A simulator was developed in MATLAB/SIMULINK for an integrated process consisting of a gasifier interconnected with a boiler. This simulator allowed the dynamic analysis of the variables of the process aiming a future study of multivariable process control. In all cases analysed, disturbances in the gasifier variables cause significant variations in the boiler pressure response. It is expected that changes in the gasifier variables cause variations in the controlled variables of the boiler, especially in pressure, because the model of boiler has a parameter associated with the calorific value.
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