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BIOMASS GASIFICATION WITH A FAST INTERNAL CIRCULATING FLUIDIZED BED – PARAMETRIC STUDY BASED ON A 0D-MODEL USING THE EXPERIMENTAL DESIGN APPROACH

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ABSTRACT

The present work deals with biomass gasification using the FICFB process (Fast Internal Circulating Fluidized bed). In order to optimize the FICFB gasifier operation for the use of syngas to produce bioSNG (Substitute Natural Gas) through a downstream methanation process, a 0D-model of the gasifier has been developed before the beginning of the GAYA project, and implemented so has to get a functional software.

This software has been used to achieve a sensitivity study on the gasification equipment. The purpose of this study is to determine which operating parameters of the gasification unit are significant in the design and operation of the reactor and how its behavior is impacted by a variation of these parameters, using the 0D-model.

Experimental design methodology was chosen for this sensibility study. It is a mathematical tool to help the experimenter to get the best knowledge of a process by running the minimum number of experiments. In this type of approach, the process is seen as a black box with outputs called *responses* or *objectives*. In the present case, the responses are, for instance, the gasification equipment energy efficiency or the syngas flow rate. The responses may vary under the effect of *factors*, or *variables*. In our case, these might be biomass moisture content, fluidization steam flow rate or biomass capacity. The study went through different levels: screening to identify the parameters having a significant effect on the responses, and a quantitative study to express the responses using a mathematical expression functions of the different parameters.

The study pointed out that some parameters have strong effects on the operation of the gasification equipment. Biomass moisture content has to be minimized in order to maximize syngas production, and thus bioSNG production. In addition to biomass moisture content, energy efficiency is impacted by combustion air temperature and biomass LHV. They tend to increase the efficiency when they are set at their highest values.

An optimization study is then carried out. The objective of this study is to determine the values of each parameter that minimize or maximize one or several responses. As the purpose of the biomass gasification is to produce bioSNG, we choose to optimize the syngas production.

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BIOMASS GASIFICATION WITH A FAST INTERNAL CIRCULATING FLUIDIZED BED – PARAMETRIC STUDY BASED ON A 0D-MODEL USING THE EXPERIMENTAL DESIGN APPROACH

1. INTRODUCTION

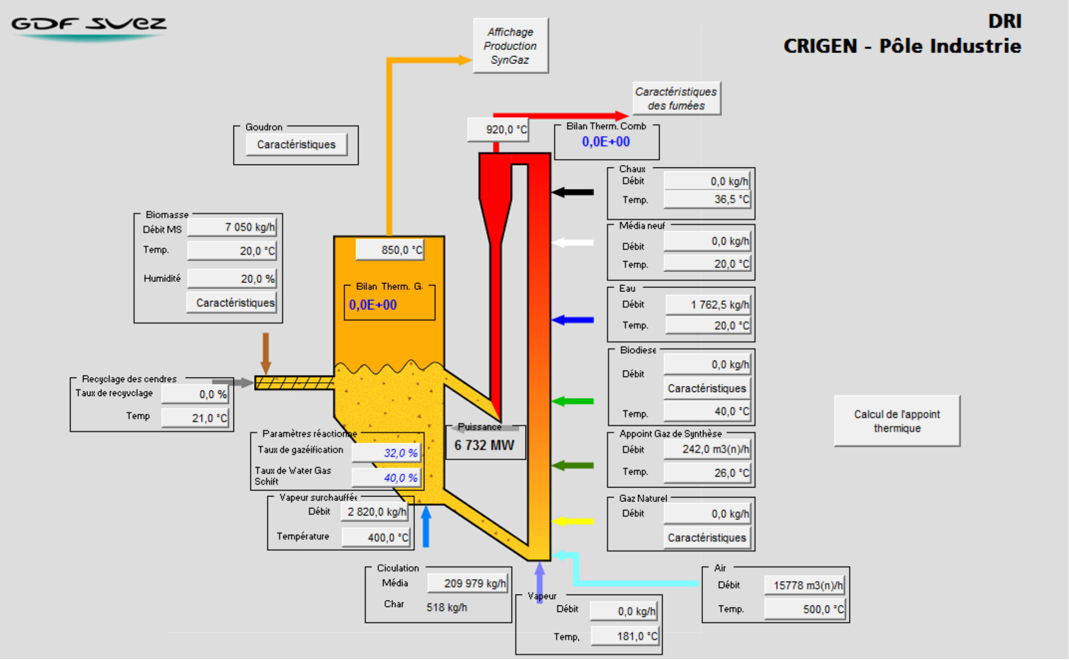
During recent years, the interest for biomass as a fuel for power generation has increased since it has significant environmental benefits. Due to this growing environmental concern, production of syngas from biomass via steam gasification in a fluidized bed is a very promising technology. The present work deals with biomass gasification using the FICFB process (Fast Internal Circulating Fluidized bed). A plant using this technology has been built in Austria. It has a fuel capacity of 8 MW and a power output of about 2 MW with an electrical efficiency of about 25%. The GAYA project is a R&D project focusing on the development of a complete pilot chain for bioSNG (Substitute Natural Gas) generation through biomass gasification. Its goal is to demonstrate the technical, economic and environmental relevance – at a pre-industrial scale – of this technological path for bioSNG production. The project is coordinated by GDF SUEZ and brings together eleven partners with financial support from the French agency ADEME [1].

The FICFB gasifier transforms the inlet biomass feedstock into syngas. The FICFB process is a special concept of a twin fluidized bed gasifier. The biomass is fed into the gasification zone which is designed as a bubbling fluidized bed. Steam is used both as a fluidization and gasification agent. The bed material, usually sand or olivine, is transported from the gasification zone to the combustion zone carrying ungasified chars. The combustion zone operates in fast fluidization regime. Chars and additional fuel for temperature control are burned in the combustion zone. Heated bedmaterial leaving this zone is separated by a highly efficient cyclone. To avoid mixing of product gas and flue gas the bedmaterial passes a seal loop recycling into the gasifier. This hot bedmaterial from the combustion chamber supplies the endothermic gasification reactions with energy. So as to complement the heat already provided by the combustion of ungasified chars but yet not at a sufficient level, recycled syngas is burned in the combustion zone as an additional fuel [1].

To understand how this equipment works, we need to analyze the effect of each operating parameter on the operation of the gasifier. A 0D-model of the gasification and combustion zones has been designed together with LGC laboratory before the start of the GAYA project, and implemented so as to get a functional software. It allows simulations of the reactors behavior with good respect of the data available in the literature on this process and from the Austrian plant. The method of experimental design has been used to characterize the FICFB unit using a minimum number of experiments with the simulation tool.

2. 0D-MODELING TOOL

The 0D-model takes into account the following reactions taking place in the gasification equipment: biomass undergoing pyrolysis, followed by the gasification of char residues and water gas shift reactions. The composition of the synthetic gas produced by pyrolysis is calculated with an Lagrange's interpolation of experimental data. The software user can set some parameters such as: input biomass capacity, biomass composition, O_2 rate in the fumes, gasifier temperature, fluidization flow rate, etc. The software generates output data such as syngas flow rate, fumes flow rate, etc. Figure 1 shows the software interface.



Biomasse
Débit MS 7 050 kg/h
Temp. 20,0 °C
Humidité 20,0 %

Recyclage des cendres
Taux de recyvclage 0,0 %
Temp 21,0 °C

850,0 °C

Bilan Therm. G. 0,0E+00

920,0 °C

Bilan Therm. Comb 0,0E+00

Paramètres réactionne
Taux de gazéification 32,0 %
Taux de Water Gas Schift 40,0 %

Vapeur surchauffée
Débit 2 820,0 kg/h
Température 400,0 °C

Puissance 6 732 MW

Ciculation
Média 209 979 kg/h
Char 518 kg/h

Vapeur
Débit 0,0 kg/h
Temp, 181,0 °C

Chaux
Débit 0,0 kg/h
Temp. 36,5 °C

Média neuf
Débit 0,0 kg/h
Temp. 20,0 °C

Eau
Débit 1 762,5 kg/h
Temp. 20,0 °C

Biodiese
Débit 0,0 kg/h
Temp. 40,0 °C

Appoint Gaz de Synthèse
Débit 242,0 m3(n)/h
Temp. 26,0 °C

Gaz Naturel
Débit 0,0 kg/h

Air
Débit 15778 m3(n)/h
Temp. 500,0 °C

Figure 1: FICFB reactor - software interface of the 0D-model

This software has been designed to enable the optimization of the operating conditions of the gasification reactor itself, but also to determine the necessary utilities for the industrial operation of the reactor and devices around the gasification equipment such as filters, or cyclones to separate particles from the gas, etc.

3. LARGE-SCALE PARAMETRIC STUDY

The purpose of the parametric study is to determine which operating parameters of the gasification step are significant in the design and operation of the reactor and how its behavior is impacted by a variation of these parameters, using the 0D-model. Based on this study, an optimization study will also be led in order to figure out a possible optimized operation of the gasification equipment.

3.1 The experimental design methodology

Experimental design methodology is a mathematical tool to help the experimenter to get the best knowledge of a process by running the minimum number of experiments. Detailed information about the various methods available can be found in the literature [3-9]. In this type of approach, the process is seen as a black box with outputs called *responses* or *objectives*. In the present case, the responses are, for instance, the gasification equipment energetic efficiency or the syngas flow rate. The responses may vary under the effect of *factors*, or *variables*. In our case, these might be the biomass moisture content, the fluidization steam flow rate or the biomass capacity.

An experimental approach goes through different levels:

- Screening: at this level, the operator only wants to identify the parameters that have a significant effect on the responses.

- A quantitative study: here a mathematical expression is sought, to enable the value of the response to be calculated from the values of the different parameters. These expressions will hereafter be polynomial correlations.

- Optimization: The objective in this case is to determine the values of each parameter that minimizes or maximizes one or several responses.

For mathematical considerations, it is necessary to normalize the real variables, also called natural variables. Centered reduced variables, also called reduced variables $\overline{U}$, are defined using the natural variables U:

$$\overline{U_{ij}} = \frac{U_{ij}-U_{0j}}{\Delta U_j} \qquad (1)$$

where *i* stands for the experiment index and *j* stands for the variable index. This requires to define a study domain for each of the variables. The centre of the domain is U_{0j}, and the variable can range between $U_{0j} - \Delta U_j$ and $U_{0j} + \Delta U_j$. ΔU_j is called the variation step for the natural variable U_j. For instance the domain for the biomass moisture content will be centered at 30% and will vary by 10% below and above this value.

The list of experiments to be carried out is determined through the construction of an experiment matrix. In a problem aiming to achieve a prediction capacity, an equiradial composite matrix is recommended. Equiradial means that the experimental points are located regularly on a circle, i.e., at the same distance from the centre of the experimental domains. The term composite means that the matrix is composed of three parts: a factorial matrix, a star matrix and several additional points at the centre of the domain.

Finally, an expression will be found to calculate each of the natural responses from the reduced variables, using a first degree linear model with interactions, i.e., of the type :

$$U = b_0 + \sum_{i=1}^{k} b_i \overline{U_i} + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} \overline{U_i}\,\overline{U_j} \quad (2)$$

3.2 Setting of factor ranges and choices of responses

The ranges of variations of each parameter is chosen regarding the operating conditions of the Güssing plant and data found in the bibliography [10-11].

The Table 1 shows examples of variation ranges for some parameters.

Parameters	**MIN**	**MAX**
Combustion air temperature (K)	573	773
Fluidization steam temperature (K)	373	673
Fluidization steam flow rate (% of wet biomass)	30	60
Gasification equipment capacity (W)	400×10^3	600×10^3
Biomass moisture content (%)	20	40
Biomass LHV (J/kg dry)	16.5×10^6	19×10^6
Gasifier temperature (K)	1073	1173
WGS conversion rate (%)	40	60
Combustion zone temperature (K)	1183	1243
Gasification conversion rate (%)	30	70

Table 1: Ranges of variations of the parameters

The responses are chosen regarding their significance in the gasification equipment operation and the design of related utilities and devices for the gasification process.

- The raw syngas flow rate is studied because it has to be considered to design the downstream equipment to produce bioSNG, such as filters, quench, etc.

- The composition of this syngas (CO, CO_2, H_2, CH_4 and C_2H_4) is an important response to identify which reactions have to be done downstream from the gasification equipment to maximize the CH_4 content of the gas (bioSNG production).

- The additional fuel needed in the combustor (flow rate). As this fuel is recycled syngas, it is useful to know how much syngas is burnt in the combustion zone and thus unavailable for the downstream bioSNG production.

- LHV of the raw syngas: this value allows to study the effect of biomass composition (carbon content…).

- The humid fumes flow rate, the syngas moisture content and fumes moisture content must be estimated to design the filters and exchangers used downstream from the gasifier.

- Energy efficiency calculated by the ratio between syngas LHV and supplied biomass energy content.

- Inlet air flow rate in the combustion zone to burn chars and recycled syngas. As it has to be preheated, the flow rate is needed to design the exchangers installed upstream the combustion zone.

- Water supplied to the combustion zone flow rate. This is the water extracted from the syngas that is recycled to be incinerated in the combustion zone. It impacts the energy efficiency of the equipment.

3.3 Results analysis

As a first step, the screening study was carried out, based on the results of a limited number of experiments, following the complete factorial matrix, in order to gain an initial estimation of the impact of each factor on each response.

To estimate if a parameter has a significant effect on a response, a confidence interval has to be calculated. If the b_i value is within the interval, then the effect can be considered as non-significant: such parameter has no influence on the response. But if the value is over the confidence interval limits, then the parameter has an observable effect and its “weight” can be compared to the one of the other significant parameters. A confidence interval with a threshold of signification of 95% is chosen. The confidence interval is calculated using the estimation of the experimental variance.

To analyze and exploit these results, a graphic representation is used to compare rapidly the difference in the influence of the parameters. The values of the b_i factors are pictured with a bar graph. Two straight lines stand for the limits of the confidence interval. If the bar of the effect b_i goes over the line, the effect is significant. But if the bar remains inside the interval, which means between the two lines, then the effect is not significant.

The Figure 2 below presents an example achieved in the present study. The response is the operation energy efficiency.

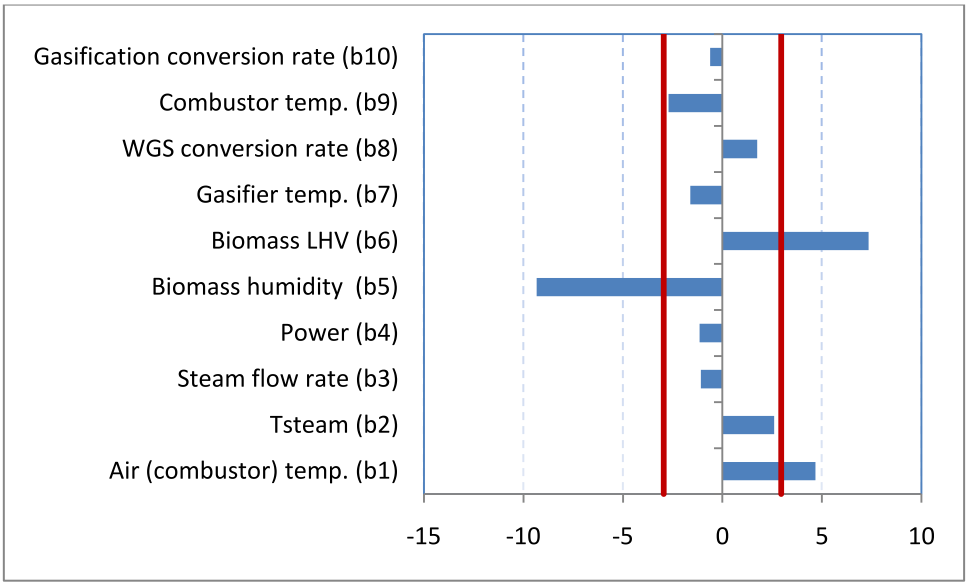


Figure 2: Effects of the parameters on the response “energy efficiency”

On the abscissa, the unit is percents (%). In this case, three parameters have significant effects. There are: the biomass LHV, biomass moisture content and inlet air temperature in the combustor. As the graph shows, the other parameters are not significant because their effect remains within the confidence interval. When the bar is within the positive part of the graph, the response is increasing when the parameter is increasing. On the contrary, when the effect is in the negative part of the graph, the response is going down when the parameter is increasing.

These results can be explained. For example it can be deduced from the graph that the energy efficiency is impacted by the combustion air temperature. In fact the recycled syngas flow rate is decreasing when the air temperature is increasing because less additive fuel is required for the combustion reaction. So there is more syngas used to produce biomethane and energy efficiency is increased. Besides when biomass moisture content is high, the water content of the syngas is increased and more water has to be incinerated in the combustion zone. So more syngas is recycled and burnt in this zone to ensure a higher energy complement to the ungasified char combustion in this reactor, this is why energy efficiency is lower. If biomass LHV is increased, at constant gasifier power, less water is present in the gasifier and thus less incinerated water in the combustion zone. So energy efficiency is higher.

In addition, this set of experiments and the mathematic expression of the responses allowed to eliminate the parameters having no influence on the responses, which helps to reduce the number of experiments to be conducted in the following steps of the studies.

3.4 Determination of the polynomial expression to predict FICFB efficiency

The previous step in the sensitivity study was a qualitative study. It has to be followed in a second step by a quantitative study of the influence of the parameters. The purpose of this study is to observe the values obtained for each output response following the input parameters, ranging from their lowest to highest values. It is done for each parameter which have not been eliminated from the list through the previous analysis. Each response is expressed with a polynomial expression that predicts the response from the values of the factors. The coefficients of the polynomial expressions were determined using multiple regression. The general form is given in Equation 3:

$$Y_i = b_0 + b_1 X_1 + \cdots + b_j X_j + b_{11} X_1^2 + \cdots + b_{jj} X_j^2 + \sum_{i=1; j=2; i<j}^{n\,factors} b_{ij} X_i X_j \quad (3)$$

3.5 Optimization of the operating parameters [12]

The objective of the optimization study is to determine the values of each parameter that minimizes or maximizes one or several responses. As the purpose of biomass gasification is to produce bioSNG, we chose here to optimize the production of syngas. Thus in this optimization study, we want to optimize four responses:

- H_2/CO has to equal 3 to ensure stoechiometry of the reactions in the downstream methanation process.

- The CH_4 fraction in the syngas has to be maximized as the objective of the process is to produce bioSNG.

- Energy efficiency has to be maximized.

- The combustor temperature has to be minimized to avoid ash melting in the combustion zone, and reduce syngas recycling rate to the combustor as well.

The purpose of the study is to find which operating points allow to meet these four conditions, or at least result in a compromise between all the performance criteria. The quantitative objectives of the compromise to be reached are described by a desirability function, d_i, for each performance criterion of the process Y_i (see Equation 4). Many authors [13-17] propose multi-criteria optimisation methods. The desirability function methodology [18] was chosen for its simplicity. We used the Derringer and Suich (1980) [19] unilateral normalisation to transform the FICFB responses (polynomials) into elementary desirabilities, d_i, according to the relation (5).

$$d_i = \begin{cases} 0 & \hat{Y}_i < Y_{i*} \\ \left[\dfrac{\hat{Y}_i - Y_{i*}}{Y_i^* - Y_{i*}} \right]^r & Y_{i*} \le \hat{Y}_i \le Y_i^* \\ 1 & Y_i^* > \hat{Y}_i \end{cases} \tag{4}$$

Then, the global desirability function, D_g, (2), which describes the total compromise between all the performance criteria, is applied.

$$D_g = \sqrt[a]{d_1^{a_1} d_2^{a_2} .. d_m^{a_m}} \qquad a = \sum_{i=1}^{m} a_i \tag{5}$$

The selected functions are linear between a target value (Y_{i*}) and an acceptable maximum value (Y_i*). The following table (Table 2) shows the required parameter values to obtain what would be an optimized operation of the gasifier. Values are given in centred reduced variables in their range of variations.

Parameters	$\bar{\bar{U}}$
Biomass capacity	0
Gasifier temperature	- 0.3493
Fluidization steam flow rate	1.000
Fluidization steam temperature	- 0.1101
Combustion air temperature	1.0000
Biomass moisture content	- 1.0000

Table 2: Parameter values for an optimized configuration of the gasification equipment

The following diagrams (Figures 3 and 4) show examples of results of an optimization study already achieved on this subject. The values of the parameters have been set to optimize the syngas production. On each diagram, two parameters vary. The deep blue zones of the graph represent operating points where the operation does not respect the different criteria for optimal bioSNG production. On the contrary, the dark red zones stand for optimized set points.

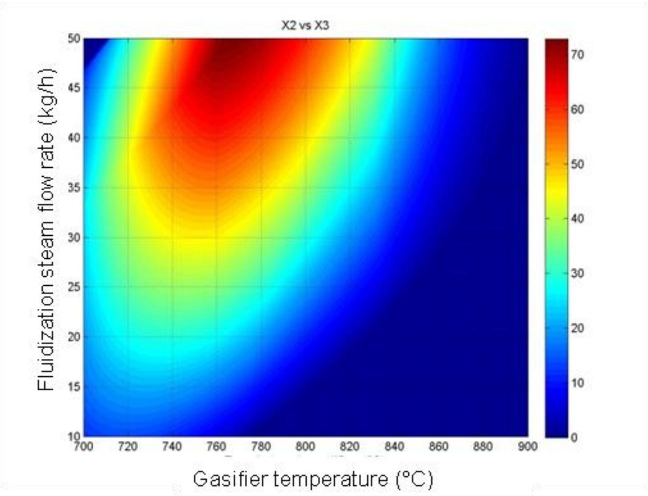


Figure 3: Fluidization steam flow rate and gasifier temperature

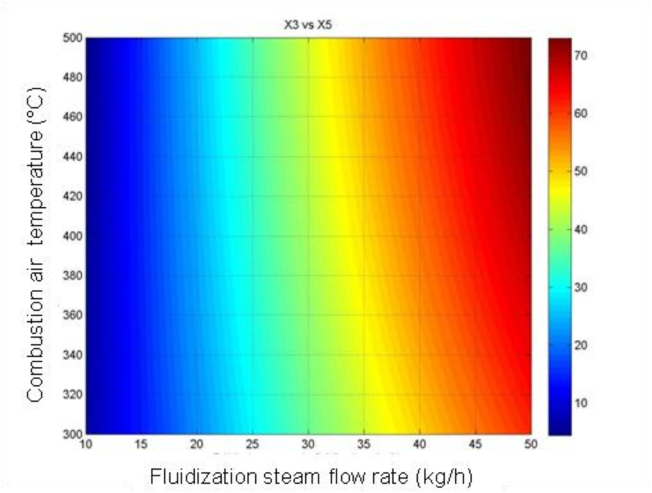


Figure 4: Combustion air temperature and fluidization steam flow rate

These diagrams show for example that the operation of the gasification equipment is optimized when the gasifier temperature equals 1033K (760°C) and the fluidization steam flow rate is 50kg/h (red zone). On the contrary, when the gasifier temperature is around 1173K (900°C), for any steam flow rate, the operation is not optimized for the production of bioSNG. It is also true when the steam flow rate is around 10% of humid biomass flow rate.

4. CONCLUSIONS

The sensibility study has been led following these steps: screening, quantitative study and optimization study.

The study pointed out that some parameters have strong effects on the operation of the gasification equipment. Biomass moisture content has to be minimized in order to maximize syngas net production, and thus bioSNG production. In addition to biomass moisture content, energy efficiency is impacted by combustion air temperature and biomass LHV. They tend to increase the efficiency when they are set at their highest value in their ranges of variations.

The present study will allow to plan the experimental tests to perform on a R&D platform that will be built in the framework of the GAYA project. This platform will allow operation of a complete chain of equipments to demonstrate the feasibility of bioSNG production and eliminate any barriers facing the technology.

The methodology developed here will also be reused during the experimental operation of this R&D platform so as to take into account feedback from experiences in terms of relevant responses and parameters to be studied, and also so as to update continuously more efficiently the set of experimental tests with respects to the previous results that will have been obtained.

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