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Multi-stage optimization in a pilot scale gasification plant

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ABSTRACT

A 2-D multiphase CFD model was coupled with advanced statistical methods to find the best operating conditions to maximize a set of selected responses that characterize the normal operation of a pilot scale fluidized bed gasifier running Municipal Solid Waste. After using CFD simulations to compute 7 responses at 27 different operating conditions, a single response optimization based on the response surface method was carried out to identify the best operating conditions. Then, the desirability concept was advantageously used to proceed with a multiple optimization where all the responses were targeted under normal industrial conditions. The operating conditions that set the optimized responses not always coincide with the most stable process. To target both optimized and robust conditions a multiple optimization combining the response surface and the propagation of error methods were employed. Finally, the tolerance intervals were reduced to increase the process Cpk and six sigma standards about 20%. New measures to further increase the process performance were identified and the transmitted variation to the response from input factors was computed.

Introduction

According to Eurostat's latest reports, municipal waste (MW) generated in the EU-27 reached 239 million tons in 2014, representing a 5% decrease from the previous decade [1]. Portugal followed EU's trend with each Portuguese citizen producing 453 kg (almost 5% below the EU-27 average) [1]. Even with all the efforts led by government institutions to improve the Portuguese MSW management system, most of the produced wastes are still being sent to landfills [2]. Recent efforts are being carried out to fund research projects based on new approaches to convert waste to energy, such as gasification or anaerobic digestion. Main results have suggested that gasification could be a valuable option to mitigate the MSW environmental impact in Portugal [2].

Gasification can be defined as the conversion of a solid waste to synthetic gas by the partial oxidation of the feedstock

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below stoichiometric combustion conditions. The synthetic gas is generally called “producer gas” or syngas and contains mainly carbon monoxide and hydrogen. However, some undesired products can be also found such as tar, alkali metals, chloride and sulphide, among others [3]. Gasification presents several advantages over waste combustion, namely and among others [3]: a) effective response to increasingly environmental restrictive regulations; b) syngas can be used both in highly efficient internally-fired cycles but also to produce valuable products as chemicals and fuels; and c) flexible use on different operating conditions and reactors.

Meanwhile, some drawbacks require further investigation. Besides high operating and capital costs, the syngas generated from MSW gasification is unstable due to changes in the feedstock properties. Indeed, the high heterogeneous nature of MSW implies significant variations in syngas yield and quality [4]. These variations can be reduced by implementing strategies such as MSW pre-processing, where undesired components are removed before introducing the wastes inside the gasifier. Further improvements can also be found by blending MSW with other feedstocks with more favorable characteristics, like forestry residues [5]. Portugal has a major potential considering biomass resources, merely forestry and pruning residues can potential produce 13,800 GWh, about 13% of the total primary energy demand in Portugal [6]. Also, running the gasifier under certain operating conditions will allow reliable operation with stable and improved syngas generation.

Optimized operation conditions for complex systems can be attained by using advanced combinations of numerical and statistical methodologies such as design of experiments (DoE) and response surface methods (RSM) [7,8]. DoE deals with several factors where all of them are varied altogether, instead of one at a time [7]. The great advantage of implementing this strategy is its success to consider multiple interactions between the factors. Furthermore, it also significantly reduces the number of runs necessary to extract meaningful information from data. Few works are found in the literature devoted to the use of DoE and RSM to analyze and optimize the operating conditions in gasification related processes [9–13]. Carpenter et al. [9] performed a total of 22 statistically designed experimental conditions to study the effects of fluidized bed temperature, the temperature of the secondary thermal cracker, and steam-to-biomass ratio on the gasification of four feedstocks. The authors concluded that there were significant differences between the feedstocks studied in terms of light gases formed. Karimipour et al. [10] applied RSM to the fluidized bed gasification of lignite coal considering as input factors coal feed rate, coal particle size and steam/O_2 ratio and as responses the quality of syngas evaluated based on five indices including carbon conversion, H_2/CO ratio, CH_4/H_2 ratio, gas yield, and gasification efficiency. They were able to find the best operating conditions to achieve syngas with a desired quality for different applications. To assess the combined effects of the operating variables on high-pressure coal gasification, Fermoso et al. [11] used a face centered central composite design based on RSM. Results revealed the effects of interaction between the tested variables, which would not have been possible by a traditional method. Silva and Rouboa [12] combined a thermodynamical dual stage model with RSM to optimize both hydrogen generation and cold gas efficiency by using forest residues for gasification. By using the operational conditions and desirability functions they were able to find the optimal conditions to achieve considerable economical energy savings without reducing the hydrogen generation. Coetzer and Keyser [13] used the method of factorial experimental design on the input factors of interest from a full-scale test gasifier concerning the Sasol-Lurgi coal gasification process. They developed empirical models (by using RSM) able to fit experimental data under different data sets. They concluded that the factorial experimental design combined with response surface analysis could be applied to a full-scale production process.

Because experimental runs conducted on industrial gasification plants or even on pilot scale gasification plants are very expensive, predictable models able to simulate the syngas composition and other responses of interest are required.

Mathematical models are being employed to work around this exact problem. By allowing for a simplified representation of reality they provide the ability to better understand the physical and chemical mechanisms inside the reactor without major investments nor time consuming experiments [14–16]. Different modeling approaches have been used by different researchers depending on the degree of complexity they are willing to endure. Equilibrium models are a popular method since they provide a quick way to calculate the maximum yield of a desired product [17]. However, since they don't take hydrodynamics, transport process or reaction kinetics into account results sometimes lack meaningful information. These setbacks led to the development of kinetic models, being much more accurate but also computationally expensive [16]. Increase in computational power is gradually replacing empirical or semi-empirical models with Computational Fluid Dynamics (CFD) to study biomass and waste gasification. These models can provide crucial insights into the flow field inside the reactor and can lead to a better understanding and improved performance of the operation while indicating solutions to potential problems [6,14,15].

There are few reports on the literature combining advanced statistical strategies with predictive models applied to gasification processes to find the most efficient combination of process variables that might be used during normal operation. Even fewer reports are found considering strategies to ensure a sustainable gasifier operability and throughput with minimal variations on the syngas generation (robust process) [18–20]. Silva and Rouboa [20] coupled the results obtained from a 2-D Eulerian–Eulerian biomass gasification model developed under the CFD framework with RSM to find the best operating conditions to generate syngas for different applications. Later, they proceed to do a multiple optimization coupling each one of the studied responses with the minimization of the error propagation. The authors were able to find the operation conditions that guaranteed both the best response and minimal variations caused by input factors.

This paper presents an advanced strategy coupling the response surface and propagation of error methods to go