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From laboratorial to pilot fluidized bed reactors: Analysis of the scale-up phenomenon

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ABSTRACT

One of the major setbacks regarding commercial size reactors is the scale-up phenomenon. Studies linking laboratory-scale to industrial-scale experiments are extremely scarce due to hard logistic and associated costs that are significant high. The use of numerical models can help to fill this gap thus minimizing the risk and uncertainty associated with this phenomenon.

To assess the potential of numerical models to correctly predict the scale-up of a laboratory-scale reactor to a pilot scale one, a previously published numerical model was used. The two-dimensional model was built using data from a pilot scale gasification plant. After validating the model with pilot scale results, model was extended to predict biomass gasification in a laboratory-scale reactor. Numerical results in laboratory-scale were validated using experimental data available from the literature. Experimental errors were collected to perform uncertainty analysis. Height/cross section ratio between both reactors was chosen according to previously relevant studies. Influence of operation parameters in produced gas was investigated for both reactors. Residence time, temperature, syngas calorific and both carbon monoxide and hydrogen contents were higher for the large scale reactor. Still, the ability to predict correct trends was present in most cases for both reactors. Residence time proved to be one of the main factors for different results for different sizes. Also, the substrate characteristics such as the volatile content and size showed a considerable influence on the obtained results.

1. Introduction

According to recent reports [1], even with all the efforts led by government institutions to reduce the consumption of fossil fuels and its resulting damage to the environment, fossil fuels now provide over 87% of the world's primary energy supply. Even more disturbing is the ever increasing energy demand that increasingly requires investment in new structures.

However, it is possible to use these new and necessary investments in opportunities to build more efficient, less polluting and more flexible energy systems that are also less vulnerable to rising and volatile fossil fuel prices [1].

In order to meet these serious issues, recent decades were characterized by an increased interest on gasification-based technologies due to its significant environmental benefits over conventional ones [2]. Gasification also presents several environmental benefits when compared with other competitive technologies such as incineration, namely, with reduced char addition to soils, NOx emissions and landfill disposal option being able to respond to the increasingly environmental restrictive regulations applied around the world [3]. Biomass can be an important source in reducing fossil fuels dependence and, therefore, should be part of a national strategy considering energy generation [3]. Due to a high content in agricultural residues [4], Portugal may become a leading example in the efficient use of biomass. Several studies [4,5] were made considering the use of substrates such as forest residues and vines pruning for energy generation purposes. Ferreira et al. [4] analyzed the potential of different substrates to be used under different energy conversion technologies and discussed their implementation and legal framework. Silva et al. [5] developed a 2-D multiphase model to simulate the gasification of large available biomasses in Portugal by using a semi-industrial fluidized bed reactor. However, a great effort is still necessary to develop and implement simple actions to value these residues and related by-products. An important first step would be conducting experi-

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ments able to characterize the substrate behavior and predict the gasification process for commercial reactors.

Most experimental studies found in the literature use laboratory scale reactors, mainly due to lower operating costs and being more accessible when it comes to controlling the various operational parameters and boundary conditions [6]. Studies conducted in industrial reactors are limited due to the difficulty of regulating the operating parameters but mainly due to the high cost of a gasification plant, which can reach tens of millions of euros depending on the generated power [7].

From the studies concerning laboratory scale reactors the following are highlights of some recent ones. Xiao et al. [8] used low-temperature gasification to study energy recovery from waste tire. Influence of equivalent ratio and temperature on carbon black yield was analyzed. Results showed that carbon balance reached 95% when temperature was over 600 °C. Sarker et al. [9] used a lab-scale fluidized bed reactor to gasify alfalfa and wheat straw pellets. Impact of semi-continuous solid feeding and equivalent ratio on several gasification variables such as gas lower heating value, specific gas yield, cold gas efficiency and carbon conversion efficiency was studied. Optimal operational point for alfalfa and wheat straw was found for equivalent ratios of 0.35 and 0.3, respectively. Moghadam et al. [10] integrated pyrolysis and steam gasification processes in order to obtain the optimum condition of syngas production. The impact of reaction temperature, equivalence ratio and steam-to-biomass ratio was investigated. The effect of using different biomasses in a steam environment was studied by Loha et al. [11]. They also developed an equilibrium model and the corresponding validation was performed using experimental data collected by the author in a laboratory scale fluidized bed gasifier.

Although these studies, among others, are very important for increasing fundamental knowledge of the gasification process, it is imperative to devote time to studies that utilize pilot scale or industrial reactors. Indeed, a major concern regarding coal and biomass gasification is the scale-up. The scale-up has brought problems for engineers since the beginnings of fluidization history, culminating in its best-known failure example of the first bubbling-bed, Fischer–Tropsch in 1950 [12]. Scale-up is not an exact science, it is too complicated to use information collected from laboratory studies and use it to design a commercial reactor that can be tens or even hundreds of times larger. There are key factors that rule this transition and whose prediction is still not well known. When changing from a small reactor to a larger one, the hydrodynamics changes significantly which means that substrate particles behave differently. Also, the residence time is different causing a great influence on the chemical reactions. Both contributions lead to final syngas compositions which can differ substantially, at least, in their absolute value. For this reason, it is necessary to gather data from reactors with similar dimensions to avoid errors and reduce high level risks and uncertainty [13]. One way around this issue without resorting to major investments and/or the need for long waiting periods (with all the bureaucratic and logistical problems associated) is the use of numerical models. These models provide the ability to theoretically simulate any physical condition while being relatively inexpensive and quickly executed. Different modeling approaches have being attempted by several research groups [14–16]. One of the most traditional and simple approaches considers the gasification process in thermodynamic equilibrium [14]. The equilibrium models are especially advantageous considering their quick and easy convergence and its importance as a design tool. However, they are unable to predict any hydrodynamics aspects of the gasification process as well as important profile distributions inside the reactor. Hameed et al. [15] used kinetic models for describing the rate equations for the different reactions that occur in the reduction zone of a biomass gasifier. More complex approaches involve gas–solid flow, chemical reactions and interaction between phases [16]. Meaningful information can be extracted from powerful simulation models and used to predict experimental results in laboratorial and industrial scales.

In the present study a previously developed numerical model was used to study the scale-up effects between a laboratory-scale and a pilot scale reactor using two Portuguese agro-industrial residues. Model was first validated against results from a pilot scale reactor. Model was then expended to predict the results in laboratory scale reactor. Literature was used to validate the model in lab-scale conditions. Influence of gasification temperature and oxygen content in both reactors was also studied. Finally, influence of biomass type on scale-up effect was analyzed.

2. Materials and experimental set-up

Experimental runs were performed in a pilot scale bubbling fluidized bed gasifier. The schematics of the pilot scale gasification plant are depicted in Fig. 1.

All components that comprise the gasification plant are fully detailed in electronic supplementary material. The upcoming analysis is considered for forest and vine pruning residues. Data regarding proximate and ultimate analysis are found in Table 1. Also, data regarding these substrate availability in Portugal can be found in [5] and in electronic supplementary material.

3. Mathematical model

Even though scale-up phenomenon is one of the major problems concerning biomass gasification there is still a clear lack of work done on the problem mainly due to the costs associated with industrial size gasifiers. In order to properly study the scale-up, a numerical study using different size reactors ranging from laboratory to pilot scale was performed. The two-dimensional mathematical model developed and detailed by Couto and Silva [17] was applied in this study. A brief description of the mathematical model is highlighted in the next lines.

Mass and momentum balances are considered for both phases (solid and gas). Due to the characteristics of fluidized bed gasifiers [18], turbulence between phases can be modeled by using the standard k–ε model in ANSYS FLUENT. Detailed equations can be found in [5]. The multi-phase approach considers the gas phase as continuous and the solid phase follows the granular Eulerian model. Equations for granular temperature were based on the Syamlal et al. [19] and Lun et al. [20] works. Detailed equations can also be found in [5].

The main equations governing the chemistry behind the developed model are depicted in Table 2. Devolatilization is the thermal decomposition of solid fuels. Biomass is assumed to be comprised of cellulose, hemicellulose and lignin [21] and with each component contributing proportionally to the biomass [22]. Devolatilization representative equations and kinetics are depicted in Table 2.

Homogeneous gas-phase reactions are modeled considering the finite-rate/Eddy-dissipation model which considers both the Arrhenius and Eddy-dissipation reaction rates. The minimum value of the Arrhenius and Eddy dissipation rates can be defined as the net reaction rate. Heterogeneous reactions follow the Kinetic/Diffusion Surface Reaction Model [25,26]. Baum et al. [25] applied this model to simulate the behavior of coal particles. Field [26] used this approach to describe the heterogeneous reactions that occur in the char gasification of a low rank coal at high temperatures. This model weights the effect of the Arrhenius rate and the diffusion rate of the oxidant at the surface particle.