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# Comprehensive experimental investigation and numerical modeling of the combined partial oxidation-gasification zone in a pilot downdraft air-blown gasifier

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A pilot downdraft gasifier is investigated experimentally using almond shell biomass as feedstock. Experimental temperature profiles along the different zones of the gasifier are measured and overlapping regions between the different gasifier stratified zones is proved: we identified two main zones (drying-pyrolysis zone and partial oxidation-reduction zone) instead of four stratified zones as proposed in the literature. In light of this experimental finding, a two dimensional mathematical model is developed for the combined partial oxidation-reduction zone based on conservation equations coupled to the heterogeneous and homogeneous chemistry. Partial oxidation and thermal cracking mechanisms of tar are proposed based on the available kinetic data. The model is developed for the quasi-steady state period of the experiment and used to simulate the heat and mass transport fields within the computational domain, analyze the interaction between the heterogeneous and homogeneous reactions and evaluate the performance of the gasifier in terms of tar conversion and syngas composition. Validation against the mean experimental temperature data and the producer gas composition at the outlet of the reactor are presented and a satisfactory agreement is observed. The influence of pyrolysis gas composition, air flow rate and bed porosity on the process and its outputs is also investigated.



## 1. Introduction

Nowadays, ambitious plans are being drawn toward the development and integration of renewable energy technologies in several countries. This trend is being driven by the future scarcity of the conventional fossil fuels and the environmental problems arising from their massive utilization. Biomass is one of the important renewable energy sources being used around the globe. So far, several conversion technologies have been developed to convert the various biomass resources into more convenient energy vectors like liquid or gaseous biofuels and electricity.

Gasification is a promising technique that enables the efficient upgrading of the energy embedded in biomass [1,2]. It consists of the thermochemical conversion of biomass feedstock into a gaseous fuel called syngas which can be used in several downstream applications like gas turbines, fuel cells and the synthesis of liquid fuels. Among the different reactor configurations, fixed bed biomass gasifiers are the most favored for small to medium scale heat and power production [3]. Particularly, the downdraft fixed bed gasifier has received a great interest in research and development. Indeed, 75% of the manufactured gasifiers in Europe were of the downdraft type [4]. The reason behind this interest is the characteristic ability of the downdraft gasifier for the production of a relatively clean syngas with low tar content. Indeed, the co-current flow of the volatile compounds and the blown air through the highest temperature zone of the reactor bottom enables the partial burning and the thermal cracking of tarry species.

Intensive experimental research work was conducted in literature to study the effect of design and operational parameters on the gasification of different biomass materials in pilot downdraft reactors [5–10]. Guo et al. [5] showed that the establishment of a high and uniform temperature field in the partial oxidation and reduction zones of the downdraft reactor enables the decrease of the tar content of the syngas. The important effect of the partial oxidation zone temperature was also highlighted in another experimental study carried out by Ma et al. [7] using wood ships as feedstock. The high temperature reached in the downdraft reactor was directly linked to the increase of the air flow rate or the air to fuel

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equivalence ratio [5–9]. However, the increase of the equivalence ratio affects negatively the composition of the syngas and its heating value. Particularly, it causes a decrease of the hydrogen fraction. Therefore, optimum values of the equivalence ratio were investigated in order to obtain a sufficiently high temperature field and a low tar yield while ensuring the production of syngas with a suitable composition and heating value [5–10]. In an attempt to increase the hydrogen fraction and the calorific value of the syngas, injection of saturated steam in the reduction zone of a downdraft gasifier was conducted by Sharma and Sheth [10]. The addition of steam resulted in a temporary increase in the hydrogen flow rate which was explained by the enhancement of the water gas shift reaction. However, the steam injection resulted in a subsequent decrease of the temperature in the oxidation zone. To avoid this negative effect, intermittent steam addition may be performed in order to ensure permanent increase of hydrogen while maintaining the oxidation zone temperature at a sufficient high level.

In addition to the experimental studies, numerical modeling of gasification process was also largely conducted in the literature [1,2,10–15]. Indeed, modeling is an important tool for the design and optimization of biomass thermal conversion systems. Valuable information could be derived about the performance of a system and eventually identify its weaknesses using robust mathematical modeling [16]. Equilibrium modeling of downdraft gasifiers was conducted in literature in order to predict syngas composition at different operating conditions [10,11]. Such models are typically based on a global reaction that describes the conversion of the biomass fuel into a gas mixture in presence of a specified amount of oxygen. Mass and energy balances are used along with the equilibrium relations of the homogeneous reactions to obtain the composition and the temperature of the syngas at the outlet of the reactor. On the other hand, the coupled kinetic and transport models of biomass gasification as well as pyrolysis and combustion in packed bed systems are among the most comprehensive and reliable models performed in the literature [1]. These numerical tools were used to simulate the loading of the processes and their related parameters (transport variables, ignition and propagation rates, etc.) and to study the effect of the main operating parameters. The most common modeling approach used in these models is the porous media approach which is also known as the quasi-continuous, the macroscopic or the Euler-Euler approach [13–20]. In this method, the solid phase and the gas phase forming the porous packed bed are treated as if they were continuous phases and the different variables and properties are volume averaged leading to a system of macroscopic conservation equations. This methodology has been used in large extent for the modeling of drying, pyrolysis, gasification and combustion of biomass fuels in packed bed systems [13–20].

A principle assumption is required in the implementation of the quasi-continuous models: the internal gradients are negligible within the individual particles that form the packed bed system. Johansson et al. [18] investigated the validity of this assumption by developing two numerical models for fixed bed wood combustion: the first was based on the macroscopic approximation while the second included a detailed model for the particle level. By comparing the modeling results, they showed that the differences are fairly of minor importance for small size particles (equivalent diameter ranging from 5 to 20 mm). Accordingly, neglecting the internal gradients could be considered as an acceptable assumption for common biomass particles used in fixed and moving bed systems like commercial pellets, wood ships and agricultural residues. The accuracy and validity of the macroscopic modeling approach is consequently not affected [18].

According to the previous research works in the literature, the process of biomass gasification in a downdraft gasifier involves four steps which are stratified along the height of the reactor from top to bottom as drying, pyrolysis, partial oxidation and char reduction (Fig. 1). The previous modeling studies were either implemented for the whole downdraft gasification process or for a unique zone of the aforementioned steps. Indeed, it was recognized that the separation of the overall process into sub-models enables a thorough analysis of each zone [3]. Most of the zone-specific models were dedicated to the reduction zone of the downdraft gasifier as it is the last and the determining step of the conversion process (a summary of some recent numerical modeling studies are gathered in Table A1 at Appendix). It should be noted that most of the models developed for the overall gasification process were based on a one dimensional treatment assuming minor variations in the reactor cross sections; while a two dimensional treatment was adopted for most of the specific zone models in order to provide better simulations and detailed insights of the chemical and the transport phenomena.

The main disadvantage of the specific zone models is that they did not account of the different transport and chemical effects coming from adjacent reacting zones (i.e. they allow for a decoupled treatment only). On the other hand, the studies based on the overall reactor modeling approach considered the continuity between the different reacting zones of the reactor. However, they emphasized on the global behavior of the reactor and its final outputs and did not address the important mutual and local interaction between the heat and mass transport phenomena and the thermochemical reactions occurring within and in between the reacting zones of the reactor.

In this work, a novel modeling approach is proposed for the study of the downdraft gasifier. Firstly, a comprehensive experimental investigation of the gasification process is performed using a pilot scale throated downdraft gasifier fueled by a locally available biomass (almond shell). Based on the analysis of the experimental observations, a novel configuration is proposed for the downdraft gasifier. Then, a detailed two dimensional numerical model is developed for the combined partial oxidation-gasification zone of the experimented gasifier. The model takes into account the different physical and chemical phenomena that can occur in the packed bed heterogeneous medium, including fluid hydrodynamics and heat and mass transfer coupled with the chemical reactions kinetics. Besides, a detailed tar oxidation and cracking mechanism is also included in the chemical mechanism. The obtained numerical results are then compared with the experimental data for validation. Finally, the developed model is used to simulate the heat and mass transport fields in the considered domain and to analyze their interaction with the oxidation and gasification reactions. The developed numerical model is also used to study the effect of operating parameters on the distribution and fraction of the syngas species.

## 2. Experimental study

### 2.1. Materials and methods

#### 2.1.1. Biomass feedstock

The biomass used in the gasification experimental study is Tunisian almond shell. This biomass fuel is an agricultural residue available in several Mediterranean countries. Tunisia is ranked 8$^{th}$ producer of almond by around 3.8% of the world production [25] which is equivalent to a production of about 36 000 tons per year of almond shell (assuming that the shell presents 60% of the overall almond fruit weight).

Almond shell is a suitable fuel for gasification in fixed bed reactors since it is readily provided in small dried pieces (bulk particle size based on equivalent sphere diameter around 0.01 m). Hence, it doesn't require any additional pretreatment. The almond shell