Biomass and Bioenergy 116 (2018) 80–88

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

Research paper

Numerical simulation of a pilot-scale reactor under different operating modes: Combustion, gasification and pyrolysis

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ARTICLE INFO

Keywords:
Gasification
Combustion
Pyrolysis
Biomass
CO_2 concentration

ABSTRACT

This paper provides a numerical analysis of a downdraft fixed bed reactor to examine the effect that the different operating modes have on temperature profile, velocity profile, gas composition and particle residence time. First, pine wood sawdust is considered as the feedstock to the reactor. Simulations of the reactor operating modes are performed using the commercial CFD code Ansys-Fluent coupled with the Discrete Phase Method (DPM). So different chemical reactions are considered in the reactor depending on the operating mode: a) pyrolyzer, b) gasifier or c) combustor. A two-dimensional modelling for the geometry is used in conjunction with 0.001 mm diameter spherical particles. The interaction of particles (discrete phase) with the continuous phase is performed by modifying the transport equations. For the purpose of model validation, experimental data of temperature profiles and syngas composition are used. Besides, the influence of concentration of an oxidant agent is numerically investigated. Results show that the maximum temperatures reached in combustion, gasification, and pyrolysis processes are, respectively, 2207.91 (K), 1559.47 (K) and 1097.55 (K). Finally, simulated gasification temperature showed a standard deviation of 5.2% from experimental one.

1. Introduction

Biomass is considered as a promising, sustainable and reliable source of energy because of its renewable and environmentally friendly characteristics [1, 2]. It is known that the thermochemical conversion of biomass is the most practical option for its treatment: a) combustion, b) pyrolysis, and c) gasification [3]. Among them, gasification is identified as a key technology for the production of energy. Gasification converts biomass into gaseous products (e.g. CO_2, H_2O, CO, H_2, and hydrocarbons), and small quantities of char (i.e. solid products), ash, and condensable compounds (e.g. tars and oils). This conversion is achieved in a gasifier with a controlled amount of oxidizing agent at high temperature so as to prevent completion of combustion. Among the different types of gasifiers, the downdraft gasifier provides the minimum amount of tar residue [3]. The operating of a downdraft gasifier consists of three stages: first, biomass is injected into the pyrolysis zone and products are solids (bio-char), liquids (tar and other organics), and gases. Then products are oxidized in the presence of some oxidizing agent like either air or oxygen. The charcoal is converted into syngas by reduction reactions in the reduction zone of the gasifier [4]. It is known that every stage in the gasifier is independent and play an important role in the gasification modelling, however the reduction stage is the most significant. The reactions in this stage are slow and control the overall conversion of biomass [5]. Several kinetic studies of gasification are found in literature where four reaction stages are considered: drying, pyrolysis (volatile release), combustion, and reduction [6]. Moreover, any process of thermochemical conversion involves complex physical and chemical phenomena including fluid flow, heat and mass transfer, as well as chemical reactions. Current computational tools are helping to predict the nature of physical and chemical phenomena in the field of engineering. Particularly, substantial progress in the studies of biomass conversion devices is made due to extensive mathematical models made for the coal gasification simulation studies [7-9]. Recently, Pierucci et al. [10] combined the chemistry model for biomass pyrolysis and gas-phase reactions of Ranzi et al. [11] with a one-dimensional model for moving bed gasifiers using a multi-zone description of the biomass particles. Validation was performed using the gas composition at the exit of a lab-scale reactor. The results show an acceptable agreement between numerical and experimental data. It is concluded that more accurate model should take into account Navier-Stokes equations coupled with the chemical reactions. Some other numerical methods of thermochemical conversion use an

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https://doi.org/10.1016/j.biombioe.2018.05.007
Received 20 November 2017; Received in revised form 11 May 2018; Accepted 21 May 2018

Table 1
Comparison of the models used in comprehensive CFD studies of biomass conversion.

Reference	[13]	[14]	[15]	[16]	[17]	[18,19]
Fuel	Coal	Biomass	Biomass	Coal	Biomass	Coal
Application	Gasification Fixed Bed	Gasification Fixed Bed	Combustion - Gasification Fixed Bed	Gasification Entrained Flow	Pyrolysis in Fluidized Bed	Combustion in Fluidized Bed
Dimensions	3	2 Axi-sym	2	3		2
Method	Lagrangian	Lagrangian	Eulerian	Lagrangian-Eulerian	Eulerian-Eulerian	Lagrangian
Turbulence	Standard k-ε	Standard k-ε	Standard k-ε	RANS	RSTM	LES
Chemistry	Multi-Step CO,CO_2,O_2, H_2O,H_2,CH_4, Char	Multi-Step CO,CO_2,O_2, H_2O,H_2,CH_4, Char	Non-Premixed Combustion	Multi-Step CO,CO_2,O_2, H_2O,H_2,CH_4, Char	Multi-Step, Tar-Char-Gas	Multi-Step, NOx species
Validation with experiments	None	Temperature Profile	None	Temperature and exit gas composition	Product Yields	None

Eulerian-Eulerian model where the discrete phase is solved in the continuous domain where interactions of the solid particles with the gas phase, are used for measuring the heat transfer and momentum exchange [12]. Table 1 summarizes works regarding combustion, gasification and pyrolysis simulations through different methods.

In particular, the hypothesis of this work is that a reactor can operate as either combustor, gasifier or pyrolyzer, as long as control conditions such as temperature, oxidizing agent, and heat of reaction are regulated in order to lead the reactions that will produce heat, gas, bio-oil and bio-char in different levels of yield and energy content in the same reactor. Therefore, in this paper, an effort is made to build a numerical model of a pilot scale fixed-bed reactor which permits to study the effect that the different operating modes have on temperature profiles, velocity profiles, species concentration and on the amount of oxidizing agent.

2. Experimental setup

2.1. Physical model description

Fig. 1 (a) shows the physical structure and schematic of the downdraft gasifier used herein. The gasifier is a downdraft reactor with an internal diameter of 25 cm and a height of 48 cm. It consists of a feed hopper, a secondary insulation with stainless steel flexible hoses around the internal reactor to be used as heat exchanger between the cold air and the hot syngas, a swirl burner, and a rotary grate in the bottom. The biomass is injected at the top of the reactor and moves downward. The total air is injected tangentially into the reactor through a set of injection nozzles at 0.05 and 0.10 m above the bottom. The biomass is then heated, devolatilized and reacted on its way down to the bottom. The produced syngas exhausts to a cyclone where a packed bed filter is used to collect both ash and tar.

Temperature is measured at six different positions in the reactor using *K*-type thermocouples. Five thermocouples are installed along the vertical center line of the gasifier as shown in Fig. 1 (b). A data acquisition system (DAQ) coupled to the LabVIEW® software is used to collect measurements. Besides, two local manometers are installed to measure gauge pressure, and one air blower with a variable speed control is connected to the reactor. The syngas samples are analyzed using a SRI 310 gas chromatograph.

3. Numerical model

The simulations of the operating modes are performed using the commercial CFD code Ansys-Fluent [20]. Different chemical reactions are considered in the reactor depending on the operating mode:

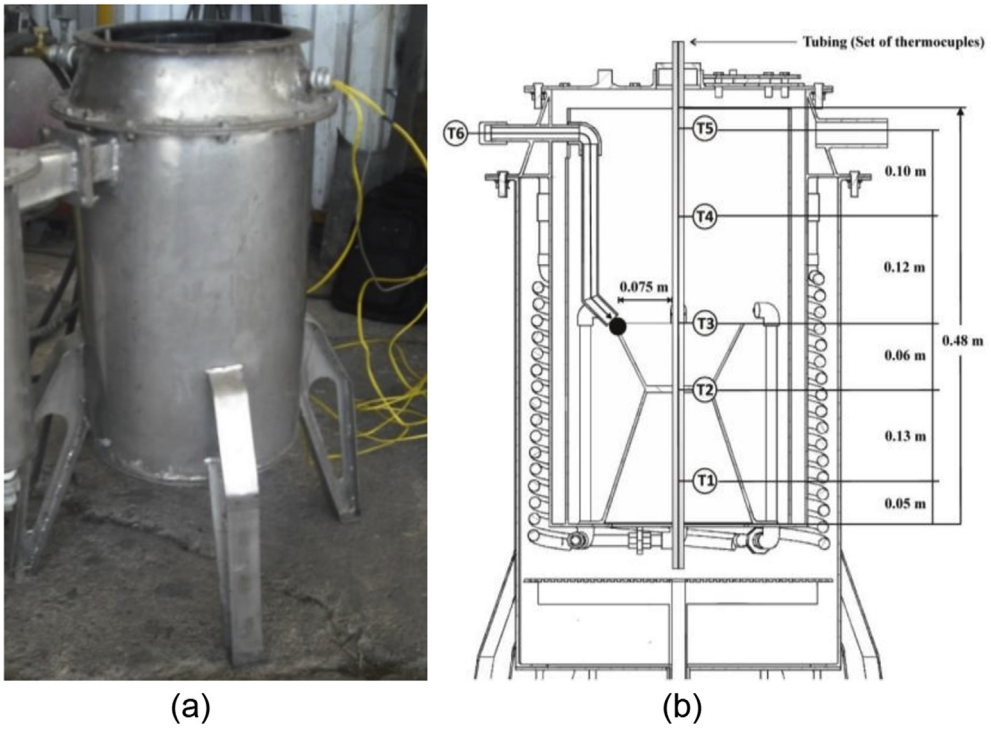

Figure 1. Physical structure and schematic of the reactor: location of thermocouples installed in the reactor.