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Kinetic modeling and simulation of throated downdraft gasifier

Ozgun Yucel *, Mehmet Alaittin Hastaoglu

Gebze Technical University, Chemical Engineering Department, 41400, Gebze, Kocaeli, Turkey

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ABSTRACT

An imbert 'throated' gasifier which has hourglass heart and varying axial area and nozzles for injection of gasification agents has been studied. The transport of reacting gas-solid two-phase mixture through the gasifier has been mathematically modeled transiently. Downdraft gasification in such a complex system has so many variables and is quite cumbersome to describe. For the first time throated gasifiers are modeled as realistically as possible. The resulting set of transport, structural, kinetic and auxiliary equations was solved via numerical methods. The modeling work was experimentally validated using a 10 kW gasifier. The actual geometry of the experimental setup was used in the model. The model results were in line with the experimental results. Throated combustion zone causes better distribution of heat and reduces heat loss. With the same core size and solid consumption, stratified gasifier output was 24.5% less than throated one. The model exit had 25.85% CO; 18.25% H_2; 7.84% CO_2; 2.9% CH_4; while the experiment had 35.07–20.77% CO; 18.30–13.66% H_2; 13.68–5.95% CO_2; 6.7–1.2% CH_4; the rest was N_2. The model can be applied to different geometries.

1. Introduction

Gasification is a thermochemical process at elevated temperatures (500–1400 °C) and it uses heat to transform biomass or other carbonaceous material into a combustible gas. The product gas mainly consists of hydrogen, carbon monoxide, carbon dioxide, methane, water vapor, nitrogen, traces of higher hydrocarbons such as ethane and also various contaminants such as char particles, ash, tar and oil. The fixed bed gasification systems are classified as updraft, downdraft, cross-draft and two stage gasifiers according to the method of contacting fuel, direction of air/gas movement, and types of bed. The fixed bed gasifier, which may be updraft or downdraft, is simple and generally operates with high carbon conversion, long residence time, and low gas velocity [1]. The Imbert downdraft gasifiers are suitable to handle biomass fuel having ash and moisture content less than 5% and 20% respectively [2]. Downdraft gasifiers usually yield syngas with low tar content (1–2 g/Nm^3) and are suitable for small-scale applications (<10 MW$_{th}$). On the other hand, composition of syngas varies with feedstock and design parameters.

A chemical process can be modeled with both equilibrium and kinetic non-equilibrium. Equilibrium models predict the maximum achievable conversion and the distribution of each species in the product streams is subject to thermodynamic constraints independent from "geometry". Also equilibrium models do not estimate the difference between the time needed to reach equilibrium and residence time. They assume that all reactions reach chemical equilibrium. But gasification process involves heterogeneous char reactions that occur slowly. Kinetic and transport models deal with heat, mass, momentum and kinetic equations and give the concentrations at any point in time and space within the system. These models can provide valuable information about reaction mechanisms to increase the conversion to syngas.

Downdraft gasification produces a syngas with very low tar content and is simple and reliable. For a downdraft gasifier, biomass moves co-currently with the gas, and passes through drying, pyrolysis, oxidation and reduction zones. Several downdraft gasifier models are available in the literature but all of them are defined for stratified (without throat) gasifiers due to complexity of imbert design, and also they inject air at the top of the gasifier not at the top of the throated region. On the other hand, most of them are at steady-state, and assume the existence of stable zones. Especially in the char reduction zone, usually the reactions are assumed to run to completion. But the actual conversion depends on air–carbon ratio, solid residence time and other kinetic factors, so that equilibrium models overestimate the H_2 and CO yields and underestimate CO_2, methane, tar and char, especially for relatively low gasification temperatures. Sharma [3]. stated that at critical char bed length and the critical reaction temperature, equilibrium models can be useful but these phenomena can be modeled depending on initial composition and initial temperature.

Gasification process can be divided into four steps: biomass drying, primary and secondary pyrolysis, combustion of products and reduction of H_2, CO_2 and H_2O with char. Early kinetic models have centered on (devolatilization) wood or cellulose conversion to gas, char and tar [4]. Later some researchers studied coal gasification and gave valuable information by combining heterogeneous char reaction kinetics and

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* Corresponding author.

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transport phenomena [5]. For the degradation of biomass three-step and one-step mechanisms are proposed in order to predict particle mass loss [6–9]. Also catalytic effect of char on the heterogeneous reactions in the reduction zone has been studied [10,11]. First dynamic model for stratified gasification was presented by Di Blasi [12]. without taking into account the pressure drop along the bed (although they have modeled the pressure drop it has not been used in simulations). Tinaut et al. [13]. built a steady state model also including hydrocarbon reforming (tar and methane reforming). Di Blasi and Branca [14]. proposed a model for the open-core downdraft gasification of wood pellets, which permits a dual air entry: from the top section and at a certain height of the packed bed. But they studied top-stabilized front (secondary air up to 50%) and double-front stabilization (secondary air up to 60–70%). In reality, air is just introduced at an intermediate level for imbert gasifiers. A very small amount of air could enter from the top when solid fuel is introduced into the gasifier at the top which is negligible for downdraft gasification. Furthermore, these models do not describe transversal variation of throated gasifier.

Fixed bed gasifiers have surrounding jacket in order to minimize heat loss. There is no work in the literature that evaluates the energies of the inner wall and the gas exiting from the reactor passing thorough the jacket which are important in reality. Dynamic behavior of the downdraft gasifier cannot be examined realistically without considering these energies. In this work the wall and exit gas are also considered in the set of energy equations of the downdraft reactors. In the present study the mathematical model is presented for gasification of the wood pellets in an imbert gasifier which has hourglass heart shape and permits the air feed at intermediate levels of the reactor. Also experiments have been performed to validate the model.

Modeling work on stratified gasifier was started similar to a previous study [14] where gas flow was calculated based on conservation of total gas mass. However, in this work, we have changed it completely by using momentum transfer approach, and since we had used a circulation pump in the experimental system, we have approached the reality more closely. We have changed all the parameters by using the actual system values and we have tried to develop as a realistic model as possible. The gas velocity is evaluated from continuity equation in general, but in our system it is evaluated from the pressure to simulate vacuum-driven system. The energy equation for the inner wall was also solved. Additionally the exit gas was modeled as it leaves the packed bed zone while traveling between the inner and outer reactor walls. All the transport equations including water–gas shift, tar reforming and methane reforming reactions were solved for the exit gas as well. This meant that the relevant PDEs were solved simultaneously for all the gaseous species. Thus the cold gas concentrations at the exhaust of the gasifier were determined.

2. Experiment

Several experiments were conducted on a 10 kW downdraft fixed-bed gasification system which is developed by All Power Labs Inc. The scheme for the gasification system is illustrated in Fig. 1. The reactor is cylindrical with an internal diameter of 28 cm and a height of 55 cm. At the inside, however, the reduction cone tapers to 20 cm and the heart cone tapers to 7 cm in order to increase solid residence time in the pyrolysis and combustion zones. Gasifier has a throat where the unit narrows below the flame zone so constriction restricts the tar content in the produced gas by forcing the volatiles to pass through the combustion zone. In the reduction zone the diameter expands to 19 cm then 23 cm and 38 cm respectively. Flue gas exits through a 21 cm equivalent diameter.

Temperatures at 6 different heights inside the gasifier were measured with a group of 6 in-line K-type thermocouples with 8 mm diameter. Two groups of thermocouples were located at the center and 5 cm off center. A perforated iron grate is installed at the bottom of the gasifier and the grate was shaken at adjustable intervals in order to dispose the ashes continuously from the gasifier and to prevent bridging and dead zones inside the gasifier. We have designed a pneumatic eccentric shaking system for this purpose. The gasifier is filled with batches of charcoal from the grate up to air injection nozzles and then followed by the wood pellets. Air is used as an oxidizing agent for biomass gasification. The top of the gasifier is sealed to prevent (primary) air inlet, pressure drop also prevents the primary air from entering the filled gasifier. The gasifier has 5 (secondary) air injection nozzles just above the hearth of the gasifier.

The experimental set-up has a limitation of working with only few kPa of vacuum (around 1–2 kPa in this work). This is applied to the gasifier in order to provide gas flow through the gasifier by an air compressor connected with the flue gas. More vacuum would cause low quality gas since the reduction reactions will not have adequate time for completion, less vacuum wouldn't let enough oxygen to get into gasifier so gasifier temperature would drop dramatically: either way detrimental to the operation of the gasifier.

The gasifier was ignited by a butane torch from the ignition port until white flue gas is seen at the outlet. The gas obtained from the gasifier enters the cyclone and packed bed filter after traveling between the inner and outer walls of the gasifier. Particulates are removed while passing through the cyclone and the tar is collected by packed bed filter. Afterwards, a portable infrared syngas analyzer, Wuhan Cubic Syngas Analyzer Gas board 3100P, was used for the measurement of the concentrations of CO, CO_2, CH_4, H_2 and O_2 in the sample gases simultaneously while heating value (calorific value) is calculated automatically by an NDIR and Thermal Conductivity Detector. Gas is also collected and analyzed using a GC-7890A. Finally, the flue gas is burnt out with a swirl burner. Otherwise this gaseous mixture can be used to generate energy at gas engine or separated in order to obtain H_2, CH_4, CO etc. via membrane. Flue gas also can be used to manufacture of ammonia, methanol, and other valuable chemicals.

Wood pellets used in the experimental runs had according to the elemental analyses 50.67% C; 6.18% H; 2% N; 0.18% S and the rest was O. The cylindrical pellets were roughly between 1 and 1.5 cm in size. Other parameters can be seen in Table 1. While the feeding rate of the fuel was determined from the loading and operating time; the flow rates of the air injected and product gases were calculated from the orifice plate measurements. During the experiments flow rates of the gases and the pressures at the gasifier exit, air injection point and the pressure at the filter exit were recorded. Vacuum is applied at the latter point. Additionally temperatures were recorded at the selected points.

3. Mathematical model

Gasification operation is not a steady state process. For example, fixed bed gasifiers are filled with fixed amount of charcoal to startup and ignited with blowtorch for a while. Also, there is a fluctuation in fuel and air consumption. On the other hand, air input is a function of pressure in the gasifier. Therefore the gasifier must be modeled as transient. The following partial differential equations have been derived typically comprising of conservation equations in the gas and solid phases for a one-dimensional unsteady state system. Within the bed 1-D modeling is used considering variable cross-sectional area of the reactor. At all grid points, contributions of the reactor walls were accounted for in the energy balance equation and at the air injection grid air is considered both in mass and energy balance equations.

The variation of the cross-sectional area in the throated section leads to varying reactor diameter which is embedded in the cross-sectional area A_c. Note that the reactor diameter is directly used in the calculation of various transfer coefficients such as overall wall heat transfer coefficient as well as particle heat and mass transfer coefficients via Reynolds number.

The model describes the processes of drying, pyrolysis, combustion, and heterogeneous char reactions. For simplification, the particles fed are assumed to have uniform size and shape. As the reaction continues,