Biomass and Bioenergy 116 (2018) 216–226

Contents lists available at ScienceDirect

Biomass and Bioenergy

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

Research paper

# Optimisation of a throat downdraft gasifier for hydrogen production

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ARTICLE INFO

*Keywords:*
CFD model
Biomass gasification
Throat downdraft gasifier
Syngas

ABSTRACT

Gasification of coal is a well-known technology used to convert solid coal into gas (syngas). The implementation of gasification for waste and biomass still requires attention due to the difference in nature of biomass compared to coal. Although, modification to a gasifier is one of the main approaches to achieve high quality syngas production (high $H_2$/CO ratio) and to eliminate tar formation, the effect of design of the gasifier has not been studied. Downdraft gasifiers are reported to produce relatively high quality syngas with low tar concentration compared to other designs. Therefore, in this study a 20 cm diameter throat downdraft gasifier was numerically optimised using Computational Fluid Dynamics modelling. The effect of throat diameter and the position of the air inlet nozzles above the throat on the properties of the gas and the temperature profile in the gasifier was systematically investigated and validated using experimental data. The throat diameter and the position of the air inlet nozzles had a significant effect on the properties of the gas and temperature profile. The modelling and experimental results agreed very well with less than 5% deviation. This confirms that the numerical approaches are valid and can be used in scaling up biomass gasification, reducing process development time from laboratory scales to pilot/industrial scales. The maximum concentration of $H_2$ (31.2%mol) and highest $H_2$/CO ratio (1.25) was found at a ratio of throat diameter to gasifier diameter of 0.40 and the position of the air inlet nozzles at 10 cm above the throat.

## 1. Introduction

Global primary energy demand is expected to increase by 48% by 2040 due to the rapid growth of population, urbanization and economic activity [1]. The majority of energy supply is currently reliant on conventional energy resources such as coal (21%), petroleum (28%) and natural gas (32%) [2], which have negative environmental impacts i.e. greenhouse gas ($CO_2$) emissions, air pollution ($SO_x$, $NO_x$, particulates and toxic metals and other impurities) and land contamination [3]. Although, alternative energy sources (e.g. solar, hydro power, biomass, wind, geothermal and nuclear power) have been sought to reduce the dependency upon fossil fuels and reduce the environmental impact, the versatility of biomass makes it most attractive as it can be used to produce not only heat and electricity but also, chemicals and fuels for the transportation sector [4] (Fig. 1). Biomass used for energy production is mostly from wood and waste wood (41%), followed by agriculture residues (24%), municipal solid waste (20%) with a small portion of energy crops (15%) [5].

Gasification is a partial oxidation process to convert carbonaceous substances into a mixture of mainly $H_2$ and CO (synthetic gas or syngas), with small amounts of $CH_4$, $CO_2$, $N_2$, char, ash, tar, oils in a temperature range of 973–1773 K [7]. The proportion of components in the syngas product is strongly influenced by the type of gasifier and its operating conditions such as choice of gasifying agent ($O_2$, $CO_2$, air or steam), equivalence ratio of gasifying agent to feedstock and properties of the feedstock. Fixed-bed gasifiers are the most common technology for small and medium scale biomass gasification due to their simplicity and low investment costs compared to fluidized bed and entrained flow gasifiers [8–10]. A downdraft gasifier is preferable in this study because it is known to produce high quality syngas, with low tar content (0.015–3 g/$Nm^3$) in the gas stream compared to that in an updraft gasifier (30–150 g/$Nm^3$) [11]. Tar is a complex mixture of condensable organic compounds from the products of gasification containing primarily aromatic hydrocarbons [12–14]. The tar content influences performance of the gasification system, the quality of the product gas and creates operational difficulties for the downstream process (e.g. corrosion, clogging and fouling of installations) [15,16].

Computational Fluid Dynamics (CFD) modelling has previously been used to predict the behaviour of biomass gasification to optimize operating conditions of an existing gasifier [17–29]. In general, only a few aspects of the gasifier design have been investigated in any one study. For instance, some CFD studies only focused on the effect of

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https://doi.org/10.1016/j.biombioe.2018.06.019
Received 10 February 2018; Received in revised form 22 May 2018; Accepted 22 June 2018

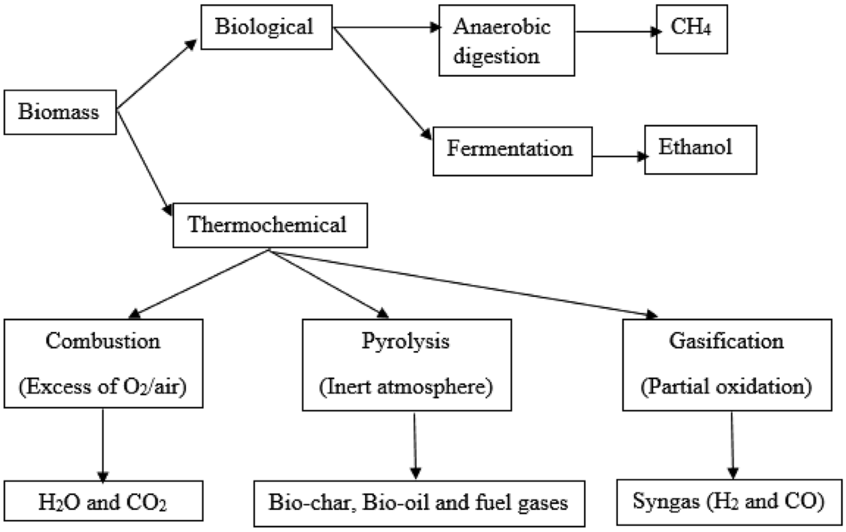

**Fig. 1.** Biomass to bioenergy conversion pathways (adapted from Sharma et al. [6]).

either (i) the number and angle of nozzles [17,30,31] or throat angle and nozzle inclination [32–34] on the performance of a throat downdraft gasifier. Very few workers have applied CFD models for studying interactions between various design aspects of a gasifier and operating conditions to propose a proper configuration of a throat downdraft gasifier for high quality of syngas production. In this study, the effect of the ratio of throat to gasifier body diameter and the position of the air inlet nozzles above the throat were numerically investigated using CFD, ANSYS FLUENT 16.1. It is essential to examine interactions between zones in the gasifier and inlet of a gasifying agent as these determine the quality of product gas. Furthermore, the synergetic effects of gasifier design and operating conditions in a throat downdraft gasifier should be investigated to provide a correlation between operating window and the design of a downdraft gasifier for biomass gasification. Either an Eulerian-Eulerian or Eulerian-Lagrange approach could be used to resolve gas and solid phases together with the conservation equations (momentum, mass and energy) and the standard k-ε turbulence model for the gas phase. The Eulerian-Lagrange approach can track individual particles inside the system so it is suitable to study particle size distributions, interactions of particles, mass and heat transfer between particles, and transient forces acting at the particle level [35,36], therefore it is more suitable for the modelling of fluidized bed gasifiers. The main disadvantage of the Eulerian-Lagrange approach is it is very computationally time intensive when tracking a large number of particle collisions coupled with chemical reactions [37]. In contrast, the Eulerian-Eulerian approach assumes both gas and solid as a second continuous phase and has been proven to effectively model for fixed-bed gasifiers [38–40] in order to predict the macroscopic characteristics of a given system with low computational time. As this study mainly focused on the gas phase for syngas production from a throat downdraft gasifier instead of characterising the particles inside the gasifier, the modified Eulerian-Eulerian approach was chosen. The modelling was then validated using experimental data available in literature.

## 2. Numerical model of a throat downdraft gasifier

### 2.1. Geometry and mesh construction

A 3D model and the volume discretization of a 20 cm diameter and 55 cm long throat downdraft gasifier (Fig. 2a) was created and meshed using DesignModeler (Fig. 2b). The height of pyrolysis, oxidation and reduction zones were estimated at 15 cm, 10 cm and 30 cm respectively. Throat diameters of 5, 6, 8 and 10 cm were varied to obtain ratios of throat to gasifier diameter of 0.25–0.50, with varying positions of the air inlet nozzles above the throat of 8, 10 or 12 cm with the purpose of isolating the effect of both design parameters on the gas properties i.e. concentration and temperature profile. A mesh independence study was carried out at various node and cells counts and the model was built at the conditions where the solutions converged (Fig. 2b).

### 2.2. Computational model

Computational Fluid Dynamic (CFD) software, ANSYS FLUENT 16.1 was used for numerical simulation in this study. The main objective of the CFD analysis was to obtain accurate and reliable modelling results in a reasonable computational time to enable design optimisation. The species transport solution is solved by using the pressure based solver under gravitational acceleration. The Eulerian-Eulerian approach was used to solve transport phenomena, with the conservation of momentum, mass and energy equations. The standard k-ε model was used to capture the turbulence flow of the gas phase inside the gasifier with the standard wall functions. The SIMPLE algorithm scheme was used to solve the pressure-velocity coupling and the standard scheme was chosen for the pressure discretization. The second order upwind scheme was implemented after grid independence studies were completed to obtain accurate results for other calculated variables.

#### 2.2.1. Model assumptions

To simplify the simulation of a throat downdraft gasifier, the following assumptions were made:

- Atmospheric pressure.
- The gasifier was operated under steady state conditions.
- No heat loss through the vessel wall.
- No-slip boundary condition at the wall of the gasifier. The wall was assumed to be insulated and the heat flux at the wall was neglected.
- The wood feed rate was 1 $\text{kghr}^{-1}$ at a temperature of 400 K with the moisture content less than 10 %wt. The drying zone was not included in the gasifier configuration but it was assumed that the feedstock would achieve moisture content $< 10$ %wt when it reached the pyrolysis zone.
- The gasifying agent (air) was introduced through nozzles at 350 K
- The ratio of the actual air/fuel to the stoichiometric air/fuel (ER ratio) was fixed at 0.25.

#### 2.2.2. Governing equations

*2.2.2.1. The momentum conservation equation.* The momentum equation