Experimental study, dynamic modelling, validation and analysis of hydrogen production from biomass pyrolysis/gasification of biomass in a two-stage fixed bed reaction system

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HIGHLIGHTS

- Experimental results at different pyrolysis temperatures for biomass steam gasification.
- Development of 2D dynamic model for biomass pyrolysis/steam reforming.
- Model validation with results from the experimental study.
- Process analysis carried out to predict product yields.

ARTICLE INFO

ABSTRACT

There is great interest in producing hydrogen from renewable sources such as biomass rather than from fossil fuels. This paper presents new experimental results at different pyrolysis temperature and development of a dynamic model for a biomass pyrolysis/steam reforming process in a two stage fixed bed reactor. The model considers the hydrodynamics of the fixed bed reactor, the interfacial mass and energy transfer between the fluid–solid systems and the porous catalyst, and the energy transfer on a kinetic model. The 2D dynamic model resulted in a system of partial differential equations which was solved numerically in gPROMS®. The model was validated with the experimental results. The model predictions show good agreement with the experimental results. The model can be used as a useful tool for design, operation, optimisation and control of the biomass steam gasification process.

1. Introduction

1.1. Background

Global energy demand is increasing with increase in world population and standard of living. Energy supply relies mainly on fossil fuels. With reserves of fossil fuels depleting and their use being the largest single source of greenhouse gas emissions, there is a shift towards the use of clean and renewable sources such as biomass fuels. Hydrogen has been identified as a clean and renewable source expected to play a significant role in future energy systems. The use of biomass pyrolysis and steam reforming for the production of hydrogen has drawn extensive interest from scientists, engineers and government agencies worldwide [1,2]. Two-stage

fixed bed reaction systems have been used extensively for investigating gasification processes due to advantages of easy temperature control at each stage, catalyst recycling and improved contacts between derived pyrolysis products and catalyst [3]. Current experimental practice is to construct fixed bed reactor for small scale research study. The fixed bed reactors are used repeatedly for experiments to predict product yields when new feedstock is used or when operating conditions change. With a model developed and validated using experimental results, the product yield can be predicted. Mathematical models of steam gasification can be used for studies of design, operation, and control of the reactors. This can avoid excessive experiments.

1.2. Literature review

Hydrogen as a clean fuel has become attractive and its production from biomass has raise a lot of interest from researchers [4–7].

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Nomenclature

ΔH_i	heat of reaction i, kJ/kg
C_j	molar concentration of component j, mol/m^3
C_{pf}	specific heat capacity of fluid, J/kg K
D_j^r	diffusivity coefficient of component j in radial direction, m^2/s
$D_{j,z}$	diffusivity coefficient of component j in axial direction, m^2/s
E_i	activation energy of reaction i, kJ/mol
K_r	thermal conductivity in radial direction, W/m K
K_z	thermal conductivity in axial direction W/m K
T_w	temperature of wall, K
X_j	conversion of component j, –
f_p	friction factor, –
K_i	rate constant of reaction i
r_i	rate of reaction of reaction i
u_j	superficial gas velocity, m/s
x_j	mass fraction of component j, –
h	heat transfer coefficient, W/m^2 K
L	length of reactor, m
N_c	number of components, –
N_r	number of reactions, –
N_j	molar flux of component j, mol/s
P1–P5	pyrolysis reactions, –
r1–r5	reforming reactions, –

R	radius of reactor, m
V	volume, m^3
R_g	ideal gas constant
$T(z, r)$	temperature in the axial and radial direction, K
g	gravitational constant, m/s^2
Q	heat flow, J/s

Greek symbol

δ_{ij}	order of reaction, –
α_{ij}	stoichiometry of reaction, –
ε	bed porosity, –
P	density of component, kg/m^3
μ	fluid viscosity, Pa s

Subscript

s	Solid
b	bulk fluid
f	fluid
w	wall
wood	wood
p	particle

Enriched hydrogen gas can be produced from biomass via pyrolysis and steam reforming processes [4,5]. Experimental studies have been carried out using fixed bed reactors [1,8–10], fluidized bed reactors [11], and screw kiln reactors [12].

Several studies through modelling and simulation have been carried out for fixed bed reactors. Ghavipour and Behbahani [13] developed a 1D unsteady state heterogeneous model to simulate adiabatic and non-adiabatic fixed-bed reactors for methanol to dimethyl ether reaction. Tinaut et al. [4] presented a 1D steady state model of biomass gasification in a fixed bed downdraft gasifier. Di Blasi [9] presented a 1D unsteady mathematical model of fixed bed counter-current wood gasifiers. The model couples heat and mass transport with wood drying and devolatilization, char gasification, and combustion of both char and gas-phase species.

Several reaction models have been applied for pyrolysis and steam reforming of biomass. Hashimoto et al. [14] pointed out that several reaction kinetics models proposed for the pyrolysis of biomass have focused on estimating kinetic parameters. However, the kinetic parameters obtained from these experimental fitted models cannot be applied to any other biomass sample, as such new experiments will be necessary to estimate these parameters. Bamford et al. [15], Bilbao et al. [16], and Matsumoto et al. [17] modelled the pyrolysis of wood with a single first order reaction scheme but with fixed heat of reaction. Matsumoto et al. modified the Bamford et al. model by considering the oxidative rate of char removal. Koufopanos et al. [18] proposed two competing and consecutive reactions accounting for both primary and secondary reactions.

1.3. Aim of this study and its novel contribution

This paper presents experiments, dynamic modelling, model validation, and process analysis of biomass steam gasification. It offers a unique approach to predict the main product yields without the need for repeated experiments. New experimental results at different biomass pyrolysis temperature are presented for pyrolysis/steam reforming of wood sawdust. Previously, Wu et al.

[10,19] presented experimental results at fixed pyrolysis temperature (500 °C) for pyrolysis/steam reforming of biomass components using different catalysts. This study also developed a 2D dynamic model for biomass pyrolysis/steam reforming. Previous models for wood gasification have been based on steady state [4] and 1D dynamic model [9]. The model was validated and then used to carry out process analysis to predict product yields.

2. Experimental setup/procedures/results

2.1. The experimental setup

Several new experiments were carried out to investigate the influence of pyrolysis temperature on the hydrogen production from catalytic gasification of biomass. 1.0 g raw wood sawdust and 0.5 g 10 wt.% Ni/Al$_2$O$_3$ catalyst were used for each experiment, which was studied using a two-stage reaction system (a schematic diagram shown in Fig. 1). In each experiment, the second stage containing catalyst was heated up to 800 °C initially, then water was injected to the middle of the two reactors with a flow rate of 4.74 g/h, and the first reactor containing wood sawdust was heated to the designed temperature (300, 400, 500 or 600 °C) with a heating rate of 40 °C/min. The derived vapours from pyrolysis of wood sawdust pass through the catalyst bed in the presence of steam. The final products were condensed with two condensers in air atmosphere and dry ice respectively. Non-condensed gases collected in the Tedlar™ bag were analysed off-line by gas chromatography (GC). The total reaction time of each experiment was around 40 min, and N$_2$ with a flow rate of 80 mL/min was used as carrier gas.

H$_2$, CO and N$_2$ were analysed with a Varian 3380 GC on a 60–80 mesh molecular sieve column with argon carrier gas, whilst CO$_2$ was analysed by another Varian 3380 GC on a Hysep 80–100 mesh column with argon carrier gas. C$_1$ to C$_4$ hydrocarbons were analysed using a Varian 3380 gas chromatograph with a flame ionisation detector, with a 80–100 mesh Hysep column and nitrogen carrier gas.