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Mathematical model to predict temperature profile and air–fuel equivalence ratio of a downdraft gasification process

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ABSTRACT

A mathematical model for the entire length of a downdraft gasifier was developed using thermochemical principles to derive energy and mass conversion equations. Analysis of heat transfer (conduction, convection and radiation) and chemical kinetic technique were applied to predict the temperature profile, feedstock consumption rate (FCR) and reaction equivalence ratio (RER). The model will be useful for designing gasifiers, estimating output gas composition and gas production rate (GPR). Implicit finite difference method solved the equations on the considered reactor length (50 cm) and diameter (20 cm). Conversion criteria for calculation of temperature and feedstock consumption rate were 1×10^{-6} °C and 1×10^{-6} kg/h, respectively. Experimental validation showed that model outputs fitted well with experimental data. Maximum deviation between model and experimental data of temperature, FCR and RER were 52 °C at combustion temperature 663 °C, 0.7 kg/h at the rate 8.1 kg/h and 0.03 at the RER 0.42, respectively. Experimental uncertainty of temperature, FCR and RER were 24.4 °C, 0.71 kg/h and 0.04, respectively, on confidence level of 95%.

1. Introduction

To help reduce green house gas emission problem which comes with the use of fossil fuels, utilization of renewable forms of energy resources such as energy from solar, wind, hydro and biomass is very important. Biomass is considered to be one of the best options because utilizing it may give possibly a near zero net CO_2 emission. Biomass can undergo thermal conversion processes to convert it to much more usable form for heat or power generation [1]. Solid biomass can be converted to useful combustible gas by using the gasification technology. The produced gas by gasification process is called producer gas and this gas can be used as fuel for internal combustion engine (ICE) or gas turbine depending on the produced gas quality [2]. The producer gas is mainly composed of CO, CO_2, CH_4, H_2 and N_2 if the gasification agent is air, of which CO, CH_4 and H_2 are the useful or combustible gas components [3–6]. The syngas can be further converted to liquid fuels in a catalytic reactor or be utilized in fuel cell systems. The gas can also be directly burned in a conventional internal combustion engines [7,8] and the power output from these engines can drive electric generators to generate electricity and even for automobile applications [5]. An example of power application integration was explored by Lee et al. [9] wherein they used a trailer-scale downdraft biomass gasification system coupled with spark-ignited IC engine/electric generator set for portable power applications on agricultural farms and in rural areas.

Though gasification may be considered as old knowledge, it is arguably is not a simple process and requires careful understanding of the reactions and phenomena involved in it. Mathematical modeling is an important tool to help researchers understand any process in numeric terms and are seen very useful to correctly design appropriate physical apparatus for the process, in this case, a gasifier. Mathematical modeling is especially useful in scaling-up from laboratory-scale to demonstration-scale or even up to commercial-scale gasifiers [2]. Gasification mathematical models can be generally separated into two methods: lump analysis and finite computation analysis. Lump analysis treats the considered system as one element while the finite computation analysis is a collection of many small elements of the considered system. Most gasification models use the concept of lump analysis rather than finite computation [10] but are only focused on particular zones in the gasification process as shown in previous works [11–13]. Jaojaruek and Kumar [10] developed the finite computation model for the pyrolysis process in the downdraft gasification. The model covered the drying and pyrolysis zone and required combustion temperature as an input to predict the temperature profile and feedstock consumption rate (FCR). The simulated results fitted very well with

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Nomenclature

A	pre-exponential factor or collision factor, s^{-1}; mass of air in combustion, kg
A_c	reactor cross section area, m^2
A_p	reactive surface area of particle, m^2
b_c	half length of consideration combustion heat source, m
c_p	gas specific heat, J kg^{-1} K^{-1}
c_{ps}	solid specific heat, J kg^{-1} K^{-1}
D	gas diffusibility, m^2 s^{-1}
E	activation energy, J g mol^{-1}
F	mass of fuel in combustion, kg
H	heat of reaction, J kg^{-1}
HHV	higher heating value, MJ kg^{-1}, MJ N^{-1} m^{-3}
$h_{fg,w}$	water latent heat, J kg^{-1}
h_p	gas convective heat transfer coefficient over particle, W m^{-2} K^{-1}
L	considered length, m
L_c	considered length up to combustion location, m
L_n	considered entries length of reactor, m
$\dot{m}_a$	air supply rate by mass, kg s^{-1}
$\dot{m}_c$	consumption rate of char that was burned with air at stoichiometric condition, kg/s
$\dot{m}_f$	feedstock consumption rate, kg s^{-1}
$\dot{m}_{pg}$	producer gas flow rate by mass, kg s^{-1}
n_p	particle equivalent number, m^{-3}
Q_{com}	heat of combustion, W m^{-3}
Q_{dry}	drying load, W m^{-3}
R	universal gas constant, 8.314 J $mol^{-1}K^{-1}$
T	gas temperature, K; temperature, K
T_s	solid temperature, K
u	average gas velocity, m s^{-1}
V	volatile gas at location z
V^*	ultimate attainable yield of volatile gas
$\dot{V}_{pg}$	producer gas production rate, nm^3 s^{-1}
w	rate of generated volatile gas, kg s^{-1} m^{-3}
Y_c	generated volatile gas fraction at $z = L_c$
Y	volatile gas fraction = $\frac{V}{V^*}$
y	mass fraction
y_w	% ash in solid fuel or feedstock
y_w	% humidity in solid fuel or feedstock
y_v	% volatile matter in solid fuel or feedstock

Greek letter

λ	gas conductive heat transfer coefficient, W m^{-1} K^{-1}
ρ	gas density, kg m^{-3}
λ_s	solid conductive heat transfer coefficient, W m^{-1} K^{-1}
ρ_s	solid density, kg m^{-3}
φ	porosity
ϕ	equivalence ratio
τ	optical thickness

Subscripts

a	air
ash	ash
c	char, combustion
com	combustion
f	fuel, feedstock
p	particle
s	solid
stoi	stoichiometric
v	volatile
w	water

the experimental data on combustion temperature range of 600–800 °C. The output from that model are seen as important input parameters for other modeling approaches such as equilibrium kinetic model, minimization of Gibbs free energy model and even chemical finite computation model, to predict gas composition in producer gas and/or gas composition profile in pyrolysis zone [2,14].

A model that can cover all reaction zones of the gasification process especially using the principle of finite computation analysis particularly one that can predict the feedstock consumption rate, reaction equivalence ratio and combustion temperature is still lacking. Numerical modeling through CFD analysis of downdraft gasification using wood chips was investigated by Janajreh and Shrah [15]. Their model was able to predict the temperature profile though the average temperature computed by CFD was higher compared to that measured experimentally, especially on the upper portion of the gasifier covering the drying and pyrolysis zones. It should be observed that their experiment used a significantly small gasifier with an internal diameter of 27 cm and a height of 48 cm, which as the authors have noted contributed to the significant heat loss [15]. Given that most mathematical models are developed with aim of predicting temperature profiles, it would be very useful if the temperature profile along all zones of the gasification process rather than only on individual zones of pyrolysis or combustion as presented in previous works can be predicted. The temperature profile on the whole length of gasification (drying, pyrolysis, combustion and gasification zones) would be a useful input for chemical kinetic and thermodynamic equilibrium models to calculate the gas composition profile on the entire length of the gasifier. This work aims to supplement previous works by developing a gasification model that can predict the feedstock consumption rate as well as temperature profile along the whole length of gasification. Furthermore, this model will also be able to predict reaction equivalence ratio (ϕ) which is a very important parameter for gasifier design [2,16,17]. These two parameters are very important and interlinked as producer gas composition depends mainly on the temperature in the reactor which in its turn is influenced by the equivalence ratio [18]. Therefore, the gasification model from this work will be more capable and would fulfill the lack of FCR and ϕ predictions in previous works and would be a helpful tool for researchers to improve gasifier designs as well.

This paper describes the methodology applied to derive the equations, solve the equations, and setup and collect data from experiments. The simulated calculation and experiments data results are shown with details in the discussion section of the paper. The final part of paper provides the summary of this research.

2. Methodology

2.1. Model development

The governing equations were developed by using heat and mass balance concepts. The analytical structure is illustrated in Fig. 1. The control volume covers from grate position at $Z = L_n$ (40 cm) up to the vertical distance at $Z = 0$ and has diameter D of 20 cm. Previous experiments showed that the temperature of feedstock start to get significantly elevated at locations near to the combustion zone within a distance of less than 15 cm [2]. Thus, the considered range for the pyrolysis zone covering 20 cm above