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Artificial neural network modelling approach for a biomass gasification process in fixed bed gasifiers

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ABSTRACT

The number of the small and middle-scale biomass gasification combined heat and power plants as well as syngas production plants has been significantly increased in the last decade mostly due to extensive incentives. However, existing issues regarding syngas quality, process efficiency, emissions and environmental standards are preventing biomass gasification technology to become more economically viable. To encounter these issues, special attention is given to the development of mathematical models which can be used for a process analysis or plant control purposes. The presented paper analyses possibilities of neural networks to predict process parameters with high speed and accuracy. After a related literature review and measurement data analysis, different modelling approaches for the process parameter prediction that can be used for an on-line process control were developed and their performance were analysed. Neural network models showed good capability to predict biomass gasification process parameters with reasonable accuracy and speed. Measurement data for the model development, verification and performance analysis were derived from biomass gasification plant operated by Technical University Dresden.

1. Introduction

The process of biomass gasification is a high-temperature partial oxidation process in which a solid carbon based feedstock is converted into a gaseous mixture (H_2, CO, CO_2, CH_4, light hydrocarbons, tar, char, ash and minor contaminates) called "syngas", using gasifying agents [1]. H_2 and CO contain only around 50% of the energy in the gas while the remained energy is contained in CH_4 and higher (aromatic) hydrocarbons [2]. Air, pure oxygen, steam, carbon dioxide, nitrogen or their mixtures could be used as gasifying agents. Products of the gasification are mostly used for separately or combined heat and power generation such as in dry-grind ethanol facilities [3] or in autothermal biomass gasification facilities with micro gas turbine or solid oxide fuel cells [4]. The products can also be used for hydrogen production using various processes [5] or various biomass stocks [6], as well as for liquid fuels, methanol and other chemical production [7].

The process of biomass gasification could be divided into three main stages: drying (100–200 °C), pyrolysis (200–500 °C) and gasification (500–1000 °C) [1,2]. The energy that is needed for the process is produced by partial combustion of the fuel, char and gases through various chemical reactions [8] with usage of different gasifying agents [9]. The performance of the biomass gasification processes is influenced by a large numbers of operation parameters concerning the gasifier and biomass [1], such as fuel and air flow rate, composition and moisture content of the biomass (which cannot be easily predicted) [10], geometrical configuration and the type of the gasifier [11], reaction/residence time, type of the gasifying agent, different size of biomass particles [1] derived from different feedstocks [12], gasification temperature [2,11] and pressure [11].

Gasifiers can be mainly classified as autothermal or allothermal gasifiers [13]. Autothermal and allothermal gasifiers could be further divided to: fluidised bed; fixed bed; and entrained flow gasifiers [14]. The downdraft gasifier is the most manufactured (75%) type of gasifier in Europe, the United States of America and Canada, while 20% of all produced gasifiers are fluidised bed gasifiers and the remaining 5% are updraft and other types of gasifiers [15]. Biomass gasification seems to have promising potential for

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Nomenclature

Main symbols

CH_xO_y	biomass composition, –
f	function
K_1	water gas shift reaction, –
K_2	methane reaction, –
K_3	methane reforming reaction, –
$LHV_{biomass}$	lower heating value of biomass, kJ/kg
LHV_{syngas}	lower heating value of syngas, kJ/m^3
M_b	biomass quantity, kg
M_{air}	air quantity, m^3
m	molar fraction of air, –
$Q_{reaction}$	energy for chemical reactions, kJ
Q_{in}	energy input, kJ
ΔT	temperature progression, °C/min
t	time, min
temp	temperature, °C
w	molar fraction of water/vapour/moisture, –
x_1	molar fraction of hydrogen, –
x_2	molar fraction of carbon monoxide, –
x_3	molar fraction of carbon dioxide, –
x_4	molar fraction of water/vapour, –
x_5	molar fraction of methane, –
x_6	molar fraction of tar, –

Abbreviations

ANFIS	adaptive network-based fuzzy inference system
ANN	artificial neural networks
C	carbon
$CH_{0.83}$	acenaphthene (tar)
C_2H_4	ethylene
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
EU	European Union
H_2	hydrogen
H_2O	water/vapour/moisture
NNM	neural network model
N_2	nitrogen
O_2	oxygen

electricity and heat cogeneration through conventional or fuel cells based technology. The number of projects related to small and middle-scale biomass gasification combined heat and power plants as well as syngas production plants in developed European countries [16] and especially in Germany [17], has been increased in the last few years [18] as shown in Table 1.

Mathematical models can be used to explain, predict or simulate the process behaviour and to analyse effects of different process variables on process performance. In order to improve efficiency and to optimise the process, a plant operation analysis in dependence of various operating conditions is needed. Large scale experiments for these purposes could often be expensive or problematic in terms of safety. Therefore, various mathematical models are utilized to predict the process performance in order to optimise the plant design or process operation in time consuming and financial acceptable way. Nowadays, special attention is given to the biomass gasification process modelling [19] which can contribute to more efficient plant design, emission reduction and syngas generation prediction or to support the development of suitable and efficient process control [20].

Artificial intelligence systems (such as neural networks) are widely accepted as a technology that is able to deal with non-linear problems, and once trained can perform prediction and generalization at high speed. They are particularly useful in system modelling such as in implementing complex mappings and system identification.

Table 1
The number of operational/planned/under construction biomass gasification facilities in Europe.

Country	Biomass gasification facilities in operation	Planned/under construction biomass gasification facilities
Germany	160 (>70 MW_{th} + 24 MW_{el})	150
Austria	6 (19 MW_{th} + 6 MW_{el})	2
Finland	3 (137 MW_{th} + 1.8 MW_{el})	2
Denmark	8 (12 MW_{th} + 1.4 MW_{el})	2
Other EU countries	31	15

2. Mathematical models for the biomass gasification process

Mathematical modelling is mostly based on the conservation laws of mass, energy and momentum. The complexity of models can range from complex three-dimensional models that take fluid dynamics and chemical reactions kinetics into consideration, to simpler models where the mass and energy balances are considered over the entire or a part of a gasifier to predict process parameters. The complexity of simpler models can also range from chemical reaction equilibrium based models that take only few important process reactions into consideration to more complex equilibrium or pseudo-equilibrium models where the tar formation is also considered. Due to need for intensive measurements, not many works on artificial intelligence system based biomass gasification models have been reported [1].

Kinetic mathematical models are used to describe kinetic mechanisms of the biomass gasification process. They take into consideration various chemical reactions and transfer phenomena among phases [1]. However, applicability of these models is limited due to several constraints. All possible reactions are not taken into account (almost all models assume pyrolysis and sub-stoichiometric combustion as instantaneous because these processes are much faster than the gasification process [21]) and the literature often offers different reaction coefficients, kinetics constants and model parameters that are related to the specific design of a gasifier [22]. However, kinetic models are very useful in detailed description of the biomass conversion during the gasification process [23], for the gasifier design and for process improvement purposes, but due to their computationally intensiveness and long computational time they are still impractical for online process control.

Models that do not solve particular processes and chemical reactions in the gasifier and instead consist of overall mass and heat balances for the entire gasifier are called equilibrium models. Equilibrium models are generally based on chemical reaction equilibrium and take into account the Gibbs free energy minimisation and the second law of thermodynamics for the entire gasification process [1]. These models are independent from the gasifier type, the gasifier design or the specific range of operating conditions but they describe only the stationary gasification process without a deep-in-analysis of processes inside the gasifier. In some cases