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Process performance improvement in a co-current, fixed bed biomass gasification facility by control system modifications

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A B S T R A C T

Advanced control solutions are a developing technology which represent a promising approach to tackle problems related to efficiency and environmental aspects of biomass gasification process in a cost effective way. In this paper the potential of advanced control concept to improve gasification process efficiency and to reduce negative environmental effects of the process has been analysed. Advanced control solution, based on feedforward–feedback control approach has been developed using collected operation data and the effects of control concept on gasification process have been analysed using developed artificial neural network based prediction model. Measurement data for the controller and simulation model development has been extracted from a 75 MW_{th} co-current, fixed bed biomass gasification plant operated by Technical University Dresden. The effects of 6 different process improvement goals for controller algorithms development have been analysed during 20 h of plant operation. The analysis has shown that with introduction of advanced control solutions process efficiency could be improved up to 20%, together with reduction of negative environmental aspects of the process.

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]. Products of the gasification are mostly used for separately or combined heat and power generation [2] such as in dry-grind ethanol facilities [3] or in autothermal biomass gasification facilities with micro gas turbine or solid oxide fuel cells [4]. Utilisation of syngas for hydrogen production through various available thermal processes is described in Ref. [5]. Hydrogen production potential from oil palm shells through gasification has been analysed in Ref. [6]. Gasification systems integrated with methanol synthesis have potential for a cleaner methanol production [7]. Other application of gasification systems for chemical production are described in Ref. [8]. Besides chemical production, gasification systems could be utilised for building material production using gasification residues [9]. A more detailed overview of biomass gasification technologies could be found in Ref. [10]. For power generation purposes, syngas should meet some technical and environmental requirements related to a certain percentage of particular gases (>20% CO and >10% H_2) and low tar content (<100 mg N m^{-3}) and it needs to be free of poisonous and carcinogenic gases [11].

Gasification is relatively well known technology, however, the share of gasification in meeting overall energy demand is small due to current barriers concerning biomass pre-treatment (drying, grinding and densification), gas cleaning (physical, thermal or catalytic), process efficiency and syngas quality issues [12]. Although a lot of effort has been focused to increase gasification process efficiency, to enhance energy savings and to improve environment aspects of gasification process, only some partial solutions to partial aspects have been obtained. Nevertheless, 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 [13] and especially in Germany [14] has been significantly increased in the last few years [15] as shown in Table 1. 75% of all commercial produced gasifiers are downdraft or co-current type [8] due to some advantages over updraft and fluidised bed gasifiers (such as cleaner syngas for

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Nomenclature

Main symbols
c_{eff} importance coefficient of process efficiency
c_{Hd} importance coefficient of syngas heating value
c_T importance coefficient of process temperature
c_{pbiom} specific heat capacity of biomass (kJ/kg K)
c_{pgases} specific heat capacity of flue gases (kJ/kg K)
$c_{psyngas}$ specific heat capacity of syngas (kJ/kg K)
i measurement number
Hd_{biom} lower heating value of biomass (kJ/kg)
Hd_{max} maximum measured value of syngas heating value (kJ/kg)
Hd_{syngas} lower heating value of syngas (kJ/kg)
m_{biom} biomass mass flow (kg/s)
$m_{biom-freq}$ biomass injection frequency (min)
m_{gases} flue gases mass flow (kg/s)
m_{syngas} syngas mass flow (kg/s)
P_{SCORE} process optimisation score
P_{th} plant load (%)
T temperature (°C)
T_{env} environment temperature (°C)
T_{max} maximum measured value of process temperature (°C)

Abbreviations
ANN artificial neural networks
CH_4 methane
CO carbon monoxide
CO_2 carbon dioxide
H_2 hydrogen
O_2 oxygen

Greek symbols
$\eta_{process}$ process efficiency (–)
$\eta_{process\_max}$ maximum measured value of process efficiency (–)

Table 1
The number of operational/planned/under construction biomass gasification facilities in Europe in 2013.

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

power generation in turbines or internal combustion engines or lower investment and maintenance costs) [11]. However, in downdraft gasifiers, the temperature of oxidation process must be kept at high values and the distribution of gasifying agent must be homogenous in oxidation area [11].

The performance of 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 [16], geometrical configuration and the type of the gasifier [17], reaction/residence time, type of the gasifying agent, different size of biomass particles [1] derived from different feedstocks [18], gasification temperature and pressure [19]. From mentioned process parameters, process temperature is one of the most important one. It influences syngas quality, reaction rate and tar concentration. Low process temperature produces high tar content [20], low syngas quality and low cold gas efficiency [21]. However, a high process temperature causes unwanted ash melting. Therefore the process temperature should be controlled [22]. In downdraft gasifiers the gasification process is usually conducted on atmospheric pressure. Higher pressures often increase tar concentration together, decrease CO content in syngas with marginally efficiency increase [23]. Air fuel ratio should be controlled in order to maintain a minimum stoichiometric ratio of air and fuel in combustion zone and to maintain a ratio of air and fuel that is lower than stoichiometric value in gasification zone. Higher air quantities enable better oxidation and therefore reduce syngas heating value and decrease overall efficiency. Lower air quantities improve syngas heating value but increase tar yield [11]. Han et al. [24] has shown that by finding optimal operation parameters, more efficient tar decomposition and reduction could be obtained.

In order to improve efficiency, to optimise the process or to maintain constant process quality during operation, a plant operation analysis tool that enables parameter prediction in dependence of various operating conditions is needed. Large scale experiments for the purpose of syngas quality optimisation respected to different fuel and bed types [25], syngas quality improvement with process parameters changes [26] or for process performance improvement [27] could be performed. However, even with implementation of Taguchi experiment optimisation methods for minimisation of number of test [28] these experiments could often be expensive or problematic in terms of safety.

A model based optimisation is a widely used tool for various optimisation purposes. For the gasification process optimisation analysis Emun et al. [29] proposed Pinch analysis to improve energy efficiency and to minimise the operation costs. Stoichiometric models could be used for analysis and optimisation of a fluidised bed gasification process [30]. For analysis of Fischer–Tropsch synthesis optimisation by changing operating conditions a non-stoichiometric based model can be utilised [31]. Artificial neural network based models can also be used to analyse gasification process and to find optimal static operating conditions for particular optimisation function [32]. Bang-Moller et al. [33] used exergy analysis to optimise gasification based energy system. For integrated plasma based waste gasification system a thermodynamic model was used to estimate process performance and to find optimal operating conditions [34]. Similar model based process analysis studies have been performed also for entrained [35] and fluidised bed gasifiers [36]. Furthermore, this kind of approach has been implemented for syngas yield control purposes [37], model based performance analysis in fluidised bed steam biomass gasifiers [38] or model based simulation tool for economic analysis of biomass facility scaling [39]. For optimisation purposes Wang et al. implemented an artificial intelligence based optimisation algorithms to optimise economic and environmental performance of a biomass gasification based system [40]. Those model based optimisation tools are applicable for unique operation point steady-state systems where only one or few process parameters are considered. However, they are not applicable for a dynamic online process control where several process parameters are controlled simultaneously.

During the past years a key issue for improving efficiency in gasification systems was integration of the gasification process dynamics and its scenario into the actual decision-making of the plant operation. The use of intelligent adaptable/evolutionary