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Experimental and numerical investigation of pellet and black liquor gasification for polygeneration plant

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HIGHLIGHTS

- Syngas from gasification of wood pellets compared with black liquor.
- Numerical simulation results are compared with pilot-scale experiments.
- Black liquor suitable for H_2 production and pellets are better for CH_4 production.
- Regression model from experiment data can be combined with dynamic physical model.

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ABSTRACT

It is vital to perform system analysis on integrated biomass gasification in chemical recovery systems in pulp and paper and heat and power plants for polygeneration applications. The proposed integration complements existing pulp and paper and heat and power production systems with production of chemicals such as methane and hydrogen. The potential to introduce gasification-based combined cycles comprising gas turbines and steam turbines to utilize black liquors and wood pellets also merits investigation. To perform such analysis, it is important to first build knowledge on expected synthesis gas composition by gasifying at smaller scale different types of feed stock. In the present paper, the synthesis gas quality from wood pellets gasification has been compared with black liquor gasification by means of numerical simulation as well as through pilot-scale experimental investigations. The experimental results have been correlated into partial least squares models to predict the composition of the synthesis gas produced under different operating conditions. The gas quality prediction models are combined with physical models using a generic open-source modelling language for investigating the dynamic performance of large-scale integrated polygeneration plants. The analysis is further complemented by considering potential gas separation using modern membrane technology for upgrading the synthesis gas with respect to hydrogen content. The experimental data and statistical models presented in this study form an important literature source for future use by the gasification and polygeneration research community on further integrated system analysis.

1. Introduction

Gasification has been utilized for many years in synthesis gas production using coal or biomass as the feedstock. The synthesis gas has been used as substrate for production of different chemicals such as methanol, dimethyl ether (DME), hydrogen (H_2) and synthetic natural gas (SNG) [1–3]. There have been a number of gasification plants built in connection with production of chemicals like ammonia, as well as for the production of gas for lime kilns in the pulp and paper industry [4].

In the pulp and paper industry, the production trend is shifting from new and fine paper towards packaging, tissue and different type of chemicals for bio-refinery system [5]. Similarly, in the power plants, the trend is to shift from base load electric power generation, to electricity grid balancing due to the rising intermittent electricity generation from renewable energy sources (wind,

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solar etc.). The latter is especially evident in Northern Europe, where Germany currently have a feed-in tariff system guaranteeing to purchase all electric power produced by PV and wind by "anyone" [6]. In Scandinavia, this is further accentuated by the competition between district heating in CHP plants and use of heat pumps for heat generation utilizing electric power. There is a significant potential for using gasification of biomass and waste fuel in connection with combined heat and power (CHP) plants connected to the district heating network. District heating loads for the larger part of the year are reducing due to better insulated buildings and also the installation of heat pumps (e.g. in Northern Europe) [7]. At the same time, the district heating demand peak demand remains very high during the coldest parts of the winter, since heat pumps are not able to operate efficiently in very cold weather. Therefore, it is techno-economically efficient to operate the CHP plants integrated with biomass gasification for chemical production (polygeneration mode) all year round taking advantage of the fact that the district heating demand is low during the summer time.

A number of concerted efforts have been made on modelling of biomass gasification with various possible approaches categorized in [8,9] based on criteria such as type of gasifier, feedstock, modelling considerations and evaluated parameters. Different approaches from artificial neural networks to computational fluid dynamics have been structured for performing the modelling work depending on the aim of the simulation [10]. Different modelling approaches for fluidized bed gasifiers with focus on system modelling were further investigated in [11]. Also, the influence of different parameters on biomass gasification in circulating fluidized bed gasifiers have been studied based on experimental results from several studies utilizing statistical tools [12]. The mathematical model was developed for an air-blown circulating fluidized bed (CFB) gasification in the 100 kW_{th} range as discussed in [13]. An overview of the kinetic processes was presented in detail to describe tar formation from a theoretical perspective [14]. For the system analysis, H_2 production from biomass gasification in a CHP plant showed substantial potential with economic viability [15,16]. In other studies, black liquor gasification systems with different cycles and solutions were compared, including CO_2 removal [17,18]. A critical review of downstream gas cleaning and upgrading after the biomass gasification step has been carried out considering also particle and tar removal [19]. Gasification-based polygeneration systems with CHP plants and pulp & paper mills may increase both the energy and the economic efficiency; to tap this potential using approaches towards process systems engineering, process integrations and process optimization is mandated [20,21]. Comparative assessments showed substantial techno-economic benefits from polygeneration plants [22,23]. Fuel upgraded from synthesis gas, originating from gasification of biomass, has the potential to be used as transport fuel, or for electricity generation enhancing the CHP plant capacity [24,25].

The aforementioned studies concluded that there are challenges in predicting with good accuracy tar formation. Furthermore, it is important to describe the thermo-chemical mechanisms taking place inside the reactors in order to be able to predict the performance of the process. It is interesting to note that when the authors were running the CFB gasifier in the range 100–200 kW_{th} with wood pellets, they did not find any detectable amounts of tar [26]. This shows that different results are obtained depending on the fuel feed and plant operating conditions that will significantly affect the gasification. In addition, it becomes difficult to obtain accurate models correlating well to experimental results if the mechanisms are not completely understood. From a system's perspective, it is important to research key uncertainties using current knowledge and understanding, focusing on comparisons between various fuel products and providing a modelling basis for the future development of the technology and for system integration. Based on our recent study [15] on H_2 production through integrated biomass gasification in CHP plants, the economic analysis showed that the H_2 production cost is in the range 0.15–0.75 €/kg which can be compared to 2.8–3.3 €/kg that the US government considers as competitive [34,35]. In this paper, the synthesis gas quality from wood pellets gasification has been compared with black liquor gasification, both through numerical simulations and experimental results. The experimental results are correlated into PLS-based (Partial Least Squares) models to predict main composition of the synthesis gas produced under different conditions. These quality prediction models then are combined using ASPEN + to perform system analysis. The quality prediction models are combined with physical models using Modelica for investigation of dynamic energy and material balances for integrated polygeneration plants at large scale. The data presented in this study could be used as input to relevant analysis using e.g. ASPEN + and similar system analysis tools. In addition, the techno-economic system analysis of H_2 and CH_4 production from different feedstock, i.e. wood pellets, black liquor and non-food waste, is presented.

2. Description of simulation model and experimental setup

2.1. Experimental setup

The experimental work has been performed in two circulating fluidized bed (CFB) gasifiers with the same dimensions i.e. one for black liquor gasification (BLG) and one for wood pellet gasification (WPG). The schematic lay out of the gasifiers is shown in Fig. 1. The BLG reactor was operated in Vasteras at ABB and was built on the design developed through the cooperation between ASEA (ABB) and LURGI. The reactor had a diameter of 170 mm and a height of 10 meters connected to a cyclone with the G-valve. The synthesis gas was cooled through a heat exchanger and the gas was cleaned using bag filter and then through a scrubber. The WPG reactor is owned by Bioregional mini-mills and situated at a pulp mill in Manchester. The main difference between the two reactors is that the BLG reactor has an electrical heating system to balance out heat losses. Conversely, the second reactor (WPG) has glass wool insulation (0.15 m) without the electric heater in the walls. Both reactors use pressurized air that is heated through an electric heater to reach the desired temperature. The WPG reactor has a combustor that heats the system during start-up, but then shuts off once the operating temperature is reached.

At a temperature of 600 °C, the electrical heating of the walls in the BLG reactor and the combustor in the WPG reactor re stopped. In the BLG reactor, black liquor is introduced 0.5 m above the reactor bottom, while wood pellets are introduced 0.7 m above the bottom of the WPG reactor. There are two ceramic filters in parallel at the WPG reactor followed by a scrubber, before the gas is combusted. At the BLG plant, a NIR meter is used to perform simultaneous analysis of several component gases. In the WPG plant, there is an ABB gas chromatographer (GC) used for the synthesis gas analysis. The synthesis gas is extracted continuously and the sample is introduced to the GC approximately every five minutes. The proximate and ultimate analysis of black liquor solids and wood pellets is given in Table 1.

2.2. Simulation model

The simulation model is developed in Modelica simulation language and is compatible with both the 'Dymola' and 'Open Modelica' implementations of the Modelica language standard. The developed model is a dynamic model that performs the heat and mass balances for the gasification system. The model consists of