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Simulation and economic evaluation of biomass gasification with sets for heating, cooling and power production

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ABSTRACT

In this work, syngas was used directly as fuel source for the renewable CCHP system, which can be producted through biomass gasification process. The advantages and limitation of entrained flow gasifier are compared, followed by discussion on the key parameters that are critical for the optimum production of syngas. Gasification agent of 450 °C temperature and 30 atm pressure has been proposed as a optical solution to a entrained flow gasifier using air as gasification agent at 0.27 ER (oxygen equivalence ratio), in that it provides a syngas of 5.665 MJ/m^3 LHV and up to 77% gasification efficiency. Depending on the key parameters of gasification process, the properties of syngas produced can be varied. It is thus essential to thoroughly understand the cogeneration system to identify the suitable methods for a renewable CCHP system. These process was simulated using Aspen Plus to perform the rigorous material and energy balances. The results obtained from simulation and experiment agreed well. This paper later focused on economic evaluation of the entire process, as well as the environmental benefits. The renewable CCHP system could able to attain lower CO_2 and SO_2 emission with total energy efficiency and gas yield of 75.43% and 2.476 m^3/kg respectively.

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1. Introduction

Combined heating, cooling, and power production (CCHP) is a system in which fuel is combusted to generate electricity. The energy for heating and cooling purposes is also formed by utilizing recoverable waste heat. During the early 21st century, the operation of CCHP systems under electric demand management (EDM) and thermal demand management (TDM) strategies have been investigated [2,3,14,24]. However, interest in CCHP has renewed due to the recent adjustment of the industrial structure and an increase in energy needs. Another major issue of concern is the recent increase in carbon dioxide concentrations in the atmosphere due to combustion of fossil fuels. Biomass which is believed to be a "renewable and low-carbon energy", has been suggested as an energy resource to reduce the buildup of carbon dioxide in the atmosphere [7,32]. Therefore, a CCHP system with a gasifier not only integrates the cooling, heating, and power generation processes for higher energy efficiency, but can also bring primary energy savings and therefore decrease CO_2 emissions.

The purpose of this study was to simulate the conversion of biomass to combustible gases, followed by simulation of a CCHP system that uses these syngas as fuel. These simulation results were used to perform a complete economic and technology analysis of the entire process. Several pieces of this process have been studied individually, but no studies that bring together the entire process have been performed. Some representative gasification projects include the down-draft gasification furnace by Imbert Energietechnik GMBH in German, the fluidized bed by Omnifuel Gasification System Limited and the fixed bed by Moore Canada Ltd in Canada. The gasification efficiency of these systems is up to 60–80% and the heating value of the produced combustion gas is 17–25 MJ/m^3 [11]. Advanced gasification systems is generally larger, higher degree of automation, and of complex process, which is mainly to generate electricity and heat. Recently, an integrated gasification system combined with internal combustion set has been developed, promoting gasification for syngas generation in large-scale [28]. Liszka et al. [21] studied several integrated gasification combined cycle (IGCC) processes that use biomass or wastes as a main feedstock. This IGCC system is similar to Narural gas fired gas turbine combined cycle generation, except for the gasification and the

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synthetic gas cleanup process. In recent years, a 1573 K-class gas turbine combined cycle power plant has been launched for iron works with a thermal-efficiency as high as 47% [34]. Maraver et al.[25] evaluated and compared the environmental performance of bio-fueled CCHP systems and conventional generation in which the same energy products would be in average stand-alone plants (i.e. a reference power plant). Many other studies [5,18] maily deal with the evaluation of natural gas-fueled CCHP and combined heat and power (CHP) through life cycle assessment (LCA). Very recent reviews have focused on technologies for renewable CHP and CCHP, including a brief system design, operation performance, and thermodynamic and economic indexes evolution [4,6,22].

Because actual achievable benefits of CCHP system may vary depending on the plant operation, its nominal loads, combined forms and the technologies involved [25]. It is necessary to apply optimization criteria to guarantee the benefit of CCHP over conventional technologies. In biomass (alone) gasification using an entrained-flow gasifier process, two cases are well known in the world. One is a gasification-DME synthesis by CHEMREC Co. Ltd. in Sweden. The other is a two-stage gasification of woody biomass by CHOREN and Shell Co. Ltd. in Germany. Both gasification processes has been developed by companies, and the final target scales planed are very large, as large as a few thousand ton/day scale, almost equal to scale of coal gasification [35]. The entrained bed gasifier has many advantage, for example the tar yield is low and various kind of biomass are available as feedstock. In this manuscript, syngas was produced by an entrained bed gasifier, combustion turbine of a 9FA type made by General Electric was choosed. Steam generation in the HRSG was a three-pressure reheat-type waste heat boiler. The report presents descriptions of each process, as well as the main design assumption for the gasification reactor, gas turbine, heat recovery stream generator (HRSG), and stream cycle. The simulation of the rigorous material and energy conversion of this renewable CCHP was carried out using Aspen Plus (Aspen Tech, USA) followed by evaluation of the economy, thermal properties, and environmental indicators. Topics of interest include the influence of input and operation parameters on the total energy efficiency and pollutant emissions performance. The results of this research can be used to optimize energy efficiency and provide the necessary information for maintenance management.

2. CCHP system description

The renewable CCHP can be conceptualized as a combination of local subsystems producing syngas *via* gasification, cooling, heating, and electricity, as illustrated in the schematic (Fig. 1). The core of the system is represented by two blocks:

1. The biomass gasification block, which can be composed of different equipment for biomass gasification, treatment, and conditioning, as well as hydrogen sulfide (H_2S) and ammonia (NH_3) removal. Because the gasification production must be cooled before being cleaned, the treatment and conditioning units include a low pressure steam heater, air preheater, and absorption chiller. Through these units the acid gas production after the gasifier exchanged heat with the low-pressure superheated steam from the boiler, and produced heat to various final uses including an air preheater, providing hot water to users.
2. The CHP block, which contains a combined cycle (Fig. 1) and 9FA type combustion turbine as a prime mover, plus a combustion heat generator composed of a boiler.

The gasifier is an entrained-bed gasifier that consists of a plug-flow system where sawdust react with oxygen [29]. Unlike moving bed or fluidized bed gasifiers, entrained flow gasifiers operate at high temperature of 700–1500 °C for biomass [35,36]. The composition of the product gas is very close to syngas quality [27]. Syngas contains CO and H_2 as the main combustible component, as well as amounts of CH_4. Trace constituent of nitrogenous compounds and sulfur heavily depend upon cleanup process [34]. Table 1 shows the typical composition of sawdust and heating value.

In this type of entrained bed gasifier, the solid feedstock needs to be grinded into small particle size (<100) for the feed system in order to achieve high conversion rate [38]. And it usually operates at high pressure of 2.94–3.43 MPa [23,27]. Tomoko Ogi et al. [35] studied gasification of oil palm residues in an entrained bed gasifier. Oil palm was gasified using H_2O or $H_2O + O_2$ as a gasification agent at 900 °C. During gasification with H_2O alone, hydrogen rich gas was obtained, and tar yield was very low (<1.0 wt %). The following is the detail parameter of the gasifier represented in this paper (see Table 2).

3. Subsystem integration

The Braden-Rankine cycle is a promising and innovative technology that greatly benefits a conventional integrated gasification combined cycle (IGCC) [33]. Similarly, on a large-scale basis, the co-generation technology most adopted is the gas-steam combined cycle, which is environmentally friendly and produces high energy efficiencies under varying load rates. In the gas-steam combined cycle, the main sets involved chamber (COMBUST), compressors, gas turbine, HRSG and multi-stage steam turbine. Gas turbine is graded by combustion temperature, 1100 °C for the E-class, 1200 °C the F-class, 1300 °C for the G-class and so on. The Central Research Institute of Electric Power Industry developed an air-blown pressurized, two-stage entrained-flow gasifier, 150 MW 1573 K-class and 1773 K-class gas turbine combustor technologies for low-Btu fuel [12,20]. The exhaust gas temperature of chamber in this paper is between 1226 and 1418 °C and gas turbine unit of a 9FA type made by General Electric was choosed. The oxygen and fixed carbon contents of sawdust are respectively about 39 wt.% and 52 wt%, whereas those of coal are 2–20 wt.% and 50–85% wt.%. The H/C ratio for sawdust is 0.15, which is higher than that of coal (0.5–0.85). therefore, sawdust is more degradable compared to coal. Takeharu Hasegawa et al. [34] shown the typical compositions of derived gases from coal-based gaisifiers and furnaces, as well as no-fossil resources. For one thing, syngas derived form water-coal slurry and sawdust is similar. It is therefore necessary to adopt suitable working parameter for each gaseous fuel. The performance characteristics of the gas turbine are shown in Table 3 [8].

In fact, the exhaust gas temperature of sawdust-based gas turbine is about 590 °C. The value obtained by simulation is lower than water-coal slurry as shown in Table .3. A heat recovery stream generator can be divided into two main categories, single pressure and multi-pressure. The large-scale modules (greater than 250 MW) operate with exhaust gas up to 590 °C, which enables the use of three-pressure reheat-type HRSG [37]. The smaller combustion turbines, between 90 MW and 200 MW, usually use dual-pressure reheat-type HRSG, which cause 3%–5% lower efficiencies to limit the recovery of the waste heat. During the design of the boiler temperature gradient, the exhaust gas temperature of the boiler should be reduced as much as possible to maximize the utilization of waste heat. The multi-pressure HRSG exhaust gas temperature, according to experimental data, can be reduced from approximately 120 to 80 °C. In combustion process, most of the sulfur in the fuel becomes SO_2. Under certain conditions, part of SO_2 is further oxided to SO_3. The SO_3 gas and water vapor can be combined into sulfuric acid vapors, whose condensation dew point

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