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Enhanced process integration of black liquor evaporation, gasification, and combined cycle

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HIGHLIGHTS

- Integrated system for power generation from black liquor is proposed.
- The system covers novel black liquor evaporation, gasification, and combined cycle.
- Evaporation system adopts the exergy recovery to minimize the exergy loss.
- Significantly high energy efficiency of evaporation is achieved.
- High net energy efficiency of 34.5% is realized.

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ABSTRACT

Energy recovery from black liquor (BL) can be performed through gasification at temperatures above the melting point of inorganic chemicals. Complementarily to BL gasification experimental research, this study is conducted to simulate the thermodynamic modeling of an integrated system for BL evaporation, gasification, and combined cycle for power generation. For BL evaporation, a novel system is proposed based on the concept of exergy recovery to minimize exergy loss, and thus, lower the required energy input for evaporation. From the process design and calculations, higher target solid content leads to lower total required energy for BL evaporation. The lowest required total energy for evaporation can be achieved at a target solid content of 75 wt% wb. Furthermore, an integrated power generation system adopting gasification and combined cycle is modeled, and an application of different BL evaporation technologies is also evaluated in terms of net energy efficiency. The integrated system with exergy recovery-based evaporation can achieve a net energy efficiency of 34.5%, which is significantly higher than those of multi-effect evaporators (24.5%) and conventional boiler-based evaporation (14.7%).

1. Introduction

Globally, the pulp and paper industry currently processes about 170 Mt of black liquor (BL) per year (measured as dry solids), making BL a very significant biomass source [1]. BL comprises viscous alkaline solutions and has various compositions depending on the properties of wood and cooking conditions. Generally, it contains organic compounds of cellulose, hemicellulose, and lignin, in addition to alkaline salts such as sodium hydroxide and sodium sulfide [2]. A pulp mill generates 1.7–1.8 t-BL/t-pulp (dry content). BL thus represents a potential energy source of 250–500 MW/mill. Energy recovery from BL is sufficient to provide the electricity and steam required by a pulping plant. A pulp mill consumes about 700 kW h-electricity/t-pulp [3,4].

A modern Kraft pulp mill is self-sufficient in energy. It can meet all internal steam and electricity demands of its processes. This energy comes from the combustion of BL in recovery boilers (Fig. 1). Unfortunately, BL has very low economic value owing to its high moisture content and requirement for pretreatment (evaporation) before being used as fuel in a combustor. The moisture content of BL produced by a pulping plant can be as high as 83–87 wt% on wet basis (wb) [5]. Most of the water must be evaporated to reach a BL dry solid level that is adequate for subsequent processes. This traditional recovery process with recovery boilers

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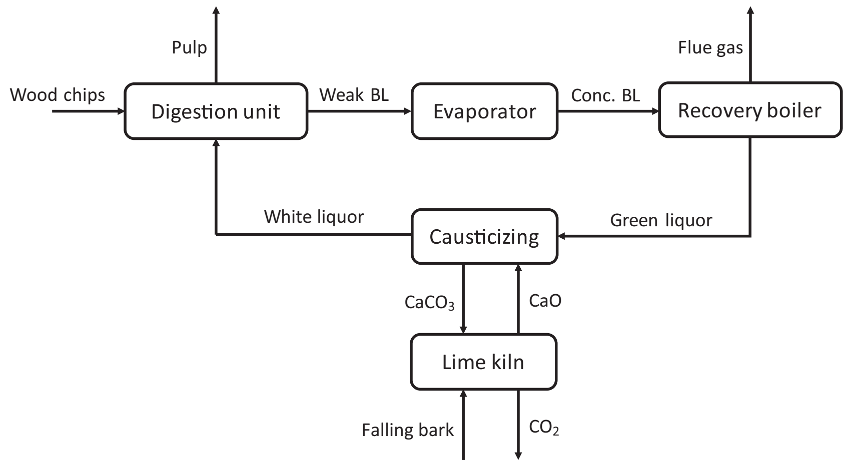

Fig. 1. Energy recovery cycle in Kraft pulping process.

has proven to work well. However, the electricity generation efficiency of recovery boilers is low.

Due to its very high moisture content, evaporation or drying of BL consumes large amounts of energy, the highest among all processes in pulp milling. We calculated that about 50% of the steam used throughout pulp milling is consumed for moisture removal from BL [7]. In a conventional system, BL evaporation is performed mainly by using multi-effect evaporators. In this case, about 60% and 40% of the energy required for evaporation is consumed in multi-effect evaporators and high-solid concentrators, respectively [8]. For combustion in a conventional boiler, BL evaporation is performed until the solid mass fraction (solid content) increases to about 75–85 wt% wb [9]. Innovative energy-efficient evaporation for BL is urgently demanded to improve the total energy efficiency of pulp milling.

Regarding energy conversion from BL, gasification exhibits faster reaction rates and excellent conversion efficiency [10]. Some industrial developments have been taken and applied in the last few decades to clarify the competitiveness of BL gasification with the objective of increasing the performance of pulp mills in terms of economy and environment. BL gasification has been demonstrated successfully in a pilot plant scale (3 MW_{th}) in Piteå, Sweden, which was operated by Luleå University of Technology [11]. In addition, an integrated gasification system has been developed to realize high total power generation efficiency from BL [12]. It has several beneficial characteristics of high carbon conversion and power generation efficiency but exhibits low environmental impacts [13]. Naqvi et al. have summarized some studies related to BL gasification and found that although it is still under development, it has excellent advantages in terms of environment, safety, and investment compared to the conventional system with heat recovery. In addition, BL gasification and combined cycle (BLGCC) has the potential to convert pulp mills from electricity consumers to electricity suppliers [6].

Naqvi et al. [14,15] analyzed BL gasification employing circulating fluidized bed with direct causticization for producing synthetic natural gas. They found that oxygen-blown gasification showed higher conversion efficiency than air-blown gasification. Unfortunately, their study did not focus on the effort required to circulate and recover the energy involved in the system. In addition, Ferreira et al. [16] investigated the combination of BLGCC system with and without CO_2 capture. However, they focused only on exergetic and economic analyses, and did not attempt to develop an innovative system to improve the total energy efficiency.

In this report, we propose a scheme for energy-efficient evaporation of BL based on the concept of exergy recovery. The effect of target solid content on the energy required for evaporation is evaluated. In addition, an integrated gasification and combined cycle based on process integration is modeled and the net energy efficiency of the integrated system is calculated.

2. Proposed integration system

To reduce significantly the exergy loss throughout the integrated system, an enhanced process integration technology is used. It is a combination of two technologies: exergy recovery and process integration [17]. Exergy recovery relates to circulation of the energy involved in a given process by combining exergy-rate elevation and effective heat pairing. However, owing to some reasons such as physical and chemical changes, and the limits of the heat exchanger used, not all heat involved in the process can be recuperated internally. Therefore, to reduce exergy loss, process integration is employed to facilitate heat utilization among the processes for significantly minimizing the total exergy loss in the integrated system [18]. This technology has been evaluated in several processes, including biomass-based power generation [19], algal energy production [20], and coal-to-hydrogen conversion [21].

Fig. 2 presents a conceptual diagram of the overall integrated system proposed in this study. The focus of the study is on two main points: evaporation system for BL and integrated system for power generation from BL including evaporation, gasification, and combined cycle. Given that we cannot show more details related to exergy recovery and process integration in the figure, detailed information regarding these issues for each module is given in the next section. The proposed integrated system consists primarily of BL evaporation, BL gasification, and combined cycle. The solid, dashed, and dotted lines represent material, heat, and electricity, respectively. As the main BL evaporator, a steam tube rotary evaporator with an internal heat exchanger is selected. Its benefits include large heat transfer area, excellent thermal efficiency, great handling ability, and ability for facilitating continuous operation [22].

The concentrated BL is further fed to the gasification module. There, it is converted to syngas, which consists of fuel gases including hydrogen and carbon monoxide. This syngas is then used as fuel for combustion in combined cycle-based power generation.

In the gasifier, pyrolysis, volatilization, combustion, and char gasification reactions take place subsequently, and syngas is produced sequentially. The produced hot syngas flows to a heat recovery module and is used to support the combined cycle process