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Integrated system of rice production and electricity generation☆

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HIGHLIGHTS

- An integrated rice production and electricity generation system is proposed.
- Rice production consists of superheated steam drying, husking, and polishing.
- Power generation comprises torrefaction, steam gasification, and a gas turbine.
- A high net total energy efficiency of ∼32% can be realized with the proposed system.
- The proposed integrated system can promote sustainable energy production.

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ABSTRACT

Research and development of approaches to improve energy efficiency in the rice industry can help stakeholders to make informed decisions. In this study, an enhanced integrated system of both rice production and power generation was proposed. The integrated system mainly consisted of superheated steam drying, husking, polishing, torrefaction, steam gasification, and power generation. In addition, suitable technology options for power generation and rice production processes for increasing the energy efficiency were also investigated. Furthermore, to contribute to minimization of the exergy loss, recovery was performed by combining the concept of heat circulation and process integration. Results show a considerably higher energy efficiency of the proposed integrated system. In a single rice production system, processing of 200 t rice grain d^{-1} can generate surplus electricity of about 3.4 MW with an electricity production efficiency of about 32%. A high economic benefit could be achieved by synergetic integration in the rice industry.

1. Introduction

Diversification of energy sources, especially by including renewables within an energy system, is urgently required to ensure that energy demand is met sustainably and sufficiently and that environmental concerns are addressed. Renewable energy sources cover a broad range of natural resources, including wind, biomass, solar, industrial and agricultural wastes, geothermal, and hydro power. Rice plantations, one of biomass resources, has recently increased continuously under high demand as main food resources in many countries, especially across Asia. Annually, the waste from rice plantation is about 1,370,000 million t consisting of rice straw and husk. Together, these represent the largest share of the total rice plantation products and have a relatively high economic value. For each kg of rice grain produced, 0.28 kg of rice husk and 1.1 kg of rice straw are generated [1,2].

This leads to many problems associated with the inappropriate disposal practices of the rice waste products, such as burning in the open fields during the peak harvesting season, resulting in pollution problems [3]. Therefore, advanced utilization of both rice husk and straw, including energy harvesting, is urgently required from both economic and environmental perspectives. About 90% of the global rice production takes place in Asian countries, and Southeast Asia provides 29% of the global total. It was estimated that the > 100,000 rice mills in Southeast Asia have the potential to generate 16,720 MW of power from 19 million t of rice husks produced every year [4].

At the industrial scale, efficient energy conservation is greatly important. In rice production, improvement of the energy efficiency of the various processes can be achieved through the implementation of

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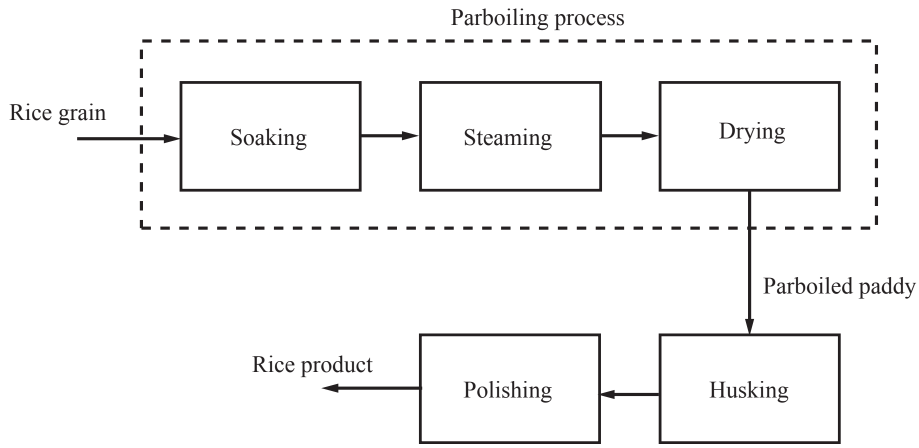

Fig. 1. Steps of rice processing in modern mills including the parboiling process.

several technologies, such as waste heat recovery, improvement of steam efficiency, improvement of insulation quality, and development of alternative technology. Each technology offers unique benefits, opportunities and challenges and is in different stages of development and application.

Researchers have proposed various drying methods for rice grain such as hot air drying [5], vacuum drying, superheated steam drying (SSD) [6], and fluidized bed drying [7] including the parboiling process. Among these treatments, the parboiling process can significantly influence the quality of paddy [8] through soaking until it is saturated (about 30% moisture, wet basis), steaming to gelatinize the starch, and subsequently drying (Fig. 1). Unfortunately, the parboiling process has several disadvantages from the energy perspective, leading to higher cost investment and extra cost in drying, time resources, and environmental problems [9]. Therefore, researchers have conducted several studies focused on replacing this method. The SSD process is considered a promising approach because of the higher drying rates [10] and better quality than conventional drying, lower net energy consumption because of the possibility of effective heat recovery [11], and elimination of fire and explosion hazards [12]. Chaiyong et al. [13] and Wu et al. [14] studied rice grain drying using superheated steam as an alternative treatment to the parboiling process. However, they focused only on the effect of SSD on the yield characteristics and, to our knowledge, no attempt has yet been made to develop an innovative approach to improve the overall energy efficiency of the system.

Electricity generation from rice husk has been well developed compared with that from rice straw. Suramaythangkoor et al. [15] observed the potential of power generation using rice straw and found high feasibility in terms of both economy and GHG emission reduction. Recently, several studies have proposed and evaluated utilization systems of wastes from rice for energy production, especially power generation [16,17]. Both thermochemical [18] and biochemical [19] conversions for rice husk and straw have previously been evaluated. Among the studied technologies, gasification of rice straw and/or rice husk was considered a promising energy conversion technology due to its high conversion efficiency [20]. Yoon et al. [17] adopted fixed-bed gasification in the power-generation system using rice husk and its pellets. They reported that cold gas efficiency of about 70% could be achieved. In addition, Calvo et al. [21] performed rice straw gasification in a fluidized bed. They found that application of fluidized bed gasification could produce high-quality syngas, with a high conversion efficiency of up to 61%. Unfortunately, their study only focused on the gasification system without any attempt to develop an integrated system for power generation.

Furthermore, Prabowo et al. [22] and Chiang et al. [23] studied rice straw gasification in downdraft and updraft gasifiers, respectively. The former reported the feasibility of CO_2 as an alternative gasifying agent of steam to obtain higher thermal efficiency in rice straw gasification. They found that utilization of CO_2 as a gasifying agent has a high potential to increase the thermal efficiency of the conversion process (by up to 60% at a gasification temperature of 950 °C). Unfortunately, the above studies mainly focused on the conversion process (gasification) without further effort to develop a fully integrated system to achieve high total energy efficiency.

To the best of our knowledge, no studies are available in the literature considering the requirements for effectively combining rice production and power generation, especially in terms of total energy efficiency. Therefore, in this study, a novel integrated system consisting of SSD for the rice grain, husking, torrefaction, steam gasification of rice straw and husk, and power generation was proposed based on exergy recovery and process integration. The objective of this study was to minimize the exergy destruction throughout the integrated system to realize high total energy efficiency. Furthermore, several operating parameters were also evaluated to determine the optimum operating conditions with the highest energy efficiency.

2. Proposed integrated system

In order to substantially reduce the exergy loss throughout the integrated system, an enhanced process integration technology is utilized by combining two technologies: exergy recovery and process integration. Exergy recovery relates to the circulation of the energy involved in any given process by combining exergy-rate elevation and effective heat pairing. This approach is quite different from that of conventional process integration. Conventional process integration is essentially based on pinch technology, which involves integrating all of the involved processes with the consideration of their operating temperature. Therefore, in the conventional process integration, the minimum temperature approach will be the main consideration when coupling two different streams. In this study, together with the consideration of the minimum temperature approach, consideration of the type of heat was also considered to be important. This holistic approach leads to greater optimization and a larger amount of heat that can be recovered. For example, in drying, enhanced process integration can easily pair (couple) each type of heat (latent and sensible) for the process in the same module, as widely used for biomass such as wood [24], black liquor [25], empty fruit bunch [26], and algae [27,28]. Applying this method in the rice industry can be considered a novel technology. To our best knowledge, no study proposing this type of solution has been conducted.

A conceptual diagram of the proposed integrated system for rice production and electricity generation is shown in Fig. 2. The wet raw rice grain is initially fed into the SSD system for moisture removal and then flows into the husking and polishing system for purification. The