CHEMICAL ENGINEERING TRANSACTIONS

VOL. 70, 2018

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Timothy G. Walmsley, Petar S. Varbanov, Rongxin Su, Jiří J. Klemeš

ISBN 978-88-95608-67-9; **ISSN** 2283-9216

DOI: 10.3303/CET1870279

Toward Sustainable Agricultural: Integrated System of Rice Processing and Electricity Generation

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Research and development of approaches to improve the 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. Rice plantations, one of biomass resources, has recently increased continuously under high demand as main food resources in many countries, especially across Asia (Balasundram et al., 2017). Annually, the waste from rice plantation is about 1,370,000 Mt 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 (Haryati et al., 2017). For each kg of rice grain produced, 0.28 kg of rice husk and 1.1 kg of rice straw are generated (Yusof et al., 2008).

At the industrial scale, efficient energy conservation is greatly important. Researchers have proposed various drying methods for rice grain such as hot air drying (Beigi et al., 2017), vacuum drying, superheated steam drying (SSD) (Rumruaytum et al., 2013), and fluidized bed drying (Swasdisevi et al., 2010), including the parboiling process. Among these treatments, the parboiling process can significantly influence the quality of paddy (Dutta et al., 2015) through soaking until it is saturated (about 30 wt% on wet basis of moisture (wb)), steaming to gelatinize the starch, and subsequently drying. 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 (Kwofie and Ngadi, 2017).

Electricity generation from rice husk has been well developed compared with that from rice straw. 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

Please cite this article as: Darmawan A., Biddinika M.K., Huda M., Tokimatsu K., Aziz M., 2018, Toward sustainable agricultural: integrated system of rice processing and electricity generation , Chemical Engineering Transactions, 70, 1669-1674 DOI:10.3303/CET1870279

objective of this study was to minimize the exergy destruction throughout the integrated system to realize high total 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 (Aziz et al., 2014). The former focuses on heat circulation in the same module (Kansha et al., 2013), while the latter deals with the integration of the whole system (Zaini et al., 2017). 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 (Darmawan et al., 2017), as widely used for biomasses, such as wood (Aziz et al., 2011), black liquor (Darmawan et al., 2018), empty fruit bunch (Aziz et al., 2015), and algae (Aziz et al., 2013). Applying this method in the rice industry can be considered a novel technology. A conceptual diagram of the proposed integrated system for rice production and electricity generation is shown in Figure 1.

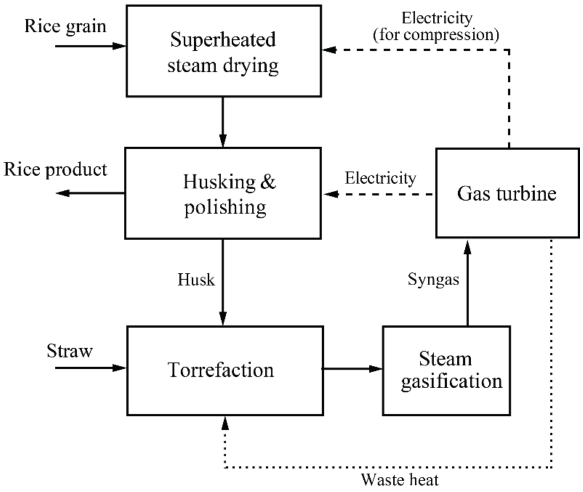


Figure 1: Conceptual diagram of the proposed integrated system of rice production and electricity generation.

3. Process modeling and analysis

3.1. Input parameters

The composition of both rice husk and straw including ultimate and proximate analyses is based on the literature (Jenkin et al., 1998). Both rice husk and straw biomass have relatively low sulfur content; therefore, they have lower tendency for SO_2 and H_2S gas formation (Demirbas, 2004). Based on study from different rice mills, the average cumulative amount of rice grain that can be processed in one mill is about 200 t d^{-1}. Specific heat for rice grain is approximately 1,109 ± 45 MJ kg^{-1} K^{-1} (Pabis et al., 1998) and moisture content is between 10 and 17 wt% wb. Modeling and calculation of the material and energy balances of the proposed integrated system were conducted using a process simulator in Aspen Plus V8.8 (Aspen Technology, Inc.). In addition, the following assumptions were made: (i) dryer consists of a mixer, a heat exchanger, and a separator; (ii) the ambient temperature is 25°C; (iii) the adiabatic efficiency of the compressor and blower is 90%; (iv) heat loss is negligible; (v) there is no air contamination inside the dryer; and (vi) in the drying process, the heat is completely transferred from the hot material to cold material. In addition, (vii) air contains 79 mol% nitrogen and 21 mol% oxygen.

3.2. Process design of rice grain drying

Figure 2 presents the process flow diagram based on exergy recovery. The proposed drying process is divided into three stages: hot soaking, drying, and steam superheating. The rice grain entering the hot soaking stage (HX1) is soaked and heated to the designated temperature by the compressed vapor streaming out from the fluidized bed dryer. In this condition, a heat exchange is performed between wet rice grain as the cold stream and condensed compressed steam as the hot stream. Subsequently, the wet rice grain enters the drying stage (HX2), which is conducted in the fluidized bed dryer. In the dryer, the condensation heat from this compressed steam is exchanged with the heat of drying from the moisture inside the rice grain.

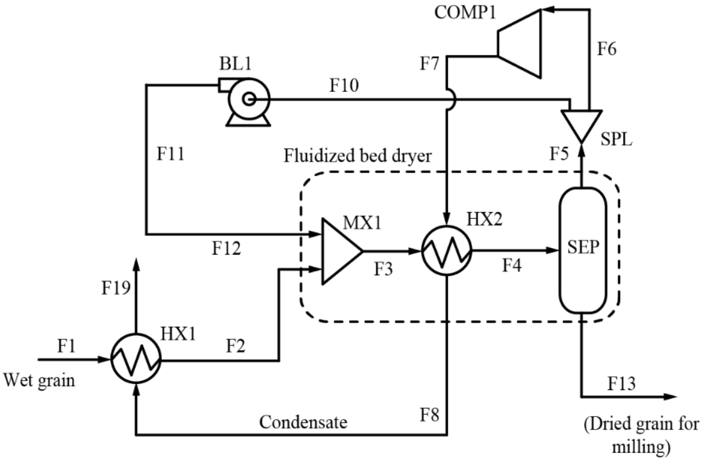


Figure 2: Process flow diagram of the drying process based on exergy recovery

3.3. Proposed integrated system for torrefaction, steam gasification, and power generation

Figure 3 presents the conceptual diagram of the overall integrated system of electricity generation proposed in this study. The integrated process consists primarily of torrefaction, gasification, gas cleaning, and power generation. The feedstock is fed to the torrefaction reactor to improve the biomass quality and further remove moisture. Subsequently, the torrefied feedstock is sent to the gasification module for effective carbon conversion to fuel gases including hydrogen and carbon monoxide. Pyrolysis, volatilization, combustion, and char gasification reactions subsequently take place in the gasifier, and the syngas is produced.

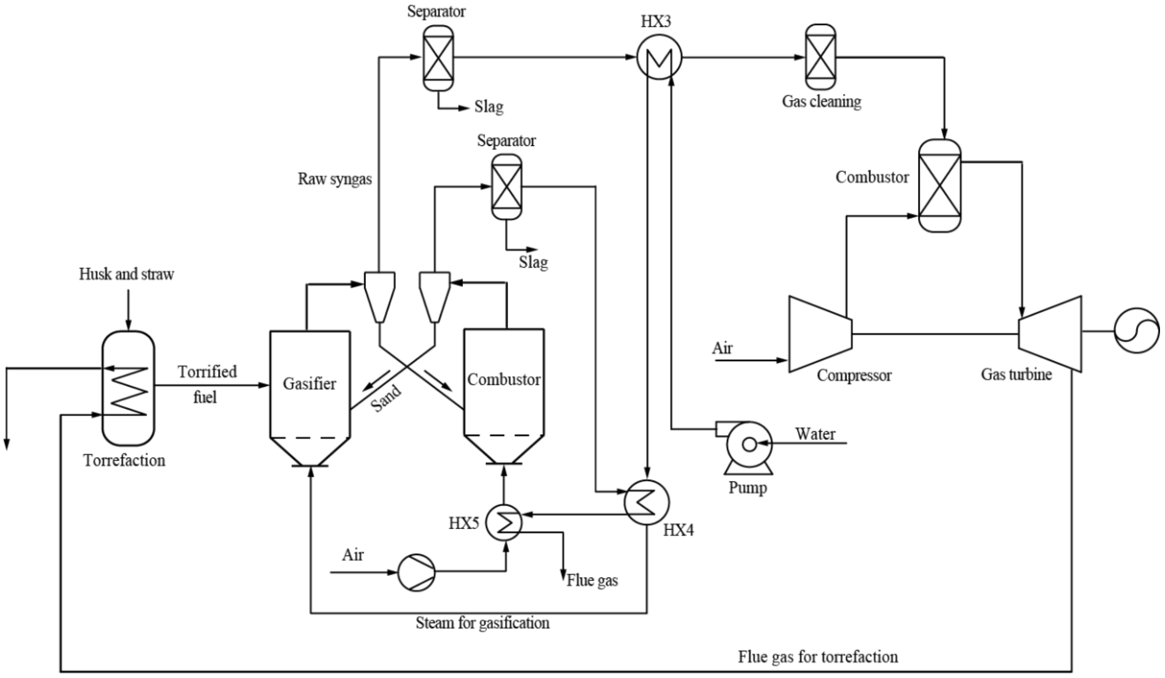


Figure 3: Process flow diagram of the proposed system including torrefaction, gasification and the gas turbine

In addition, the hot syngas containing a high amount of thermal energy was used for steam generation. To avoid gas condensation, the temperature of the syngas before cleaning was maintained at over 300 °C. Subsequently, the syngas was cleaned up before being injected to the combustor. The hot, high-pressure gas during combustion expanded in the gas turbine, producing electricity. Table 1 shows the calculation conditions for the gasification and combined cycle processes. Sand (particle size of 0.2–0.8 mm) was used as the bed material to enhance fluidization and gas transfer inside the gasifier.

Table 1: *Assumed conditions of the gasification and combined cycle processes*

Module	Properties	Value
Torrefaction	Temperature (°C)	200–290
	Pressure (MPa)	0.1
	Flow rate (t h^{-1})	3.6
	Husk-straw ratio	4:6
Gasification	Gasifier type	Dual circulating fluidized bed
	Gasifier temperature (°C)	700
	Combustor temperature (°C)	850
	Average particle size (mm)	0.3–1
	Fluidizing medium	Sand (limestone)
	Fluidizing medium average diameter (mm)	0.2–0.8
Combustor and gas turbine	Discharge pressure (MPa)	0.15
	Combustor pressure drop (%)	2
	Gas turbine isentropic efficiency (%)	90

To evaluate the system performance of torrefaction, gasification, and power generation, the total net energy efficiency of the integrated system was calculated as follows:

$$\eta_{net} = \frac{P_{output} - P_{internal}}{P_{input}} \tag{1}$$

where $P_{output,}$ $P_{internal}$, and P_{input} are total generated power, internal power consumption, and total energy input (the biomass input (MW)), respectively. The internal power consumption comprised the pump and compressor work in the gasifier, and the compressor for the gas turbine.

4. Results and Discussion

4.1. SSD and milling performance

The main advantage of SSD as a parboiling replacement is that there is no decrease in the quality of the rice product. In this case, the target moisture content in the SSD process was fixed to 18 wt% wb at temperature of 150 °C. The head rice yield would decrease significantly when the moisture content was lower than 18 wt% wb, especially for temperatures higher than 150 °C. In the SDD process, rice grain is fully gelatinized, and its physicochemical properties are similar to those of parboiled rice. Table 5 shows the results of the exergy-recovery-based SSD system and the required energy for husking and polishing. From the simulation of SSD, the required compressor duty is 0.589 MW. By employing exergy elevation and heat coupling, heat recovery could be performed effectively. In addition, the outlet steam pressure and compressor temperature are 195 kPa and 230 °C, respectively. The minimum recycled steam required as fluidizing agent is 0.2 kg s^{-1}; therefore, the required work is 5.5 kW. The blower work is increasing when the flow rate of the recycled steam is increased. However, a higher steam flow rate may cause faster and more effective drying because of the increased level of contact between the rice grain and the steam. The effect of the increase of recycled steam flow rate, especially on the quality of rice product, needs to be clarified for further research.

Table 2: *Results of SSD performance*

Section	Properties	Value
Compressor performance	Compressor outlet temperature (ºC)	230
	Compressor outlet pressure (kPa)	195
	Steam condensing temperature (ºC)	119
	Compression work (MW)	0.589
Dryer	Mean temperature difference/LMTD (ºC)	65
	Duty (MW)	8.38
	Bed temperature (ºC)	150
	Drying time (min)	5
Husking and polishing	Dried grain product (t d^{-1})	118.95
	Electrical consumption (MW)	0.22

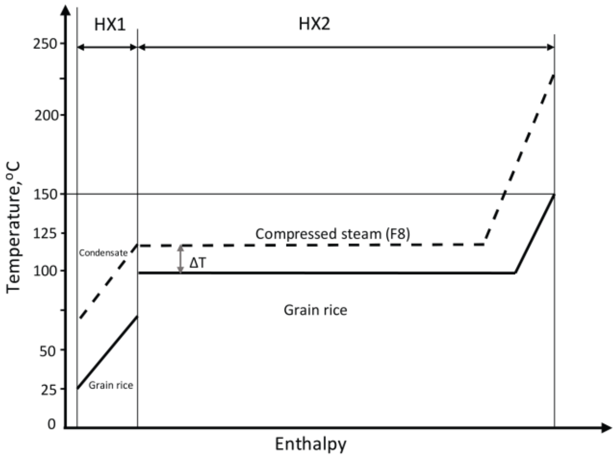


Figure 4: Temperature–enthalpy diagram during SSD process of rice grain employing exergy recovery. ΔT is the temperature difference between the rice grain and the compressed steam inside the heat exchanger (19 °C)

4.2. Comparison with parboiling process

Parboiling as a hydrothermal treatment is an energy-intensive process. In the parboiling system, the energy intensity is mainly influenced by soaking temperature, soaking time, steaming time, and its pressure. Figure 5 shows the energy requirements during the parboiling process compared with the SSD system proposed in this study.

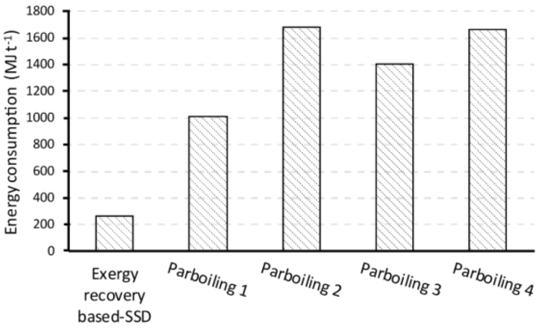
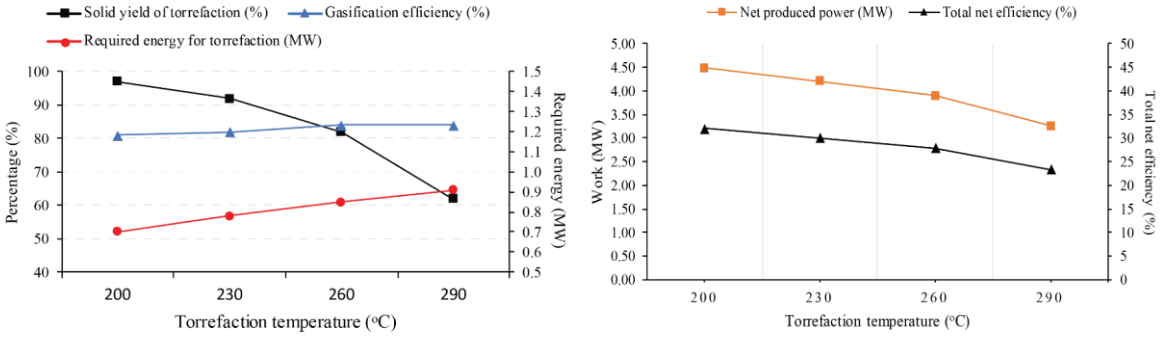


Figure 5: Comparison of required energy during the parboiling process and exergy-recovery-based SSD

4.3. Performance of torrefaction, gasification and power generation

Figure 6(a) shows the relationship between torrefaction temperature and solid yield of torrefied biomass, the energy requirement, and the gasification efficiency.



(a)

(b)

Figure 6: (a) Effect of torrefaction temperature on torrefaction and gasification performance, (b) Net produced power and total efficiency at different torrefaction temperatures

Increasing the torrefaction temperature would decrease the solid yield due to higher volatile removal during the torrefaction process. The torrefaction process at 200°C is similar to the drying process but with higher removal amount of water and small amount of evaporated volatile matter. In general, the required energy for torrefaction and gasification efficiency are not strongly influenced by temperature increase in the torrefaction process. By changing the torrefaction temperature from 200 to 290°C, the required energy slightly increases from 0.7 to 0.91 MW. However, the increase of torrefaction temperature can substantially decrease the total energy efficiency from 32 % to 23 % (Figure 6(b)).

5. Conclusion

An integrated system was proposed to improve the energy efficiency in the rice industry. The proposed system substantially reduces the energy consumption for rice production by adopting the exergy recovery and process integration. The utilization of rice by-product also independently provides electricity to meet electricity demand in the rice production process. From the calculation, a single rice production system with a factory capacity of 200 t d^{-1} can generate surplus electricity of about 81.6 MWh d^{-1}. The synergetic integration of rice production and electricity generation using rice husk and rice straw is important to enhance sustainable energy supply.

Acknowledgments

The authors greatly appreciate the support of The Indonesia Endowment Fund for Education (LPDP).

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