Energy 140 (2017) 1087–1095

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Exergy analysis of a new lignocellulosic biomass-based polygeneration system

Fang Liu [a], Guanyi Chen [a, b, c], Beibei Yan [a, *], Wenchao Ma [a], Zhanjun Cheng [a], Li'an Hou [a]

[a] School of Environmental Science and Engineering/ China-Australia Centre for Sustainable Urban Development/ State Key Laboratory of Engines, Tianjin University, Tianjin, 300072, China
[b] School of Science, Tibet University, Lhasa, 850012, China
[c] Tianjin Engineering Centre of Biomass-derived Gas and Oil/Key Lab of Biomass-based Oil and Gas, Tianjin, 300072, China

ARTICLE INFO

Article history:
Received 9 March 2017
Received in revised form
2 August 2017
Accepted 9 September 2017
Available online 13 September 2017

Keywords:
Lignocellulosic biomass
Bio-ethanol
Exergy analysis
Polygeneration
Process simulation

ABSTRACT

A new polygeneration system for production of ethanol, xylose, combined heat and power from lignocellulosic biomass is introduced as it may be much more competitive than those considered before. The polygeneration system is simulated by Aspen Plus based on mass and energy balances and evaluated from exergy point of view and the output value per unit of raw materials. The system can process corn cob 340,000 t/a with a production capacity of anhydrous ethanol 40,000 t/a and xylose crystals 51,600 t/a. The ratio of produced ethanol to dry biomass is 179.7 L/t. The output value per unit of raw biomass is much higher than other systems due to production of high value co-product xylose. The net energy ratio is 1.6 indicating the system has net energy gain. The power generation efficiency and thermal efficiency are 31.2% and 86.2%, respectively. The general exergy efficiency of the system is 62.8% and the largest irreversibility occurs in combined heat and power system (CHP). The work is valuable to find key unit of improving the process exergy efficiency and build an optimal energy network. Further work should take into account the process heat integration to improve the exergy efficiency of the system.

1. Introduction

Bio-ethanol produced from biomass is renewable, environment-friendly and even economically obtained in the near future, and therefore has been widely studied in recent years [1]. The first-generation bio-ethanol uses starch crops and sugar crops as feedstock, and the second-generation bio-ethanol uses lignocellulosic biomass, such as agricultural residual, herbaceous crops, forestry wastes, and municipal waste and so on [2]. Until now bio-ethanol is mainly produced from sugar or starch crops. This leads to the social argument of “food versus fuel”. Therefore the use of lignocellulosic biomass for second-generation bio-ethanol has been paid significant attention by industry.

Bio-ethanol production from lignocellulosic biomass is often integrated in polygeneration system because of its energy intensive nature leading to high production cost [3]. To evaluate the polygeneration system, exergy analysis provides a very valuable tool for process assessment that can identify material flow and energy loss thereby determining units of the system to be improved technologically [4,5]. The polygeneration system of bio-ethanol in terms of exergy analysis has received increasing attention in recent years due to its potential benefits. Modarresi [6] reported a complex process of producing bio-ethanol, bio-methane, heat and power from wheat straw using pinch and exergy analysis. The results from exergy analysis showed that the bio-ethanol process has the highest exergy efficiency because of usage of stillage for other processes in which a considerable part of exergy entering is converted into irreversibility because of heat losses and non reacting unknown material produced as material losses. Christoffer [3] investigated the potential irreversibilities from a polygeneration system in which bio-ethanol production was integrated into an existing combine heat and power (CHP) plant. The results showed that the standard exergy efficiency of integrated operation was higher than that of separate operation and the exergy efficiency of integrating lignocellulosic ethanol production into CHP plants was highly dependent on operation parameters. Bösch [5] evaluated five polygeneration processes for production of anhydrous ethanol, power and district heat from wheat grain or/and straw via exergy analysis and found out exergy analysis was a very valuable tool for process evaluation since it allowed for an objective comparison of

* Corresponding author.
E-mail address: yanbeibei@tju.edu.cn (B. Yan).

https://doi.org/10.1016/j.energy.2017.09.040
0360-5442/

Notations

CHP	combine heat and power
WWT	wastewater treatment
SSF	simultaneous saccharification and fermentation
LP Steam	low pressure steam
BFW	boiler feed water
FPU	filter paper unit
HMF	5-hydroxymethyl furfural
$E_{x,lost}$	lost exergy (irreversibilities)
$E_{x,mass}$	exergy of mass streams
$E_{x,work}$	exergy of work
$E_{x,heat}$	exergy of heat steams
E_x^{ph}	physical exergy
E_x^{ch}	chemical exergy
E_x^{pt}	potential exergy
E_x^{kn}	kinetic exergy
C_p	heat capacity of the flow
$\eta_{general}$	general exergy efficiency
$\eta_{irreversibility}$	efficiency of exergy loss
$\eta_{products}$	exergy efficiency of products

product streams as different as anaerobic digestion residue and electric power.

In addition to energy integration, some other high-value co-products besides ethanol produced from lignocellulosic biomass in the polygeneration system may be a breakthrough point for constructing an ethanol production system economically [7]. In this work, a new polygeneration system of producing ethanol, xylose, combined heat and power (CHP) from lignocellulosic corn cob is proposed in Fig. 1 considering corn cob is a large amount in China, and analyzed from exergy point of view. Xylose is the main sugar obtained from hemicellulose and can be used as substrate of producing a variety of compounds, such as xylitol, xylo-oligosaccharides, furfural, lactic acid, 2,3-butanediol, succinic acid, and even feed yeast [7,8]. In this case, the polygeneration system may much more competitive than those considered before. Of corn cob, cellulose is used to produce to ethanol while hemicellulose is extracted for xylose production instead of low-yield bio-ethanol. Lignin is used as feedstock for Combined Heat and Power (CHP) production which can be further utilized by the polygeneration system. The wastewater treatment (WWT) is also simulated. In this case, the corn cob-based polygeneration system may reduce production cost and appears competitive in market covering environmental elements. Exergy analysis takes the production sections/components/units into account separately and is able to find the quantity of irreversibilities for bio-ethanol processes by calculating exergy efficiencies.

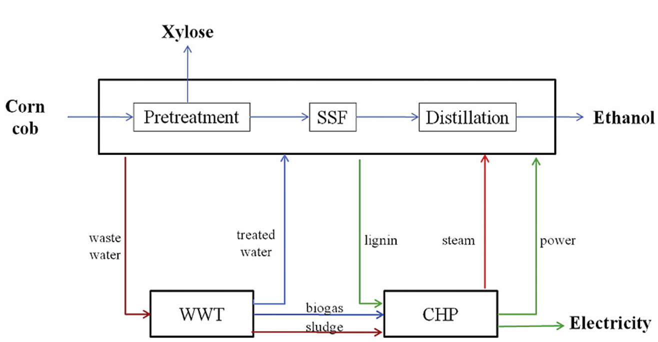

Fig. 1. Schematic flow of corn cob-based polygeneration system.

2. Methodology

2.1. Process simulation

Fig. 1 shows the schematic flow of a corn cob-based polygeneration system. The polygeneration system consists of the following main parts: pretreatment, xylose and ethanol production, wastewater treatment (WWT) and CHP system. Aspen Plus software has been widely used to analyze, design, and evaluate economically the chemical processes [9], and it is therefore used to simulate the polygeneration system.

The capacity of the polygeneration system is to process about 340,000 t/a corn cob with 8400 h/a operation. Physical property data for major key components of this polygeneration system are not available in the standard Aspen Plus databank, and may be obtained from literature developed by NREL [10,11], such as corn cob, enzyme, cell mass and so on. Thermodynamic method is described by NRTL model [11,12]. The feed of corn cob is 40424.8 kg/h, and its moisture content is 17 wt %. The dry composition is showed in Table 1 [13].

2.2. Process description

The detailed flow diagram of the polygeneration system is shown in Fig. 2 and the parameters used have been summarized in Table 2.

2.2.1. Pretreatment

The purpose of the pretreatment was to remove lignin and hemicellulose to disrupt the crystalline structure of cellulose, and to increase the porosity of the materials, making the materials more accessible to enzyme attack [14,15]. Particle size reduction is also an important pretreatment of biomass for energy conversion [16], as the current bio-refinery technologies cannot efficiently digest whole stems of grass and woody feedstock [17]. According to Venkata [18], agricultural biomass was prepared to approximately 1–6 mm by a disc refiner for ethanol production. In this paper, the raw materials corncob are first milled by crusher with 3.2 mm-screen size [18]. Particles which size are bigger than 3.2 mm are sent back to crusher to reduce the size, while the others which can pass through the screen are delivered to pretreatment process (showed in Fig. 3). The total specific energies is 103. 7 MJ/Mg (28.8 kWh/t) for corncob [18].

Pretreatment is carried out using steam and dilute sulfuric acid as catalyst to convert the hemicellulose to xylose. Xylose is the main sugar obtained from hemicellulose conversion and most of the xylose is released as monomers for just dilute acid system [19]. Minor hemicellulose carbohydrates (arabinan, mannan, galactan) are assumed to have the same conversions as xylan [11]. Furfural, 5-hydroxymethyl furfural (HMF) are considered as the byproducts of this process [8,12,20,21]. After pretreatment, the hydrolyzed slurry

Table 1
The components of corn cob.

Components	wt % (dry)
Hemicellulose	36.4
Cellulose	38.8
Lignin	13.1
Ash	3.2
Protein	5.5
Extractives	3.0