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System-level cost evaluation for economic viability of cellulosic biofuel manufacturing

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HIGHLIGHTS

- A system-level cost model for cellulosic biofuel manufacturing is established.
- The relationships between individual process characteristics are studied.
- Two numerical cases are conducted to illustrate the effectiveness of the proposed model.
- The result shows that 12.8% of total cost can be reduced from baseline case.

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ABSTRACT

Biofuel is a clean and renewable energy source and is considered a promising alternative to traditional fossil fuels. The economic viability is crucial in promoting large-scale adoption and long-term sustainability of biofuel. Most of the current literature on biofuel economics assumes the individual biofuel manufacturing processes are independent of each other. Consequently, the interrelationships between parameters within and across processes regarding manufacturing cost and biofuel yield are not well investigated. In this paper, a system-level cost model for cellulosic biofuel manufacturing is established across multiple production processes to investigate the relationships between the individual process characteristics and the system performance to reduce the overall cost under the constraint of biofuel yield. Two numerical case studies are conducted to illustrate the effectiveness of the proposed model. Compared with the baseline case, the cost-effective case shows that 12.8% of the total cost is reduced without ethanol yield loss.

1. Introduction

The continuously increasing energy consumption coupled with limited fossil fuel reserves is one of the most serious challenges to the sustainable development of human society. Although significant research progress has been made to investigate renewable energy resources as sustainable energy alternatives, fossil fuels accounts for the largest portion of the worldwide energy supply. The usage of fossil fuels has become the main source of carbon dioxide (CO_2) emission, which is one of the major greenhouse gases (GHGs) that lead to global warming. The global temperature increase associated with GHGs emissions from burning fossil fuels is expected to be 3.6 °C by 2040 [1]. The severe environmental burdens caused by fossil fuels make it critical to highly prioritize sustainable low-carbon fuels.

As a promising alternative, biofuel gains its popularity as a renewable energy source that can be sustainably developed [2]. Biofuels, especially bio-ethanol produced from cellulosic feedstock, appear to be environmentally friendly with no net CO_2 and very low sulfur emissions. In addition, biofuels can help decrease a country's energy dependence on imported oil, and have positive impacts on both the economy and the environment [3]. Given these advantages, biofuels have been receiving growing attention from countries around the world. As a result, global biofuel production in 2013 has increased seven times compared to 2000 [4]. Moreover, it is estimated that 30% of the U.S. liquid transportation fuels will be replaced by biofuels by 2022 [5].

Based on different biomass feedstocks and associated manufacturing systems, biofuels are divided into several categories such as corn-based biofuel, cellulosic biofuel, and algae biofuel, etc. Cellulosic biofuel has been considered as the most promising biofuel due to its capability of satisfying the fuel demands using agricultural wastes such as corn stover. As shown in Fig. 1, a typical

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Nomenclature

Bold face

R	reaction diagonal matrix
F	formation diagonal matrix
S	state variable set

Upper case

A	pre-exponential factor (1/s)
A_{G2}	area of the cellobiose lattice (m^2)
A_{max}	maximum enzyme adsorption per g cellulose
AS	total surface area accessible to enzyme (m^2)
A_s	reactor surface area (m^2)
C_{acid}	active acid concentration (w/w%)
C_0	initial acid concentration (w/w%)
C^D	process-dependent cost ($)
C^{ID}	process-independent cost ($)
E_a	activation energy
E_b	bound enzyme concentration (g/kg)
E_{b1}	bound concentration of endo-β-1,4-glucanase and exo-β-1,4-glucanase (g/kg)
E_{b2}	bound concentration of β-glucosidase (g/kg)
E_f	free enzyme concentration (g/kg)
E_{f2}	concentration of free β-glucosidase (g/kg)
E_h	energy consumption by heat transfer (kJ)
E_r	energy consumption by reaction (kJ)
E_s	energy consumption by heating up steam (kJ)
E_{tot}	total energy consumption (kJ)
$K_{1,gl}$	inhibition constant of glucose when glucan transforms to glucose (g/L)
$K_{1,gb}$	inhibition constant of cellobiose when glucan transforms to glucose (g/L)
$K_{1,xl}$	inhibition constant of xylose when glucan transforms to glucose (g/L)
$K_{2,gl}$	inhibition constants of glucose when glucan transforms to cellobiose (g/L)
$K_{2,gb}$	inhibition constants of cellobiose when glucan transforms to cellobiose (g/L)
$K_{2,xl}$	inhibition constants of xylose when glucan transforms to cellobiose (g/L)
$K_{3,gl}$	inhibition constants of glucose when cellobiose transforms to glucose (g/L)
K_{3m}	cellobiose saturation constants when cellobiose transforms to glucose (g/L)
$K_{3,xl}$	inhibition constants of xylose when cellobiose transforms to glucose (g/L)
$K_{i,g}$	inhibition constant of glucose when glucose transforms to ethanol (g/L)
$K_{i,x}$	inhibition constant of xylose when glucose transforms to ethanol (g/L)
K_p	dissociation constant in terms of L/g cellulose
$K_{s,g}$	limitation constant of glucose (g/L)
$K_{s,x}$	limitation constant of xylose (g/L)
M_g	molecular weight of glucan (g/mol)
M_{gl}	molecular weight of glucose (g/mol)
M_x	molecular weight of xylan (g/mol)
M_{xl}	molecular weight of xylose (g/mol)
M_{xo}	molecular weight of xylose oligomer (g/mol)
N_o	amount of substance of accessible cellobiose lattices/g cellulose
N_A	Avogadro constant
$P_{i,g}$	threshold ethanol concentration of glucose (g/mol)
$P_{i,x}$	threshold ethanol concentration of xylose (g/mol)
$P_{m,g}$	maximum ethanol concentration of glucose (g/mol)
$P_{m,x}$	maximum ethanol concentration of xylose (g/mol)
R	gas constant
T	temperature (K)

Lower case

A	ratio of the liquid volume and solid spheres volume
c_e	concentration of ethanol (kg/L)
c_g	concentration of glucose (kg/L)
c_{gb}	concentration of cellobiose (kg/L)
c_{xl}	concentration of xylose (kg/L)
c_{xo}	concentration of xylose oligomer (kg/L)
c_z	concentration of recombinant (kg/L)
d	feedstock particle diameter (m)
d_r	thickness of reactor (m)
$h_{cellubiose}$	entropy of cellobiose (kJ/kg)
h_{cond}	conductivity of pretreatment reactor (W/m)
h_{conv}	convection coefficient (W/m^2)
$h_{ethanol}$	entropy of ethanol (kJ/kg)
h_{glucan}	entropy of glucan (kJ/kg)
$h_{glucose}$	entropy of glucose (kJ/kg)
h_{xylan}	entropy of xylan (kJ/kg)
h_{xylose}	entropy of xylose (kJ/kg)
$h_{xylose\text{-}oligomer}$	entropy of xylose oligomer (kJ/kg)
k	reaction rate (1/s)
$\dot{q}$	heat flux (W/m^2)
$q_{emax,g}$	overall maximum specific ethanol production rate by glucose (g)
$q_{emax,x}$	overall maximum specific ethanol production rate by xylose (g)
$q_{smax,g}$	overall maximum specific glucose utilization rate (g)
$q_{smax,x}$	overall maximum specific xylose utilization rate (g)
p_g	mass of glucan in feedstock (kg)
p_x	mass of xylan in feedstock (kg)

Greek

α	weight factor of glucose consumption
β	initial water volume (L)
λ	ratio of cellobiose lattices occupied to bound enzyme molecule
ρ_{solid}	density of the solid (kg/m^3)
$\mu_{max,g}$	maximum overall specific growth rate of glucose (1/s)
$\mu_{max,x}$	maximum overall specific growth rate of xylose (1/s)

cellulosic biofuel manufacturing system consists of three main individual processes: pretreatment, enzymatic hydrolysis, and fermentation [6]. In the pretreatment process, the resistance of biomass cell walls is reduced by the overheated steam and acid. In enzymatic hydrolysis, the exposed cellulose chains are decomposed into fermentable sugars. These fermentable sugars are subsequently converted into biofuel (e.g., ethanol) in the fermentation process. Most research efforts regarding the biofuel manufacturing system are devoted to improving these processes from a biochemical perspective, such as pretreatment technology development [7–9] and fermentation bacterial cultivation [10–12]. The outcomes of these research efforts have built a theoretical foundation for the biofuel manufacturing industry.

The U.S. government has given a mandate to produce 16 billion gallons of cellulosic biofuel annually by 2022 [13]. To achieve this production target, many additional large-scale biofuel manufacturing plants are being constructed. Economic viability is one of the most critical aspects affecting the evaluation of large-scale implementation and long-term sustainability of cellulosic biofuel manufacturing system. Consequently, studies regarding the cost-benefit analysis of cellulosic biofuel have emerged [14–17]. However, in the current literature, most cost evaluation studies on cellulosic