Energy Conversion and Management 145 (2017) 82–92

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Energy consumption and exergy analyses of a supercritical water oxidation system with a transpiring wall reactor

Fengming Zhang [a,c,*], Boya Shen [a], Chuangjian Su [a], Chunyan Xu [b], Jianan Ma [a], Yun Xiong [a], Chunyuan Ma [b]

[a] *Guangdong Key Laboratory of Membrane Materials and Membrane Separation, Guangzhou Institutes of Advanced Technology, Chinese Academy of Sciences, 511458 Guangzhou, China*
[b] *National Engineering Laboratory for Coal-fired Pollutants Emission Reduction, Shandong University, 250061 Jinan, China*
[c] *Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, 518055 Shenzhen, China*

ARTICLE INFO

Article history:
Received 6 February 2017
Received in revised form 16 April 2017
Accepted 25 April 2017

Keywords:
Supercritical water oxidation
Energy consumption
Exergy
Transpiring wall reactor
Aspen plus
Optimization

ABSTRACT

A supercritical water oxidation system with a transpiring wall reactor was simulated by Aspen Plus, and simulation model was validated by comparisons with experimental reactor outlet temperatures and product properties (total organic carbon and CO). Energy and exergy analyses were conducted to reduce energy consumption and exergy loss of the system. It is indicated that the system's energy efficiency and exergy efficiency are 97.73% and 13.28% at typical operating conditions, respectively. The exergy loss of electric heater, heat exchanger and reactor account for 39.89%, 26.64%, and 17.23% of the system's total exergy loss, respectively. The process optimization is conducted by preheating the middle branch of transpiring water with the heat of the reaction products to reduce energy consumption, and the net electric cost is reduced from 7.43 ¥/h to 5.96 ¥/h. It can be observed that when the split coefficient for split 2 equals to 0.6, the minimum electricity input is required for the system. When the feed concentration is increased from 2 wt.% to 10 wt.%, net electric cost per COD significantly decreases from 14.05 ¥/kg to 1.31 ¥/kg, which indicates that higher feed concentrations are beneficial for reducing the cost of energy consumption. What is more, when feed flow rate increases from 6 kg/h to 16 kg/h, net electric cost per COD increases from 3.21 ¥/kg to 4.61¥/kg, which shows that higher energy consumption costs will be required at higher feed flow rates.

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1. Introduction

Treating high concentration and refractory organic wastewater is a tough problem. Supercritical water oxidation (SCWO) uses the excellent properties of supercritical water (SCW) to achieve rapid and complete degradation of organic waste, and it has been proven to be a promising technology to treat organic waste [1–3]. SCW refers to water under high temperature and high pressure ($P > 22.1$ MPa, $T > 647$ K), which acts as a non-polar solvent with high diffusivity and excellent transport properties [4,5]. When pressurizing as well as heating waste water to its supercritical state, organic compounds can be fully oxidized within a single-phase mixture and become non-toxic products, such as CO_2, H_2O, etc [6,7]. Only a residence time of a few seconds to 1 min is required to fully destroy the organic compounds under a fast reaction rate, and thus the reactor requires a very small volume.

Although SCWO has plenty of unique advantages in treating wastewater, some technical problems such as corrosion, salt plugging have blocked its development for many years. The inorganic acid (such as HCl, H_2SO_4, etc.) combining with high temperature and high concentration of oxygen can cause severe corrosion of the reactor and other devices [8]. The inorganic salt is hardly soluble in supercritical water, and thus leading to the plugging of the reactor, as well as the preheating and cooling section [9]. For now, an effective solution to solve both corrosion and salt plugging is the usage of a transpiring wall reactor [10,11]. The transpiring wall reactor usually consists of a dual shell with an outer pressure-resistant vessel and an inner porous tube. Transpiring water at subcritical temperatures passes through the porous pipe to form a protective film on its inner surface. This water film can prevent the reactants spreading to the porous wall and can dissolve some of the salt, thus reducing corrosion and avoiding salt

* Corresponding author at: Guangdong Key Laboratory of Membrane Materials and Membrane Separation, Guangzhou Institutes of Advanced Technology, Chinese Academy of Sciences, 511458 Guangzhou, China.
E-mail address: fm.zhang@giat.ac.cn (F. Zhang).

http://dx.doi.org/10.1016/j.enconman.2017.04.082
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Nomenclature

Abbreviations

COD	chemical oxygen demand
CWR	cooling water revenue, ¥/h
EC	electrical cost, ¥/h
EH1	electric heater 1
EH2	electric heater 2
EH3	electric heater 3
EI	electricity input, kW
ex	specific exergy, kW/kg
F	mass flow rate, kg/h
F^*_{cw}	the modified value for F_{cw}, kg/h
FINAL	final products
FLASH	flash drum
g	gravitational acceleration, m/s^2
h	specific enthalpy, kJ/kg
h_0	specific enthalpy at reference state, kJ/kg
HE1	heat exchanger 1
HE2	heat exchanger 2
HE3	heat exchanger 3
HE4	heat exchanger 4
M	molar mass, kg/mol
M1	mixer 1
M2	mixer 2
M3	mixer 3
M4	mixer 4
NEC	difference between electric cost and cooling water revenue, ¥/h
NECPC	net energy cost per COD, ¥/kg
P	pressure, MPa
P1	pump 1
P2	pump 2
P3	air compressor
PLUG	plug flow reactor
q_r	specific reaction heat, kW/kg
Q_r	reaction heat, kW
Q	energy, kW
Q_u	recovered energy, kW
Q_{all}	refers to the system's overall energy input, kW
r	reaction rate
R	transpiration intensity; universal gas constant, 8.3145 kJ/mol
$\triangle H_f^0$	standard enthalpy of formation, kJ/mol
SCW	supercritical water
SCWO	supercritical water oxidation
s	specific entropy, kJ/(kg K)
s_0	specific entropy at reference state, kJ/(K kg)
t	time, s; temperature °C
tw	transpiring water
tw1	the upper branch of transpiring water
tw2	the middle branch of transpiring water
tw3	the lower branch of transpiring water
T	temperature, K
TOC	total organic carbon
v	velocity, m/s
z	elevation, m
W	work, electricity, kW

Greek letters

ω	the concentration of methanol
η	energy efficiency
ψ	exergy efficiency
ξ	exergy loss coefficient

Subscripts

0	environmental state
cw	cooling water
cold	cold stream
hot	hot stream
in	inlet
ox	oxygen
out	outlet
p	pressurization system
r	reaction
split2-1	the split coefficient for the first stream in split 2
split2-2	the split coefficient for the second stream in split 2
w	organic waste water

Superscripts

ch	chemical
ph	physical

plugging [12]. Large quantities of researches certify that the transpiring wall reactor has an effective role in resisting corrosion and salt plugging [10–12].

Pressurization and heating are the essential steps for the SCWO process, and thus the requirement of energy consumption is considerably high. Energy recovery from the effluent is the leading method to reducing energy consumption of the system. It has been reported that autothermal operation can be achieved when feed concentration reaches 2 wt.% [13]. What is more, many theoretical studies suggest that power generation is an efficient solution for energy recovery [14–18]. However, we should remind that large amounts of transpiring water at relatively lower temperatures (20–350 °C) will be injected into the reactor to protect the transpiring wall, and the temperature of reactor effluent ranging from 300 °C to 350 °C is much lower than that of the traditional SCWO process, which ranges from 400 °C to 650 °C [19]. Therefore, lower-grade energy of the reactor effluent makes power generation or autothermal operation not applicable for a supercritical water oxidation system with a transpiring wall reactor, and a cascade utilization of heat energy recovery will be more effective and feasible [19]. Besides, an exergy analysis is frequently used in the process optimization to reduce energy consumption [20,21]. However, few publications have focused on a SCWO system [6,22,23], and no publication focuses on a SCWO system with a transpiring wall reactor yet.

In this paper, a supercritical water oxidation system with a transpiring wall reactor is simulated by Aspen Plus. Experimental data are provided to compare with simulation results. Firstly, exergy analysis of the system is conducted to obtain the exergy loss distribution. Then a process optimization is performed to reduce energy consumption. What is more, the influences of operating parameters (such as split coefficient, feed concentration, and feed flow rate) on the cost of energy consumption are analyzed.

2. Experimental setup

During early studies, a SCWO system (Fig. 1a) with a transpiring wall reactor was built and successfully operated, and plenty of

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