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Process simulation and optimization of municipal solid waste fired power plant with oxygen/carbon dioxide combustion for near zero carbon dioxide emission

Guangchao Ding, Boshu He, Yang Cao, Chaojun Wang, Liangbin Su, Zhipeng Duan*, Jingge Song, Wenxiao Tong, Xuezheng Li

Institute of Combustion and Thermal Systems, School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, People's Republic of China

A R T I C L E I N F O

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A B S T R A C T

As a new type of high-intensity combustion technology, oxy-fuel combustion technology can effectively reduce the generation and emission of pollutants, particularly near zero emission of carbon dioxide when applied to the waste incineration process. Compared to the conventional air waste-to-energy incineration power generation, the municipal solid waste oxy-fuel combustion power generation system is more complex, resulting in a relatively large space for optimization. In this work, a waste-to-energy incineration power plant in Shenzhen, China, is taken as the original object, and used to establish the process simulation of the conventional plant using Aspen plus. The results are compared and verified with the operation data. Based on the results, models or subsystems are set up for the air separation unit, the municipal solid waste oxy-fuel combustion power system and the flue gas processing compression system, respectively. Then, the subsystems are coupled and connected to establish the whole process simulation of the waste oxy-fuel combustion power plant, and the optimization analyses of the overall plant operating parameters are presented. The results show that the best supplying oxygen concentration is 96%, the carbon dioxide recovery rate of the entire system is 96.24%, and near-zero carbon dioxide emission is basically achieved. The energy consumptions sharing by the flue gas processing compression subsystem, the air separation subsystem, and the others account for 19.82%, 54.29%, and 25.89% of the total energy consumption, respectively. After coupling optimization analysis, the net power generation efficiency of the municipal solid waste oxy-fuel combustion plant increases 2.69%, from 6.88% to 9.57%.

1. Introduction

With the rapid growth of China's economy, the expanding size of cities and the growing population have led to the increasing production of municipal solid waste (MSW). The growing accumulation of MSW has created serious environmental and social problems. The total annual amount of MSW produced in China has reached 191.4 million tons in 2015 [1], and production is predicted to increase to 480 million tons in 2030 [2]. Among the currently used MSW disposal technologies, the waste incineration power generation technology has attracted great attentions due to its advantages of large reducing capacity and energy recovery [3]. However, there exist still some disadvantages in the incineration process due to the complexity of the MSW components [4], such as combustion instability, complex gaseous pollutants and heavy metals emissions. This brings amounts of challenges to the application and the development of incineration technology.

As one of the most promising emission reduction technologies, the oxy-fuel combustion (OFC) technique, which utilizes O_2/CO_2 mixture as the oxidizer instead of air, can achieve high combustion efficiency, low pollutant emissions and low cost of CO_2 capture, etc. [5]. Moreover, the OFC technique can in principle be applied to any type of fuel used for thermal power production [6]. Currently, there have been a few researches related to the MSW O_2/CO_2 combustion. Through thermogravimetric analysis (TGA) experiment, Tang et al. [7] studied the co-combustion characteristics of plastic, rubber and leather in O_2/CO_2 atmosphere. They found that the oxygen-enriched combustion technology could alleviate the inhibitory effects of the replacement of N_2 by CO_2. Also by virtue of non-isothermal TGA, Chen et al. [8] investigated pyrolysis and combustion characteristics of petrochemical wastewater sludge under oxy-fuel condition. The results showed characteristic combustion rates and combustion performance indexes increased while characteristic temperatures decreased with the increase

* Corresponding author.
E-mail address: zpduan@bjtu.edu.cn (Z. Duan).

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Nomenclature

C_{ar}	carbon content of as received basis [–]
G	total Gibbs free energy of the system [kJ]
H_{ar}	hydrogen content of as received basis [–]
M	total number of phases [–]
O_{ar}	oxygen content of as received basis [–]
p_1	inlet pressures of the air compressor [MPa]
p_2	outlet pressures of the air compressor [MPa]
P	number of components [–]
R	the gas constant of air [kJ/(kg K)]
S	number of single phase [–]
S_{ar}	sulphur content of as received basis [–]
T	inlet temperature of the air compressor [K]
V	air volume flow rate [m^3/h]
V_{O2}	oxygen volume produced in the air separation unit [Nm^3/h]
$V_{t,O2}$	amount of the theoretical oxygen consumption [Nm^3/h]
w	power consumption of unit produced oxygen [kWh/Nm^3]
$W_{air,c}$	power consumption of the air compression [kW]
W_{ASU}	energy consumption of air separation unit [kW]
W_{F-1}	power consumption of compressor F1 [kW]
W_{F-2}	power consumption of compressor F2 [kW]
W_{F-3}	power consumption of compressor F3 [kW]
W_{F-4}	power consumption of compressor F4 [kW]
W_{F-5}	power consumption of compressor F5 [kW]
W_{FPC}	power consumption of flue gas processing compression [kW]
W_O	other electricity consumption of power plant [kW]
W_{TP-1}	work of turbine TP1 [kW]
W_{TP-2}	work of turbine TP2 [kW]
W_{TP-3}	work of turbine TP3 [kW]
W_{TP-3}	work of turbine TP4 [kW]
W_{gross}	total power generation [kW]
W_{net}	net power generation [kW]

Greek symbols

ρ	density of air [kg/m^3]
φ	excess oxygen ratio [-]
η_T	isentropic efficiency of compressor [–]
η_M	mechanical efficiency of compressor [–]
η_{gross}	gross energy efficiency [–]
η_{net}	net energy efficiency [–]

Abbreviations

ASU	air separation unit
CCS	CO_2 capture and storage
CWEP	conventional waste-to-energy plant
FPC	flue gas processing compression system
HDC	high distillation column
HRSG	heat recovery steam generator
LCA	life cycle assessment
LDC	low distillation column
LHV	lower heating value
MSW	municipal solid waste
MSA	molecular sieve adsorber
OFC	oxy-fuel combustion
PC-UPO	power consumption of unit produced oxygen
RKS-BM	Redlich-Kwong-Soave equation of state with the Boston-Mathias alpha function
TGA	thermogravimetric analysis
SNCR	selective non-catalytic reduction
TEG	triethyleneglycol

of O_2 concentration. Furthermore, Tang et al. [9] focused on the NO_x and SO_x emission characteristics of MSW combustion in the O_2/CO_2 atmosphere by the fixed bed combustion experiment. The main influence factors, such as the combustion temperature, the oxygen content, and the Ca/S ratio were analyzed. As expected, NO_x and SO_x emission reduced under oxy-fuel condition when the temperature was 800–1000 °C. The same conclusion was obtained in another literature [10]. In addition, they also studied heavy metal enrichment characteristics in the ash of MSW combustion in CO_2/O_2 atmosphere [11]. The results indicated that the replacement of N_2 by CO_2 increased enrichment of these heavy metals in bottom ash, which was beneficial for their removal. Effects of sorbents on the heavy metals control during tire rubber and polyethylene combustion in O_2/CO_2 and O_2/N_2 atmospheres were also studied by Tang et al. [12]. It was found that the replacement of N_2 by CO_2 can increase heavy metal capture for tire rubber. Based on the publications, one can conclude that the application of oxy-fuel combustion technology to MSW incineration offers an effective solution for overcoming the disadvantages of conventional incineration technology mentioned above, and near-zero CO_2 emission may be achieved during MSW disposal.

However, due to the inclusion of the air separation unit (ASU) and the flue gas processing compression system (FPC) in the commercial application, the cycle efficiency of oxy-fuel power plant is greatly reduced by 9–13% compared to the conventional air-firing power plant [13]. This has become the key challenge to its large-scale promotion and application of this oxy-fuel technology. Many studies have been conducted to evaluate the performance of oxy-fuel power plant, and coal and biomass are typically used as the feedstock. Skorek-Osikowska et al. [14] studies a supercritical coal-fired power plant of 460 MW by using commercially available GateCycle and Aspen Plus. Thermodynamic analyses and economic analyses were conducted to evaluate their different structural oxy-fuel systems. It was found that the efficiency decrease of the optimized case was reduced by only 3.5%. In addition, Skorek-Osikowska et al. [15] also founded that the oxygen separation method of hybrid membrane-cryogenic installation can improve the net efficiency of electricity generation by 1.1%. Yan et al. [16] conducted comprehensive sensitivity analyses to assess the performance of a 600 MW oxy-fuel bituminous coal-fired power plant including comparative analyses between dry, half-dry or wet recirculation recycle and concluded that the acid dew point of the wet recycle system is the highest and the dry recycle system is the lowest. By heating the feed water with hot flue gas, the net efficiency of an oxy-fuel process can rise by approximately 1%. Espatolera et al. [17] modeled a circulating fluid bed (CFB) oxy-fuel power plant, including the comparison with oxy-fuel reference power plant and founded that the net electric efficiency of the operational concept power plant is 35.83%, about 3.0% increase compared to the reference power plant. Cormos [18] evaluated the main techno-economic performances of oxy-combustion power plants operated with fossil (coal and lignite) and renewable (sawdust) fuels. Compared to the same supercritical power plant without CO_2 capture and storage, the investigated three kinds of fuels oxy-combustion cases showed energy penalties of 9–12% net efficiency, 37–50% increase of total capital investments, and the operational and maintenance costs are increased 7–15%. Most studies have focused on biomass and coal-fired oxy-fuel combustion power plant, whereas very few studies have considered the MSW as a feedstock for the analysis of oxy-fuel power plant. Only Fu et al. [19] evaluated the flue gas heat losses and the economic analysis of MSW oxy-fuel incineration, the results indicated that the scale of the flue gas cleaning system can be reduced due to the reduction of flue gas rate in oxy-