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Performance analysis and modeling of energy from waste combined cycles

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ABSTRACT

Municipal solid waste (MSW) is produced in a substantial amount with minimal fluctuations throughout the year. The analysis of carbon neutrality of MSW on a life cycle basis shows that MSW is about 67% carbon-neutral, suggesting that only 33% of the CO_2 emissions from incinerating MSW are of fossil origin. The waste constitutes a "renewable biofuel" energy resource and energy from waste (EfW) can result in a net reduction in CO_2 emissions. In this paper, we explore an approach to extracting energy from MSW efficiently – EfW/gas turbine hybrid combined cycles. This approach innovates by delivering better performance with respect to energy efficiency and CO_2 mitigation. In the combined cycles, the topping cycle consists of a gas turbine, while the bottoming cycle is a steam cycle where the low quality fuel – waste is utilized. This paper assesses the viability of the hybrid combined cycles and analyses their thermodynamic advantages with the help of computer simulations. It was shown that the combined cycles could offer significantly higher energy conversion efficiency and a practical solution to handling MSW. Also, the potential for a net reduction in CO_2 emissions resulting from the hybrid combined cycles was evaluated.

1. Introduction

In recent years, interest has been growing in developing environmentally benign methods for disposal of municipal solid waste (MSW). Dumping in landfills is not a sustainable solution, and in fact, pressure against landfilling is constantly rising in many cities in Canada due to increased environmental and sanitary concerns, shortage of landfill void and continually increasing landfill costs. For instance, it is expected that by 2013, the majority of landfill space available in the Niagara Region will have been used up. Therefore, alternative disposal methods must be taken into consideration.

MSW is produced with minimal fluctuations throughout the year. The quantity of waste can be estimated from a residue factor and the population. In industrialized countries, MSW is produced at a rate of approximately 400 kg or more, per person per year [1]. This is a substantial amount, constituting a "renewable biofuel" energy resource. Incineration of MSW reduces the volume of waste substantially and provides a source of energy. The energy production helps offset the cost of processing the waste. Energy from waste (EfW) can be accomplished with minimal pollution. These drivers provide an opportunity for development and deployment of cost-effective energy recovery systems. More important, reductions in greenhouse gas emissions, particularly CO_2 and methane can be made by EfW. Estimation of the carbon neutrality of MSW on a life cycle basis indicates that about 33% of the total CO_2 emissions from incineration of unsorted waste are of fossil origin. The waste that would otherwise be converted into methane in the anaerobic processes taking place in landfills is converted into CO_2 in EfW processes. Methane has a global warming potential 25 times higher than CO_2. Otoma et al. [2] performed a life cycle analysis for MSW-based power plants and concluded that EfW provides net CO_2 reduction.

However, conventional incineration of MSW with a steam Rankine cycle provides poor electrical efficiency and often involves problems in operation. Compared to fossil fuel-fired power plants, steam parameters in MSW incineration boilers are severely limited due to aggressive corrosivity of MSW flue gases. This constrains the efficiency of MSW incineration boilers. In this study, we explore an approach to extracting energy from MSW more efficiently – MSW/natural gas hybrid combined cycles. In the combined cycles, the topping cycle consists of a gas turbine, while the bottoming cycle is a steam cycle where the low quality fuel – waste is utilized. In addition, the potential for a net reduction in CO_2 emissions resulting from the hybrid combined cycles are evaluated quantitatively.

2. MSW combustion and integration of MSW boiler with gas turbine

2.1. MSW combustion

MSW is a highly heterogeneous blend of many constituents, but is ultimately composed of combustible/volatile matter, moisture

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Nomenclature

P_{S0}	electric power from autonomous MSW-fired steam cycle
P_G	electrical power production by gas turbine (topping cycle)
P_S	electrical power production by steam turbine (bottoming cycle)
Q^f_{MSW}	energy input of solid fuel MSW
Q^f_G	energy input of natural gas

Greek symbols

δ	fraction of energy transferred from topping cycle to bottoming cycle
η_{CC}	efficiency of pure gas-fired combined-cycle
$\eta_{el,CC}$	electrical efficiency of hybrid dual-fuel combined cycles
$\eta_{el,G}$	efficiency of gas turbine
$\eta_{el,MSW}$	MSW-based efficiency in combined cycles
$\eta_{el,S}$	efficiency of steam cycle in combined cycles
$\eta_{el,S0}$	electrical efficiency of autonomous MSW-fired steam cycle
τ	ratio of electrical power from steam turbine in combined cycles to electric power from autonomous MSW-fired steam cycle
φ	ratio of natural gas energy input to total energy input

and ashes. The combustible/volatile matter is of most interest and consists primarily of carbon, oxygen, hydrogen, nitrogen, sulfur, and other minor elements such as chlorine, fluorine and heavy metals. The heating value of MSW varies with lifestyle, economic activities and location. Typically, MSW has a heating value of 8–12 MJ/kg. Table 1 presents the heating value and composition of typical MSW in Canada. There is evidence that the composition of MSW is shifting toward higher contents of combustible materials and lower organic fractions due to changes in lifestyle, resulting in a higher calorific value.

Combustion of MSW is more complex than coal combustion, due to the inhomogeneity and variations in moisture content and composition of the feedstock. During MSW combustion, the volume of MSW is reduced by about 90% and the weight by about 75%. Chain-grate and fluidized bed combustors are commonly used for MSW combustion. Modern chain-grate combustors often use a sloping, reciprocating water-cooled grate. Air is added at various points in the combustion chamber and above the fire. MSW passes through the stages of drying, ignition, combustion and burnout. Ultimate burnout is ensured by regulating the residence time of the material on the grate, and air distribution.

Fluidized bed combustion can improve the combustion efficiency of high moisture content fuels, and is adaptable to a variety of solid wastes. Fluidized bed combustors operate at relatively low temperature (typically in the range 820–920 °C). This ensures that the formation of thermal NO_x is kept to a minimum. As a result of low temperature, good mixing and low excess air, fluidized bed combustion features low CO and NO_x emissions. 80–90% of SO_x emissions can be captured by limestone directly in fluidized bed combustors. Table 2 summarizes a number of EfW power plants using fluidized bed combustion technologies [3].

Table 1
Composition and heating values of typical non-sorted MSW produced in Canada.

Fraction	% By weight	Material	% By weight (per dry mass)
Food and garden residues	29	Carbon	39
Paper and paperboard	27	Hydrogen	6.4
Plastics and rubber	13	Oxygen	26
Glass	3	Nitrogen	3.5
Metals	3	Sulfur	0.3
Textiles	5	Chlorine	1.2
Other combustibles	14	Phosphorus	0.2
Other non-combustibles	6	Ash	23.4
		Lower heating value	10.5 MJ/kg
		Moisture	31
		Combustibles	45
		Inert	24

2.2. Limitations of MSW-fired steam cycles

The aggressive nature of flue gases from MSW combustion sets a ceiling of steam superheat temperature to avoid severe corrosion of the metal structures of heat exchangers. In other words, the aggressive compounds are the obstacle to raising the steam parameters in conventional MSW-fired steam cycles. Superheater tubes bear the highest metal temperature due to poor internal heat transfer coefficients and are most exposed to hot corrosion. Therefore, MSW-fired power facilities have low steam parameters and consequently poor electrical efficiency. For instance, steam superheating temperatures are usually below 380 °C with the electrical efficiency being below 25%. Use of the low steam parameter is further motivated by small-scale and low-investment construction [4]. Due to the low steam parameter, there are few extraction points on the steam turbine, thereby limiting feedwater temperature. In addition, the flue gases should not be cooled below 200 °C to avoid the risk of condensation of aggressive compounds [1,4,5]. This entire practice makes the steam/water cycle inefficient.

2.3. MSW and natural gas hybrid combined cycles

Increasing steam temperature externally in the Rankine cycle will improve the efficiency of electricity generation for MSW-fired power plants. This can be achieved by MSW and natural gas hybrid combined cycles that involve two different thermodynamic cycles with two types of fuel. In the combined cycles, the topping cycle consists of a gas turbine, while the bottoming cycle driven by low quality fuel MSW is a steam cycle. The combined cycles are a thermodynamic integration of an EfW system with a gas turbine at the water/steam side.

Various configurations for the hybrid combined cycles are possible, including (a) serial combined cycle where the topping cycle exhaust is used as hot combustion air for firing MSW; (b) parallel coupled combined cycle where the heat of the topping cycle exhaust is used for parallel steam generation, superheating and feedwater preheating; (c) mixed systems combining (a) and (b) or other possible variants. In a dual-fuel combined cycle system, there must be a well-designed thermal link between the toping cycle and the bottoming steam cycle. The integration ought to provide thermodynamic and operating advantages for both the topping cycle and the bottoming cycle. Generally, steam superheating by turbine exhaust heat is viable. This arrangement can substantially increase the efficiency of MSW energy conversion while avoiding the corrosion problems. Also, hot turbine exhaust can be used as combustion air for MSW combustors. This design has been successfully applied for power plant repowering. An increase of 20% in total plant efficiency has been reported [6]. Gas turbines are available