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Advanced exergy analysis and environmental assesment of the steam cycle of an incineration system of municipal solid waste with energy recovery

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ABSTRACT

This work presents an advanced exergy and environmental analysis of a steam cycle of a municipal solid waste incineration plant, with energy recovery for electricity generation; employing MSW of the city of Santo André in São Paulo State, Brazil. Initially, a plant energy analysis is accomplished to determine some thermodynamic performance indicators, as well a conventional exergetic analysis is performed, to determine the magnitude of exergy destruction in each one of plant main components. To identify the potential for improvement in the incineration steam cycle, an advanced exergetic analysis was done, with exergy destruction divided into four categories: endogenous, exogenous, avoidable and unavoidable. With all this it was calculated that total plant exergy destruction can be reduced by 8.4%, through increments in efficiency in plant components taking into account best existing technologies and operating parameters that represent an avoidable total cost of $2′830,624 per year.

Finally, a Life Cycle Analysis using the IMPACT Method 2002 + was carried out to determine environmental impacts of plant operation considering two cases: Reference Case (Case A) and the Improved One (Case B). Case B was divided in three comparative scenarios (B1, B2 and B3) which were considered to evaluate the environmental impact of plant operation and dislocation of primary energy. The results shows that reduction of avoidable exergy destruction in a steam generating cycle leads to an emission index reduction from 531 to −224 kg CO_{2eq}/MWh, while a primary energy displacement about 3.69 kWh per unit of electric energy available was reached, using MSW as fuel in steam cycle.

1. Introduction

According to the World Meteorological Organization (WMO), year 2016 made history, with a record global temperature, exceptionally low sea ice, unabated rise of sea level and an increase of ocean temperature. Extreme weather and climate conditions have continued into 2017 [1]. By three mean dataset used by WMO, 2016 was 0.83 °C +/− 0.10 °C warmer than average of reference period from 1961–1990, 0.52° C above 1981–2010 average, 0.06 °C above previous highest value set in 2015 and it was also 1.1 °C above pre-industrial period [2].

With carbon dioxide reaching a record annual average concentration of 400 ppm (ppm) in the atmosphere, human activities influence over climate system has become more and more evident [2].

Other environmental problem is a growing amount of generated municipal solid wastes (MSW). As global population increases dramatically, there is also systematic changing consumption patterns, economic development, rapid urbanization and industrialization, because of this, MSW is being generated at a rate that outstrips capability of natural environment to assimilate it and of municipal authorities to manage it [3]. Moreover MSW is the fourth largest global emissions contributor; approximately 550 Tg of global methane emissions per year [4].

Recently waste-to-energy incineration is receiving a growing attention in many countries, due to need of promotion of renewable energy developments and pressure over an efficient land use. Incineration is suitable WtE technology for MSW energy recovery especially with

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Nomenclature

COND1	condenser
DA1	deaerator
ECON1	economizer
FB1	steam generator
HX1	air preheater
LCA	life cycle analysis
MSW	municipal solid waste
SP	flow separators
SPHT1	superheater
ST	steam turbine
WtE	waste to energy

Latin

B	bifurcation
b_{ch}	specific chemical exergy of fuel (kJ/kg)
b_{chw}	specific chemical exergy of water (kJ/kg)
$\dot{C}_{avoidable}$	avoidable cost ($/h)
$\dot{C}_{unavoidable}$	unavoidable cost ($/h)
e	specific exergy (kJ/kg)
$\dot{E}$	exergy (kW)
h_n	specific enthalpy (kJ/kg)
J	junction
LHV	lower heating value (kJ/kg)
$\dot{m}_{fuel}$	mass flow of fuel (kg/s)
$\dot{m}_n$	mass flow rate (kg/s)
$\dot{W}$	power (kW)
$\dot{Z}$	hourly cost ($/h).

Greek symbols

Δ	increment
ε_k	exergetic efficiency of component k

Superscripts

AV	avoidable
EN	endogenus
EX	exogenus
UN	unavoidable

non-biodegradable matter and low moisture content [5].

WtE plants have dual objective: reducing amount of waste sent to landfills and simultaneously, to produce useful energy (heat and/or power). However, some incineration plant suffers high ignition loss, due to high excess of air often required to attain an acceptable burnout, in addition to low efficiency induced by high internal energy consumption causes by waste handling [6].

WtE supply chain provides a method of simultaneously addressing problems of energy demand, waste management and GHG emissions, achieving a circular economy system (CES). In other words, CES is based on “win–win” philosophy stating that a prosper economy and healthy environment can co-existed [7]. Energy efficiency, an efficient energy transformations and effective energy recovery should be insured to avoid unnecessary entropy production but also to make processes more cost effective and ecofriendly [8].

Last generation of incineration plant is characterized by an improvement of chemical conversion process, and by advanced technologies of pollution control systems. Today there are efficient industrial units integrating destroying hazardous organic substances, recovering energy and materials, and saving landfill space [9].

There are 86 facilities in the United States recovering energy from combustion of municipal solid waste. Those 86 facilities have capacity to produce 2720 megawatts of power per year by processing more than 28 million tons of wastes [10]. In the EU 28 in 2014, 27.3% of municipal wastes are incinerated (total incineration including energy recovery) [9]. In Japan, approximately 80% of MSW are incinerated, where energy recovery has been included in a certain proportion of waste incineration plants and Chinese Government put forward “The 12 th Five-Year Plan (2011–2015)”, which specified that electricity generated from waste incineration technologies will grow by 10%, reaching a proportion of 30% of the total energy (mix) in 5 years [11].

Because world importance of incineration, several works have been carried out, some of them focused on energetic and exergetic evaluation of cycles [12,13]. As an example, Solheimslid and coworkers calculated first-and second-law-efficiency of a Norwegian combined heat and power facility driving municipal waste incineration [13]. Work [14] evaluated an energy analysis for advanced WtE technologies, including a landfill gas recovery system, incineration, anaerobic digestion and gasification. Others focused on optimizing system’s parts [15] and some in repowering of steam cycles using gas turbines [16]. Another work on incineration [17], is a study of combined power cycle using waste incineration.

Separately, other studies have focused on environmental aspects of incineration plants using the Life Cycle Assessment (LCA), like Refs. [18–22].

Recently, advanced exergy analysis had been used in evaluation of different types of energy conversion systems. Soltani and coworkers [23] applies this methodology to a combined cycle plant with biomass integrated. Vučković and coworkers [24] make advanced exergy analysis of thermal processes in tires production industry.

Another application is made by Ref. [25] in a plant for electricity generation from natural gas in Turkey, Ref. [26] performed an advanced exergy analysis of a hydrogen liquefaction plant and Ref. [27] performed an advanced exergy analysis for a trigeneration system. Yamankaradeniz [28] evaluated thermodynamic performance of a district heating system using advanced exergy analysis. All these studies show how this methodology is now fundamental when evaluating an energy conversion system and show how exergy destruction associated to a process can be reduced.

In all literature consulted, an advanced exergetic analysis applied to steam cycle of an urban solid waste incineration plant, has not yet been found, and no study found about how identification of reduction potential of avoidable destroyed exergy can contribute to reduce environmental impacts, resulting from the energy recovery of the MSW in an incineration plant.

In this work an exergetic and environmental advanced analysis in steam cycle of an incineration system to be installed in Santo André city in São Paulo metropolitan region is analyzed, to determine how much possible is to diminish plant destroyed exergy, and which are avoidable economic costs that can be achieved, with technologies current state, making up a system cycle and selecting operating parameters. Finally, a system LCA is performed, to quantify potential environmental impacts resulting from reduction of plant exergy destruction.

2. General aspects

2.1. Main aspects related to waste incineration in WtE plants

Due to heterogeneous nature of wastes, some differences from a conventional fossil fuel power plant have to be considered, when working in a chemical to electrical energy conversion process; for example, efficiency of a coal burning cycle is generally around 40%, while for a garbage incineration cycle varies between 20 and 30% [12,29]. Net electricity efficiency of a modern WtE facility in the Netherlands is