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Process analysis of an industrial waste-to-energy plant: Theory and experiments

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ABSTRACT

Thermal conversion is fundamental in an integrated waste management system due to the capability of reducing mass and volume of waste and recovering energy content from unrecyclable materials. Indeed, power generation from industrial solid wastes (ISW) is a topic of great interest for its appeal in the field of renewable energy production as well as for an increasing public concern related to its emissions. This paper is based on the process engineering and optimization analysis, commissioned to the University Campus-Biomedico of Rome by the MIDA Tecnologie Ambientali S.r.l. enterprise, ended up in the construction of an ISW thermo-conversion plant in Crotone (Southern Italy), where it is nowadays operating. The scientific approach to the process analysis is founded on a novel cascade numerical simulation of each plant section and it has been used initially in the process design step and after to simulate the performances of the industrial plant. In this paper, the plant process scheme is described together with the values of main operating parameters monitored during the experimental test runs. The thermodynamic and kinetic basics of the mathematical model for the simulation of the energy recovery and flue gas treatment sections are presented. Moreover, the simulation results, together with the implemented parameters, are given and compared to the experimental data for 10 specific plant test runs. It was found that the model is capable to predict the process performances in the energy production as well as in the gas treatment sections with high accuracy by knowing a set of measurable input variables. In the paper fundamental plant variables have been considered such as steam temperature, steam flow rate, power generated as well as temperature, flow rate and composition of the resulting flue gas; therefore, the mathematical model can be simply implemented as a reliable and efficient tool for management optimization of this kind of plants.

1. Introduction

A rise in a country's prosperity is parallel to an increasing amount of waste produced by the population. Waste management constitutes one of the main problems of daily life in all the industrialized countries and its efficacy depends on various aspects such as the level of technological development, the kind of waste material, the availability of large areas for landfills and even the cultural level of the local population. Raising concerns about potential health effects and land value loss are increasing the cost for treating wastes. Some EU member countries have already banned landfilling

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Nomenclature

A_a	number of sites available for adsorption (mol/N m^3)
b	stoichiometric coefficient (–)
C°_A	initial concentration of gaseous reactant A (mol/N m^3)
C°_B	initial concentration of solid reactant B (mol/N m^3)
C_{AC}	activated carbon concentration (g/N m^3)
C_{lime}	lime concentration (g/N m^3)
C_F	fly ash concentration (g/N m^3)
Cp	specific heat at constant pressure (kJ/kg K)
$D_{A_{eff}}$	effective diffusion coefficient of A (m^2/s)
D_e	NO effective diffusivity (cm^2/s)
h	half thickness of the wall (cm)
h_0	heat transfer coefficient inside the kiln (W/(m^2 s K))
h_3	heat transfer coefficient outside the kiln (W/(m^2 s K))
k_1	transport phase adsorption coefficient (N m^3/(s mol))
k_2	filter cake coefficient (g m/(s mol))
k_{ij}	thermal conductivity of the layer between R_i and R_j (W/(m s K))
ka	kinetic constant for specific surface (s^{-1})
k_{cin}	reaction kinetic constant (m/s)
k_G	mass transfer coefficient in gaseous film (m/s)
k_m	film mass transfer coefficient (cm/s)
L	kiln length (m)
$LHV_{aux\,f}$	lower heating value of auxiliary fuel (kJ/kg)
LHV_{waste}	lower heating value of the waste fed into the kiln (kJ/kg)
L_r	total length of honeycomb reactor (cm)
MW_B	particle molecular weight of solid B in the Shirking Core Model (g/mol)
$Q_{unburned}$	heat flow of the unburned waste (kW)
Q_{loss}	heat flow loss (kW)
R	particle radius in the Shirking Core model (m)
R_i	radius of section i of the kiln (m)
Sc	cross-sectional area of the cell in the honeycomb (cm^2)
t	time (s)
t_f	flue gas residence time (s)
T_0	reference temperature (25 °C)
T_A	average temperature inside the kiln (°C)
T_a	temperature of air (°C)
T_{ash}	temperature of ashes leaving the kiln (°C)
T_B	ambient temperature (°C)
T_f	temperature of flue gases (°C)
$T_{f\,rec}$	temperature of recirculated gases (°C)
u	gas linear velocity (cm/s)
v_f	filtration velocity (m/s)
W_{air}	flow rate of air (kg/s)
W_{ash}	flow rate of ashes (kg/s)
$W_{aux\,f}$	flow rate of auxiliary fuel (kg/s)
$W_{unburned}$	flow rate of unburned waste in the kiln (kg/s)
W_{waste}	flow rate of the waste fed into the kiln (kg/s)
W_f	flow rate of flue gases (kg/s)
$W_{f\,rec}$	flow rate of recirculated gases (kg/s)

Greek letters

ε	excess air (–)
η	removal efficiency (–)
ϕ^2	Thiele module (–)
ρ_B	particle density of solid B in the Shirking Core model (kg/m^3)
θ	mean residence time in the kiln (s)
σ	perimeter length of a cell in honeycomb (cm/cell)
χ	generic reaction conversion (–)
χ_A	reaction conversion of A (–)

of organic or biodegradable waste in order to match EU directive for a better sustainable development (EEA, 2009). In this framework, thermal treatment is very attractive as a way to recover renewable energy from the waste through different energy forms such as electricity and process heat for both industrial facilities and district heating utilization, and to reduce the waste volume and the total greenhouse gas emissions. Further advantages can be found in the destruction of organic contaminants and in the concentration and immobilization of inorganic ones (Arena, 2012), and in the possibility of utilization of recyclables from the thermal residues from bottom ash and slag (Lam et al., 2010). Moreover, as a consequence of the better environmental performances and more severe emission regulations with respect to other energy sources, the thermal conversion of municipal solid waste (MSW) has a minor environmental impact compared to almost any other source of electricity (Arena, 2012).

The process of solid waste incineration consists in the heat recovery by a steam generator for electrical energy conversion through a steam turbine. The variability in waste composition and the severity of the incineration operating conditions may result in many practical operating problems such as high maintenance requirements and equipment unreliability. Moreover, a large number of constraints must be fulfilled throughout the entire operating life of the plant. It is important to remember that the health risk related to air emissions from an incinerator can be minimized only if it is properly designed and managed (Fodor and Klemes, 2012; Yassin et al., 2007).

Because of the magnitude of the involved phenomena, the experimental investigations reported in the literature are often conducted on lab or pilot plant scale dealing mainly with particular aspects of the whole process, such as the combustion efficiency (Chen et al., 2008), emissions estimation (Vermeulen et al., 2012) and control (Skodras et al., 2005).

On the other hand, the scientific research has produced various mathematical models that describe the solid waste thermal conversion involving different approaches (de Souza-Santos, 2010). A first category includes the "zero-dimensional" models based on mass and energy balances, particularly suitable for commercial software simulators (Cimini et al., 2005). Antonioni et al. (2014) have recently applied this approach to the minimization of the operating costs of a flue gas treatment process in a MSWI plant. Other types of models focus on the reactor geometry, reaction kinetics as well as point-by-point analysis of transport phenomena in order to predict the composition of the flue gas in particular reactor geometries, such as internally circulating fluidized bed (Mukadi et al., 2000). Rovaglio et al. (1998) simulated the dynamic behaviour