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Numerical analysis of the incineration of polychlorinated biphenyl wastes in rotary kilns

Ehab Hussein Bani-Hani[a], Mahmoud Hammad[b], Ali Matar[b], Ahmad Sedaghat[a,*], Khalil Khanafer[a]

[a] School of Engineering, Australian College of Kuwait, P.O. Box 1411, Safat 13015, Kuwait
[b] Faculty of Engineering and Technology, The University of Jordan, Amman 11942, Jordan

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ABSTRACT

Polychlorinated biphenyls (PCBs) wastes are among hazardous wastes that must be incinerated for environmental and human health reasons. The incineration process of polychlorinated biphenyls (PCBs) wastes in a rotary kiln are governed by a dynamic model consist of a set of nine stiff nonlinear equations. The dynamic model accounts for variations in composition of PCBs on number of chlorine atoms and process conditions such as excess air, temperature and pressure of operation. To solve these equations, a MATLAB routine is written which is used to study the PCBs waste incineration processes. The results are presented and discussed on the holdups of ash, oxygen, carbon dioxide, water vapor, hydrochloric acid, methane, and gas at different conditions.

1. Introduction

International conventions, which state laws and regulations to protect the environment, are setting tighter restrictions on industries to achieve higher standards for more environmental friendly products. Hence, the problem of coexistence of sustainable industry and safe environment are among challenges for most industrialized countries in the scene of fuel prices and availability.

Rotary-kiln incinerator is used by municipalities and by large industrial plants as a method of safe disposal of hazardous substances [1]. The design of incinerators has two chambers: a primary chamber and secondary chamber. The primary chamber in a rotary kiln incinerator consists of an inclined refractory lined cylindrical tube. Movement of the cylinder on its axis facilitates movement of waste. In the primary chamber, there is conversion of solid fractions to gases, through volatilization, destructive distillation and partial combustion reactions.

The secondary chamber is necessary to complete gas phase combustion reactions. The ash spills out at the end of the cylinder. A tall gas stack, fan, or steam jet supplies the needed draft. Ash drops through the grate, but many particles are carried along with the hot gases. These particles and any combustible gases may be combusted in an afterburner. To control air pollution, the combustion product gases are further treated with acid gas scrubbers to remove sulfuric acid and nitric acid emissions, and then routed through bag houses to remove particulates before the gases are released into the atmosphere. Fig. 1 shows an example of the rotary kiln incinerator.

The rotary kiln model that is examined here is the pilot project designed by Rovaglio et al. [2] to investigate experimentally the incineration process. The geometry and characteristics of this model are briefly summarized in Table 1.

The objective of this paper is to investigate incineration of hazardous PCBs waste materials using an in-house developed simulating routine in MATLAB. The incineration processes are explained and detailed mathematical models are given here. The study aims to report the emissions in both gas and solid phases from the combustion during incineration process and to relate these to environmental impacts. The paper is outlined as follows:

- A more detailed background research is provided in Section 2 to give an overview to reader on incineration processes.
- Detailed development of the mathematical model is given in Section 3.
- Section 4 provides results and discussion on holdups of ash, oxygen, carbon dioxide, water vapor, hydrochloric acid, methane,

* Corresponding author. Fax: +965 2537 6222.
E-mail address: a.sedaghat@ack.edu.kw (A. Sedaghat).

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Nomenclature

A	Area (m^2)
C	Species hold up (kg)
c	Black emissivity factor
C_p	Specific heat at constant pressure (J/kg K)
C_v	Specific heat at constant volume (J/kg K)
$\overline{Cp}_{solid}$	Average heat capacity of solid material (J/kg K)
D	Internal combustion chamber diameter (m)
E	Energy (J)
$\overline{GS}$	Gas-wall surface contact area (m^2)
h	Convective heat transfer coefficient ($W/m^2 K$)
H	Enthalpy (J/kg)
K	Thermal conductivity (W/m K)
k	Reaction rate coefficient
L	Internal combustion chamber length (m)
M	Holdup inside the kiln (kg)
P	Pressure of the gas (atm)
Q	Heating value (J/kg)
R	Reaction rate (kg/s)
r	gas recirculation ratio
S	Kiln slope (degree from horizontal)
T	Temperature (K)
t	Time (s)
v	Velocity (m/s)
V	Combustion chamber volume (m^3)
W	Flow rate kg/s
w	Mass fraction of species in total mass flow rate
y	Mole fraction

Greek letters

ε	Emissivity
μ	Stoichiometric coefficient for waste combustion, $KmolO_2$/kmol waste refers to the combustible fraction and the O_2 consumption refers to CO_2 formation
σ	Stefan Boltzmann constant (W/m^2k^4)
ν	angle between the surface normal and a ray between the two differential areas, rad
τ	Gas transmittance
ω	Fraction

Superscripts

air	Air phase
in	Inlet property

Subscripts

bf	Burning fraction
CH_4	Methane
dr	Destruction rate
gas	Gas phase
H_2O	Water and water vapor
i	Stream components
in	Inlet
N_2	Nitrogen
O_2	Oxygen
out	Outlet
p	Perimeter
ref	Reference state
solid	Solid phase
s	Surface
tot	Total property
vi, vj	Power coefficients
w	Wall
waste	Waste

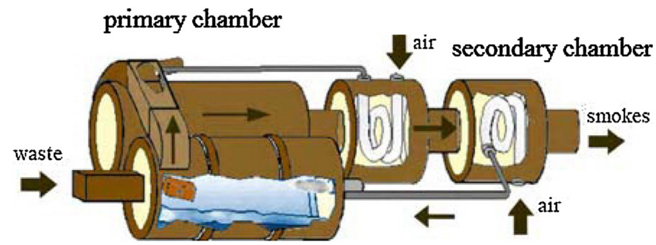

Fig. 1. Rotary kiln incinerator [2].

Table 1
Geometry and characteristics of rotary kiln [2].

Property	Rotary kiln	Post combustion chamber
Internal length (m)	4.43	3.66
Internal diameter (m)	1.5	1.7
Refractory thickness (m)	0.1	0.11
Refractory conductivity (W/m K)	1.7	1.35
Refractory heat capacity (J/kg K)	700	600
Refractory density (kg/m^3)	2550	2000
Insulating thickness (m)	0.12	0.125
Insulating conductivity (W/m K)	0.29	0.198
Insulating heat capacity (J/kg K)	500	400
Insulating density (kg/m^3)	890	475

and gas at different amount of excess air and different numbers of chlorine atoms.

- Finally, the conclusion of this study is drawn in Section 5.

2. Background research

Leuser et al. [3] have explained remediation of PCB soil contamination in an incineration process in Beardstown, Illinois. The process included prescreening of soil to remove oversize materials, incineration process, treat soil at high temperatures, slag formation in kiln and secondary combustor, and procedures for testing burn. The procedure described was in compliance with TSCA (Toxic Substance Control Act) regulation.

Rovaglio et al. [2] presented a dynamic model which is capable to capture large variations in process conditions and has practical value in process control. The model describes the behavior of a rotary kiln (primary combustion chamber with heterogeneous combustion) as well as an afterburner system (secondary combustion chamber with homogeneous combustion). A heat recovery system was also integrated to the hot section of the incineration plant. Their model has correctly predicted certain conditions comparable to some available experimental data.

Ficarella and Laforgia [4] have designed an incineration unit (kiln and afterburner) for hazardous wastes using a new methodology. Optimization has been performed within the new design methodology. An extensive theoretical and experimental analysis had been carried out on a pilot plant to test the methodology and to optimize the entire system in terms of reduction of the polluting emissions and to achieve higher combustion efficiency. In particular, the combustion chamber and the afterburner had been thoroughly investigated. A computer code was developed based on multiple chemical reactions occurring in an afterburner to evaluate the decomposition rate of dioxins in different afterburner chamber geometries. They found that dioxins emission depends on both the thermal efficiency of the combustion chamber (temperature and excess air) and the turbulent mixing (associated with CO component). For the afterburner, temperature was not the important parameter of