Journal of Analytical and Applied Pyrolysis 110 (2014) 66–78

Contents lists available at ScienceDirect

Journal of Analytical and Applied Pyrolysis

journal homepage: www.elsevier.com/locate/jaap

Mathematical modeling of waste plastic pyrolysis in conical spouted beds: Heat, mass, and momentum transport

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ARTICLE INFO

Article history:
Received 13 March 2014
Accepted 3 August 2014
Available online 26 August 2014

Keywords:
Spouted bed
Pyrolysis
Waste plastics
Streamtube model
Mathematical modeling

ABSTRACT

A mathematical model has been developed for unsteady-state operation of waste plastic pyrolysis in spouted bed reactors. Such a model is not yet available in the literature. This model predicts radial distributions of solid conversion, yields of individual gas products, solid and gas temperatures and velocity profiles inside the bed. To prevent application of a bulk of empirical equations for determining the hydrodynamic parameters, the momentum balance equations have been included in the model. The results predicted from the model have been compared with those determined experimentally by other researchers for pyrolysis of polystyrene in a spouted bed. A satisfactory agreement has been observed with a mean relative deviation of 0.8%. The model predictions for a scaled-up spouted bed demonstrates that due to the existence of an excellent gas–solid contact in spouted beds the limitations imposed by heat and mass transfer are minimized. In addition, the bed is maintained under isothermal condition. The inlet gas temperature highly affects the model's results in comparison with mass of initial plastic. The amount of inert particles used can be reduced as less as a stable spouting is preserved. A critical value exists for power intensity of heating elements to keep the isothermal conditions of spouted bed that should be carefully considered in design purposes.

1. Introduction

Spouted bed reactors (SBR) are being used as an appropriate alternative for pyrolysis of waste plastics [1–6]. So far, many experimental investigations have been carried out on characterization of pyrolysis products and the determination of kinetics and hydrodynamics parameters in SBRs. Although some authors have presented certain models for various processes implemented in spouted beds including drying [7–10], gasification [11,12], oxidation [13], and desulfurization [14,15], nevertheless, literature reviews show a lack of mathematical models for pyrolysis operation.

Tao et al. [16] presented a steady state one-dimensional model for flue gas desulfurization with multi-level humidification in a underfeed circulating spouted bed. Mendes et al. [17] have studied the process of coal gasification in a SBR operating at high temperature applying a one-dimensional model in which the mass and energy balances and the chemical reaction have been included. The gasification process in SBR was also considered by Lim et al. [11] and a mathematical formulation was presented based on the streamtube hydrodynamic model of Mathur and Lim [18]. A mathematical model was presented by Madhiyanon et al. [7] for a continuous spouted bed dryer. The model is capable of predicting moisture content, air and grain temperatures and energy consumption in the dryer. Niksiar et al. [8] presented a general model for analyzing heat and mass transfers in a drying process occurring in SBR. In this model the annulus zone in spouted bed was assumed to be a series of streamtubes according to the hydrodynamic model of Mathur and Lim [18]. The available models have been developed essentially based on a number of empirical correlations for determination of the required hydrodynamic parameters. Recently, a number of correlations for evaluation of spouted bed's hydrodynamic parameters have been presented from a comprehensive analysis [19]. However, it has been revealed that certain correlations impose large errors in determination of design parameters.

A number of computational fluid dynamic (CFD) models have been presented so far to study the hydrodynamic behavior of spouted beds [20,21]. Nevertheless, no comprehensive mathematical model has been yet developed to predict profiles of temperatures, concentrations, and velocities inside SBRs.

The models presented so far for several phenomena occurring in spouted beds are typically derived for steady-state conditions. However, the assumption of steady-state conditions may not be valid for a number of applications of spouted beds. Batch pyrolysis

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http://dx.doi.org/10.1016/j.jaap.2014.08.005
0165-2370/

Nomenclature

A_{ak}, A_f, A_s	cross-sectional area of streamtube k in annulus, of fountain core, and of spout, respectively (m^2)
C_D	drag coefficient
c_g,c_p	specific heat of gas and solid, respectively (J/kg K)
D_b, D_o, D_i	upper diameter of the stagnant bed, of the bed bottom, and of the bed inlet, respectively (m)
d_p	particle diameter (m)
d_s	diameter of spout (m)
E	activation energy (J/mol)
E, F	conductive heat transfer between adjacent streamlines given by Eqs. (21) and (22), respectively (W/m)
g	gravitational constant (m/s^2)
H, H_f	height of the stagnant bed, and of fountain, respectively (m)
h	gas–solid convective heat transfer coefficient (W/m^2 K)
k_{max}	total number of streamtubes considered in the model
L	fictional stress between adjacent streamlines given by Eq. (26) (N/m)
L_k	lower bound of streamtube k at the spout-annulus interphase
$\dot{m}_{g,i}$	mass flow rate of individual gas product i (kg/s)
$\dot{m}_{g,t}$	total mass flow rate of gas (kg/s)
Pr	Prandtl number (–)
p	pressure (Pa)
R	fictional stress between adjacent streamlines given by Eq. (25) (N/m)
R_A	rate of pyrolysis reaction (kg/kg s)
R_i	rate of formation of an individual gas product i (kg/kg s)
Re_p	particle Reynolds number (–)
r	radial coordinate (m)
r_f,r_s, r_k	radius of fountain core, and of spout, and of streamtube k (m)
Q	thermal intensity of heating elements wrapped around the bed wall (W/m^2)
T_g, T_p	gas and solid temperature, respectively (K)
$\bar{T}_{pa}$	average solid temperature at the top of bed (K)
T_0	reference temperature (K)
t	time (s)
U_k	upper bound of streamtube k at the spout-annulus interphase
U_r	radial gas velocity at the spout-annulus interface (m/s)
U'_r	radial gas velocity at the interphase between fountain core and fountain periphery (m/s)
u	interstitial gas velocity (m/s)
V_r	radial particle velocity at the spout-annulus interface (m/s)
V'_r	radial particle velocity at the interphase between fountain core and fountain periphery (m/s)
V_{sand}	volume of entire sand particles (m^3)
v, $\bar{v}_a$	interstitial solid velocity, and average value at the top of bed (m/s)
W_0	initial mass of waste plastic (kg)
W_{sand}	mass of entire sand particles (kg)
$\dot{w}_p$, $\dot{w}_{sand}$	mass flow rate of unreacted waste plastic, and inert sand particles, respectively (kg/s)
X	conversion degree of plastic material (kg/kg)
X_∞	conversion at infinite time (maximum pyrolysable fraction)
x, $\bar{x}_a$	mass fraction of waste plastic in plastic free basis, and average value at the top of bed (kg/kg of sand)
y	mass fraction of gas (kg/kg)
z	vertical coordinate (m)

Greek letters

β	fluid-particle interaction coefficient
ε	void fraction of bed (–)
ε_0	initial void fraction of bed (–)
ε_{mf}	void fraction of bed at minimum fluidization condition (–)
γ	cone angle (°)
Λ	conductive heat transfer coefficient between adjacent streamlines (W/m K)
λ_p	solid bulk viscosity (Pa s)
μ_q	bulk viscosity of phase q (Pa s)
$\tau_{q,z}$, $\tau_{q,r}$	normal stress and shear stress of phase q (N/m^2)
ΔH_r	heat of pyrolysis reaction (J/kg)

Subscripts

a	annulus
f	fountain core
mf	minimum fluidization conditions
p	particles
s	spout
$sand$	sand particles
t	waste plastic materials

of waste plastics in a SBR is an inherently unsteady-state phenomenon.

Pyrolysis of waste plastics has been carried out in SBRs and a number of kinetic models have been proposed [1,2,22–24]. However, no mathematical model is yet available in the literature to analyze theoretically the profiles of concentrations, temperatures, and velocities in the pyrolysis process in such an equipment.

The aim of the present study is to develop a comprehensive mathematical model to analyze the pyrolysis of waste plastics in batch SBRs. The kinetic expression for the pyrolysis process has been extracted from the literature. Thereby, the performance capability of a spouted bed under unsteady-state conditions has been evaluated.

2. Mathematical model

2.1. Model description

The spouted bed consists of spout, annulus, and fountain zones (Fig. 1). According to Fig. 1, the gas and particles flow co-currently from bottom to the top of the spout, while the particles in the annulus region enter the spout along the length of the latter. Pyrolysis gas flows upward, passes the spout and enters the annulus region. In the fountain, air and particles move upward co-currently. The particles, on leaving the spout, drop down to the annulus region. It is assumed that air simply flows out of the bed.

The annulus zone is modeled based on the concept of streamtube approach of Lim and Mathur [18]. In this model, the annulus is considered to consist of a series of plug-flow stream tubes. According to the literature, the solids move almost in plug flow in the upper part of the annulus and this assumption is reasonable [25]. The locus of streamlines is predicted as a model's parameter by solving the rest of model's equations.