Chemical Engineering & Processing: Process Intensification 121 (2017) 111–124

Contents lists available at ScienceDirect

Chemical Engineering & Processing: Process Intensification

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

Mathematical modeling of electrothermal regeneration of modified carbonaceous adsorbent bed in inductively heated column

K. Witkiewicz, J. Nastaj*, F. Moskal

Department of Chemical Engineering and Environmental Protection Processes, West Pomeranian University of Technology, Szczecin Al. Piastów 42, 71-065 Szczecin, Poland

A R T I C L E I N F O

Keywords:
Mathematical model
Induction heating
ETSA process
Desorption
Carbonaceous adsorbent

A B S T R A C T

A novel, two-dimensional, non-isothermal, non-adiabatic and non-equilibrium mathematical model of desorption step (regeneration) in electrothermal temperature swing adsorption (ETSA) process in cylindrical coordinates was proposed. Regeneration concerns desorption of the carbonaceous adsorbent (modified Sorbonorit 3 adsorbent bed) loaded with *n*-butanol. The unique mathematical model has been developed for the internal volumetric heat source capacity, generated in adsorbent bed by induction heating. The internal volumetric heat source capacity depends on temperature, concentration of desorbed compound in solid phase, volumetric fraction in bed of granular iron, electric current intensity, and radial coordinate.

Mathematical model of ETSA process was solved by numerical method of lines in non-dimensional, cylindrical coordinate system.

The fairly good agreement of computed and experimental results with respect to process characteristics was obtained.

1. Introduction

Volatile organic compounds (VOCs) are a significant group responsible for the about 45–50% of the total emissions to atmosphere. Various industrial chemical processes, bonding, coating, painting, lacquering, drying and cleaning with use of organic solvents, pharmaceuticals, dyes and lacquers production, extraction, impregnation and lamination of wood-like and plastics as well as engine fuels distribution are the main emission sources [1].

Waste gases are characterized by large volumetric fluxes in which VOCs concentration practically does not exceed 50 g/m^3 [2]. Adsorption methods of air purification enable removal and recovery of various VOCs such as hydrocarbons, chlorohydrocarbons, perfluorocarbons etc. with efficiency above 95% at relatively low investment costs [3–7]. The costs of adsorbent regeneration are crucial when concerning the adsorption process to be used to purify gases from VOCs. A life time of carbonaceous adsorbents is about 1000 adsorption-desorption cycles. In practice, typical adsorbent regeneration methods used to restore the adsorbent capacity make use of hot inert gas or superheated water vapor flowing through the adsorbent bed [7–9]. However, these methods are expensive, energy consuming and do not guarantee effective recovery of adsorbed components.

The novel electrothermal heating methods of the adsorbent bed include ohmic (resistive), induction or microwave treatment. As a result of electric or magnetic field energy conversion, the heat is generated directly in the adsorbent bed volume.

The cyclic ETSA process is a novel method used to remove volatile organic compounds (VOCs) from gaseous streams, especially from polluted waste gases emitted mainly by chemical and petrochemical industries.

Most commonly, the resistance [10–16] and microwave heating [17] are used. In the resistance heating the Joule's heat is generated during passing an electric current through the bed of granular adsorbent. In microwave heating intermolecular friction of dipoles (dipolar rotation phenomenon) or ions (ionic conduction phenomenon) takes place due to changing direction of electric field.

Induction heating is based on well-known physical phenomena: electromagnetic induction and then the Joule effect [18–22]. It can be applied to regeneration of carbonaceous adsorbent fixed bed in a column after the adsorption step of the ETSA process, when activated carbon is loaded with the volatile organic compounds (VOCs) [22,23] adsorbed from an air stream. Induction heating has several advantages: high capacity of internal volumetric heat source, no contact between adsorbent and heating medium, simplicity of heating system control, etc.

Full adsorption cycle of the electrothermal temperature swing

* Corresponding author.
E-mail address: jonas@zut.edu.pl (J. Nastaj).

http://dx.doi.org/10.1016/j.cep.2017.08.007
Received 3 March 2017; Received in revised form 11 July 2017; Accepted 9 August 2017
Available online 24 August 2017

Nomenclature

$a_{s_{AC}}$	Specific area of activated carbon particle (m^2/m^3)
b_0	Toth multitemperature isotherm constant (Pa^n)
bei	Imaginary part of the Bessel-Kelvin function of the first type, zero order (−)
bei'	Imaginary part of the Bessel-Kelvin function of the first type, first order (−)
ber	Real part of the Bessel-Kelvin function of the first type, zero order (−)
ber'	Real part of the Bessel-Kelvin function of the first type, first order (−)
$\boldsymbol{B}$	Vector of magnetic induction (T)
$c_{b_{AC}}$	Specific heat capacity of dry activated carbon bed (J/kg K)
$c_{b_{Fe}}$	Specific heat capacity of dry granular iron bed (J/kg K)
$c_{s_{eff}}$	Specific heat capacity of unloaded bed of AC and granular Fe mixture (J/kg K)
C_{l_A}	Molar specific heat of adsorbed component (liquid) (J/mol K)
$C_{p_{g_A}}$	Molar specific heat of adsorbed component in gas phase (J/mol K)
C_{p_g}	Molar specific heat of gas phase (J/mol K)
$C_{p_{inert}}$	Molar specific heat of inert gas (J/mol K)
D	Diffusion coefficient (m^2/s)
$\boldsymbol{D}$	Vector of electric induction (C/m^2)
D_{ic}	Inductor coil diameter (m)
D_K	Knudsen diffusion coefficient (m^2/s)
D_L	Axial mass dispersion coefficient (m^2/s)
D_M	Molecular diffusion coefficient (m^2/s)
D_R	Radial mass dispersion coefficient (m^2/s)
D_S	Surface diffusion coefficient (m^2/s)
$d_{p_{eff}}$	Effective diameter of AC and Fe mixture (m)
$d_{p_{Fe}}$	Equivalent iron particle diameter (m)
$d_{p_{AC}}$	Equivalent AC particle diameter (m)
$\boldsymbol{E}$	Vector of electric field intensity (V/m)
$\boldsymbol{E}_m$	Amplitude of electric field intensity (V/m)
f	Current frequency (Hz)
G_{inert}	Molar flux density of inert gas (mol/m^2 s)
G_{air}	Molar flux density of air (carrying gas) (mol/m^2 s)
$\boldsymbol{H}$	Magnetic field intensity (A/m)
$\boldsymbol{H_m}$	Amplitude of magnetic field intensity (A/m)
$\boldsymbol{H}_{m0}$	Magnetic field intensity (A/m)
I_{ic}	Current intensity of the inductor coil (A)
$\boldsymbol{J}$	Vector of magnetic field strength (A/m)
K_{ic}	Nagaoka coefficient of the inductor coil (−)
L	Adsorbent bed height (m)
L_{ic}	Inductor coil length (m)
m	Toth multitemperature isotherm constant (mol/kg)
m_{ads}	Mass of the adsorbed component (kg)
m_{cnd}	Mass of the condensed component (kg)
m_{rmv}	Mass of the removed component from adsorbent bed (kg)
M_A	Molar mass of adsorbed component (kg/mol)
n	Toth multitemperature isotherm constant (−)
N_{ic}	Number of turns of the inductor coil (−)
N	Number of particles (−)
P	Pressure (Pa)
q	Concentration of component in solid phase (mol/kg)
q_0	$=q_{ads}$, initial concentration of component in solid phase in desorption step (mol/kg)
q_{ads}	Final concentration of component in solid phase in adsorption step (mol/kg)
Q_V	Internal volumetric heat source capacity (W/m^3)
Q_{V_p}	Internal volumetric heat source capacity generated in a particle (W/m^3)
r	Radial coordinate (m)
r_e	Mean pore radius of adsorbent (m)
R	Bed radius (m)
R_g	Universal gas constant (J/(molK))
$R_{p_{AC}}$	AC particle radius (m)
$R_{p_{Fe}}$	Fe particle radius (m)
t	Time (s)
t_{ads}	Total duration time of adsorption step (s)
t_{des}	Total duration time of desorption step (s)
T	Temperature (K)
T_{des_0}	Inlet inert gas temperature in desorption step (K)
T_{con}	Desorbed component condensation temperature (K)
T_{reg}	Regulation temperature in adsorbent bed (K)
T_{wall}	Internal wall temperature of adsorption column (K)
V	Volume (m^3)
Y	Mole ratio of component in gas phase (mol/mol inert)
$Y_{ads_{in}}$	*n*-Butanol concentration in gas phase at column inlet during desorption step (mol/mol inert)
$Y_{ads_{out}}$	*n*-Butanol concentration in gas phase at column outlet during desorption step (mol/mol inert)
z	Axial coordinate (m)

Greek symbols

δ	Penetration depth of magnetic field in cylindrical adsorbent bed (m)
δ_p	Penetration depth of magnetic field in particle of adsorbent bed (m)
ΔH	Isosteric heat of adsorption (J/mol)
ε	Absolute permittivity of dielectric (F/m)
ε_b	Bed voidage (activated carbon or iron) (−)
ε_{eff}	Effective bed voidage (additive fraction of activated carbon and iron voids – Eq. (56), (−)
ε_p	Particle porosity (m^3/m^3)
ϕ	Volumetric fraction of granular iron in the adsorbent bed (−)
γ	Electrical conductivity (Ω^{-1} m^{-1})
γ_{AC}	AC particle electrical conductivity (Ω^{-1} m^{-1})
γ_{Fe}	Fe particle electrical conductivity (Ω^{-1} m^{-1})
η_g	Gas phase viscosity (Pa s)
η_{rmv}	Efficiency coefficient of adsorbed component removal from adsorbent bed (%)
η_{rcv}	Efficiency coefficient of adsorbed component recovery (%)
η_{cnd}	Efficiency coefficient of adsorbed component condensation (%)
λ	Effective thermal conductivity (W/(mK))
$\lambda_{b_{AC}}$	Thermal conductivity of bulk activated carbon bed (W/(mK))
$\lambda_{b_{Fe}}$	Thermal conductivity of bulk iron bed (W/(mK))
λ_{inert}	Inert gas thermal conductivity (W/(mK))
$\lambda_{L,R_{eff}}$	Effective heat dispersion coefficient in axial or radial direction (averaged value for activated carbon and iron – Eq. (55) (W/(mK))
μ	Magnetic permeability (H/m)
μ_{AC}	AC particle magnetic permeability (H/m)
μ_{Fe}	Fe particle magnetic permeability (H/m)
ν_g	Gas phase kinematic viscosity (m^2/s)
ρ_b	Adsorbent bed bulk density (kg/m^3)
$\rho_{b_{eff}}$	Adsorbent bed mixture (activated carbon and iron) bulk density (kg/m^3)
ρ_M	Gas molar density (mol/m^3)
ρ_{M_0}	Gas molar density at column inlet (mol/m^3)
ρ_p	Adsorbent particle density (kg/m^3)
ρ_g	Gas phase density (kg/m^3)
$(\Sigma \upsilon)_A$	Sum of atomic diffusion volumes of component molecule (cm^3)