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Experimental studies on electrothermal regeneration of carbonaceous adsorbent in inductively heated column

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ABSTRACT

A new electrothermal cyclic desorption process at induction heating taking place in the adsorption column filled with mixture of Sorbonorit 3 activated carbon and granular iron particles loaded with *n*-butanol is considered. The various volumetric fractions of the iron particles (equivalent diameter: $d_{p_{Fe}} = 1.7$ mm) in adsorbent bed ($\phi = 0.1$ and $\phi = 0.2$) were used in experiments to intensify internal heat sources capacity. The cyclic adsorption-desorption steps were carried out at various inductor coil current intensities, nitrogen mass flux densities and inlet temperatures. Maximum adsorbent bed regulation temperature was imposed at level of $T_{reg} = 453.15$ K to avoid activated carbon overheating. The analysis of experimental results enabled assessment of the process parameters range for which proposed modified adsorbent bed regeneration method is feasible and efficient.

1. Introduction

A civilization progress and continuous industry development cause increasing amount of toxic chemical compounds emitted to atmosphere. Among them volatile organic compounds (VOCs) constitute a significant group responsible for the about 45–50% of the total emission. The main emission sources are 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 [1]. Usually, 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 allow removal, recovery and reuse of various VOCs such as hydrocarbons, chlorohydrocarbons, perfluorocarbons etc.

Adsorption process is typically carried out in cyclic system adsorption-desorption on fixed adsorbent bed [3–6]. Adsorbent beds are mainly activated carbons in the various forms, as powders, formed granules and also activated carbon fibers. In the process adsorbed components can be removed and recovered with efficiency exceeding 95% at relatively low investment costs [7–11]. Effective adsorbent regeneration in the cyclic adsorption-desorption processes enables its multiple reuse. In the case of carbonaceous adsorbents a life time of about 1000 adsorption-desorption cycles is assessed. In practice, many adsorbent regeneration methods are used to restore adsorbent bed adsorption capacity [3,4,11]. In general the thermal methods of adsorbents regeneration are used by means of hot inert gas or superheated water vapor flow through adsorbent bed. Unfortunately, these methods are expensive, energy consuming and do not guarantee cost effective adsorbed components recovery. The novel investigations are focused on electrothermal adsorbent bed heating methods such as: ohmic, induction or microwave ones. In these methods heat is generated directly in the adsorbent bed volume as a result of electric or magnetic field energy conversion.

These various electrothermal heating methods are used in adsorption processes. The electrothermal temperature swing adsorption (ETSA) is a novel method applied to remove VOCs from gaseous streams, especially from polluted exhaust gases emitted mainly by chemical and petrochemical industries.

Induction heating utilizes electromagnetic induction phenomenon and then the Joule effect caused by eddy currents flow in material placed in alternating electromagnetic field [12,13]. The common and distinctive feature of inductive heating method applied in desorption process is low amount of the purge inert gas used to remove desorbed components. It causes a considerable increase of VOCs concentration in desorbed gas stream. Thereby it facilitates VOC's recovery by vapor condensation at relatively moderate cooling temperatures. This method of heating has

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Nomenclature

$a_{s_{AC}}$ Specific area of activated carbon particle, m^2/m^3
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, –
$d_{p_{Fe}}$ Equivalent iron particle diameter, m
$d_{p_{AC}}$ equivalent AC particle diameter, mEquivalent AC particle diameter, m
f Current frequency, Hz
G_{inert} Molar flux density of inert gas, mol/(m^2s)
G_{air} Molar flux density of air (carrying gas), mol/(m^2s)
I_{IC} Current intensity of the inductor coil, A
K_{IC} Nagaoka coefficient of the inductor coil, –
L Adsorbent bed height, m
L_{IC} Inductor coil length, m
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 Number of particles, –
N_{IC} Number of turns of the inductor coil, –
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_{Vp} Internal volumetric heat source capacity generated in a particle, W/m^3
r Radial coordinate, m
R Adsorbent bed radius, m
r_e Mean pore radius of adsorbent, m
R_p 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
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 adsorption step, mol/mol inert
$Y_{ads_{out}}$ N-butanol concentration in gas phase at column outlet during adsorption step, mol/mol inert
z Axial coordinate, m

Greek symbols
δ Penetration depth, m
ε Adsorbent bed porosity (activated carbon or iron), –
ε_p Particle porosity, m^3/m^3
ϕ Volumetric fraction of granular iron in the adsorbent bed, –
γ AC particle electrical conductivity, $\Omega^{-1}m^{-1}$
λ_b Bed heat conductivity, W/(mK)
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, %
ω Angular frequency, s^{-1}
μ Particle magnetic permeability, H/m
ξ Terms in Eq.id=6#(2), –

Subscripts
AC Value related toid=6#activated carbon
Fe Value related to granular iron

Acronyms and abbreviations
AC Sorbonorit 3 activated carbon
ETSA Electrothermal swing adsorption
Fe Granular iron
VOCs Volatile organic compounds

several advantages: high capacity of internal volumetric heat source, no contact between adsorbent and heating medium, simplicity of heating system control etc.

The inductive ETSA is a cyclic separation process and usually carried out in two adsorption columns (Fig. 1). Full adsorption cycle of the inductive ETSA process consists of the three following steps carried out in each column: adsorption, desorption by means of induction heating of loaded bed and adsorbent bed cooling. In the desorption step, energy of electric field is used to generate heat sources in a loaded adsorbent bed in order to desorb and remove VOCs. If in the column A1 VOCs adsorption process takes place, then in column A2 the electrothermal regeneration of adsorbent bed (VOCs removing from bed and recovery by vapor condensation) and successive bed cooling is carried out. Next, the processes are interchanged between columns. The duration time of electrothermal regeneration and cooling processes in column A2 should not be longer than that of adsorption process in the column A1. The cyclic ETSA processes enable multiple reuses of the adsorbents, although the slight decrease of the bed adsorption capacity is observed in the following cycles.

In the paper an attempt of internal heat source capacity intensification in desorption step of ETSA process is undertaken using mixture of granular Sorbonorit 3 activated carbon and some fraction of granular iron [14,15]. *N*-butanol is tested here as desorbed component. The efficient heat generation is going to take place in iron particles which are typical electric conductors. Moreover, the directions of heat and mass fluxes are the same – from modified adsorbent bed to the purge gas stream. However, iron fraction is not taking part in mass transfer process (adsorption and desorption of VOC component). The more iron particles will be used in unit volume of adsorbent bed, the less will be fraction of activated carbon. Therefore such amount of iron particles should be used so that the advantage of intensified desorption will be greater than disadvantage of decreased overall adsorption capacity of modified adsorbent bed. In the examined process granular iron particles are expected to generate more thermal energy in the bed volume to achieve effective Sorbonorit 3 activated carbon regeneration.

2. Experimental

2.1. Materials

Sorbonorit 3 activated carbon (Norit, Netherlands) was selected during preliminary studies [14] because of its superior ability to be