Applied Thermal Engineering 73 (2014) 929–937

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Analysis of a new methodology applied to the desorption of natural gas in activated carbon vessels

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HIGHLIGHTS

- The desorption of natural gas in activated carbon is investigated.
- A 1D model based on mass and energy for pellets and column is investigated.
- A numerical code was developed to analyze the dynamics of discharge.
- The effect of regeneration temperature and pressure drop on desorption process is investigated.

ARTICLE INFO

Article history:
Received 13 February 2014
Accepted 21 August 2014
Available online 30 August 2014

Keywords:
Adsorbed natural gas
Discharge process
Activated carbon
Finite-volume method

ABSTRACT

The presented work performs a numerical investigation of natural gas desorption process in activated carbon vessels. The numerical results show that increasing the inlet temperature of gas increases the desorption of the adsorbed material. It also observed that the desorption time is a function of the applied pressure drop. For the investigated cases of the presented work, the desorption time varied from 250 s to 600 s. It is proposed that in order to reduce the negative effects of the heat of adsorption to the process, one fraction of desorbed gas must be circulated in an external heat exchange to use the energy of exhaustion gas to increase the gas's inlet temperature. This approach avoids the use of additional devices to the system, such as external heating jackets and fins that increase the complexity of the system.

1. Introduction

Today, one of the main concerns of environmentalists and researchers is related to the gas emissions that cause the greenhouse effect in the atmosphere, especially that caused by carbon dioxide. Emissions of carbon dioxide in the atmosphere result mainly from burning fossil fuels and deforestation. Natural gas (NG) is an excellent alternative fuel for application in automotive vehicles since it is cheaper than gas and diesel and produces a cleaner combustion with less carbon dioxide and other air pollutant emissions. Without major engineering drawbacks, the actual automotive engines can be converted to using NG. However, the drawbacks associated to the storage and transportation has limited the large-scale use of NG. NG mainly consists of about 95% methane, which in turn cannot be liquefied at ambient temperature. Therefore, the storage of NG requires the use of expensive high pressure compression process (about 20 MPa) [1]. Additionally, the vases of compressed natural gas (CNG) reduce the available space in automotive vehicles, and due to weight, require the suspension to be reinforced. Therefore, in order to use safe and light tanks and to reduce the compression costs, all efforts have been addressed to reduce the storage pressure. Also, working in reduced pressure allows different geometries to be employed rather than cylindrical tubes, and thus provides a greater design flexibility. Finally, if the pressure is reduced, it is possible to use lighter material such as aluminum.

A storage system by adsorption is one viable technology choice to lower the pressure storage (3.5–4 MPa) of NG, which represents a good compromise between compression costs and storage capacity [2]. The adsorbed natural gas (ANG) is based on high-density gas confined within the adsorbent's pores that offsets the volume taken by the media's solid particles and the low density of the compressed gas that resides in the voids between the adsorbent particles [3]. Currently, microporous-activated carbons have presented the best performance in conjunction with NG vessels. However, there are two drawbacks in the ANG systems that are not

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http://dx.doi.org/10.1016/j.applthermaleng.2014.08.046
1359-4311/

found in the CNG systems. The first is related to the shape of the adsorption isotherm (type I isotherm), which avoids a linear response of the system relative to the pressure. The second problem is related to the dependence between the adsorption equilibrium and the adsorbent temperature. While the physical adsorption of a gas is an exothermic phenomenon, the gas desorption is endothermic. During the fast charge of the ANG system, in conditions in which the heat of adsorption is not removed, less methane is adsorbed into the system when the temperature increases. Alternatively, during the discharge cycle, the temperature decreases; therefore less gas is released to the corresponding discharge pressure. Ridha et al. [4] and Ridha et al. al [5] showed the harmful effects associated with the heat of adsorption in ANG vessels.

In order to minimize the effects of heat of adsorption in ANG vessels, various solutions have been proposed [3,6–8]. All of these solutions require accessories to be inserted into the tank which, reduce the space available for gas storing, increase the complexity of the project, and have serious limitations in the heat transfer process due to the low effective thermal conductivity of the activated carbon bed. The main problem of the aforementioned solutions is that all heat generated in the adsorbent bed is dissipated by conduction only.

A new tank configuration was proposed by Santos et al. [9] to analyze the charge process in ANG vessels using the constant velocity assumption in the numerical model. In this work, we neglect the assumption of constant velocity to investigate the dynamics of the desorption of natural gas in activated carbon. The effect of regeneration temperature and pressure drop applied in the gas desorption process performance is analyzed. Based on the numerical results, a new methodology for discharging natural gas in activated carbon vessels is proposed. The new vessel consists of several tubes packed with activated carbon; the new system uses forced convection between the adsorbent and the gas flow in order to increase the rate of heat transfer in the adsorbent bed.

2. Mathematical model

Fig. 1 shows the configuration investigated. In order to perform the analysis, a single column filled up with activated carbon and open on both sides is considered. The natural gas flows from one side of the column to the other. The constitutive equations are based on the mass, momentum and energy balances [10,11] and ideal gas equation. Next, we show the models along with the initial and boundary conditions for the column and the adsorbent material.

2.1. Column model

For the column model, the following assumptions are considered:

- Radial effects are neglected;
- The natural gas is constituted of pure methane;
- The sorbate behaves as ideal gas.

Under the above assumptions, the column model is constituted by the continuity equation, momentum equation, energy equation, and the perfect gas equation, respectively:

$$\frac{\partial \rho_f}{\partial t} + \frac{\partial}{\partial x}(\rho_f u) = -\frac{1-\varepsilon}{\varepsilon}\frac{\partial \overline{q}}{\partial t} \tag{1}$$

$$\frac{\partial}{\partial t}(\rho_f u) + \frac{\partial}{\partial x}(\rho_f u u) = -\frac{\partial p}{\partial x} - \frac{150\mu}{d_p^2}\frac{(1-\varepsilon)^2 u}{\varepsilon^2} - \frac{1.75\rho_f}{d_p}\frac{(1-\varepsilon)u^2}{\varepsilon} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho_f T_f) + \frac{\partial}{\partial x}(\rho_f u T_f) = \frac{\partial}{\partial x}\left(\frac{\lambda_f}{cp_f}\frac{\partial T_f}{\partial x}\right) + \frac{6h_p}{d_p}\frac{(1-\varepsilon)}{\varepsilon cp_f}\left(T_s - T_f\right) + \frac{2U_g(T_\infty - T_f)}{\varepsilon R_i cp_f} \tag{3}$$

$$\rho_f = \frac{p}{R_g T_f} \tag{4}$$

where ρ_f is the density of gas (kg/m^3), p is the pressure (Pa), T is the temperature (K), λ is the thermal conductivity (W/m K), ε is the bed porosity, R_g is the ideal gas constant (J/kg K), c_p is the specific heat at constant pressure (J/kg K), d_p is the pellet diameter (m), U_g is the overall heat transfer coefficient (W/m^2 K), R_i is the internal column radius (m), and subscript f denotes the fluid phase.

In order to study the desorption process, it is assumed that an overheated gas stream with constant temperature (T_{in}) and pressure (p_{in}) is suddenly forced into an activated carbon packed column which is initially saturated with gas at a temperature (T_0) and pressure (p_0). The outlet pressure is kept at $p_{0,}$ while the initial temperature is assumed to be equal to ambient temperature. Therefore, the bed equations are subjected to the following initial and boundary conditions:

$$p(x,t=0) = p_0; \quad T_f(x,t=0) = T_0; \quad u(x,t=0) = u_0 \tag{5}$$

$$p(x=0,t) = p_{in}; \quad T_f(x=0,t) = T_{in} \tag{6}$$

$$p(x=L,t) = p_0; \quad \frac{\partial T_f(x=L,t)}{\partial x} = 0 \tag{7}$$

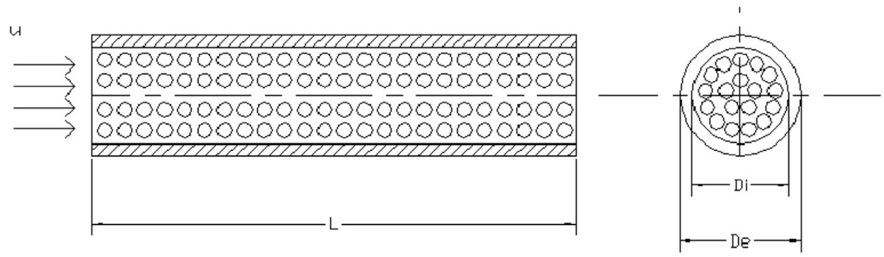

Fig. 1. Activated carbon packed column.