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Influence of exhaust gas heating and L/D ratios on the discharge efficiencies for an activated carbon natural gas storage system

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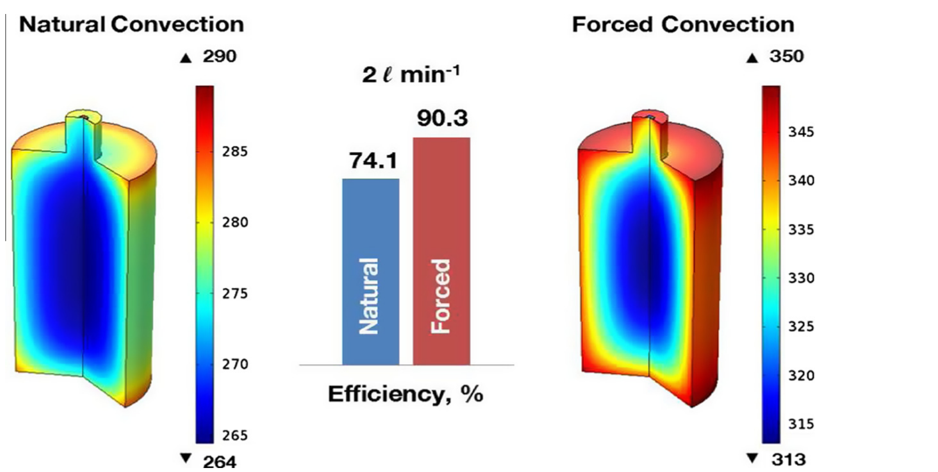
HIGHLIGHTS

- Experimental and simulation study to assess discharge efficiency of ANG system.
- Developed 2D axi-symmetric and lumped parameter model for discharge.
- Increasing L/D ratios has only a marginal increase in efficiency.
- Efficiencies increase by about 15% using exhaust gas heating and lie between 88.7% and 92.8%.

GRAPHICAL ABSTRACT



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ABSTRACT

A transient 2D axi-symmetric and lumped parameter (LP) model with constant outflow conditions have been developed to study the discharge capacity of an activated carbon bed. The predicted discharge times and variations in bed pressure and temperature are in good agreement with experimental results obtained from a 1.82 *l* adsorbed natural gas (ANG) storage system. Under ambient air conditions, a maximum temperature drop of 29.5 K and 45.5 K are predicted at the bed center for discharge rates of 1.0 $l\,\mathrm{min}^{-1}$ and 5.0 $l\,\mathrm{min}^{-1}$ respectively. The corresponding discharge efficiencies are 77% and 71.5% respectively with discharge efficiencies improving with decreasing outflow rates. Increasing the L/D ratio from 1.9 to 7.8 had only a marginal increase in the discharge efficiency. Forced convection (exhaust gas) heating had a significant effect on the discharge efficiency, leading to efficiencies as high as 92.8% at a discharge of 1.0 $l\,\mathrm{min}^{-1}$ and 88.7% at 5 $l\,\mathrm{min}^{-1}$. Our study shows that the LP model can be reliably used to obtain discharge times due to the uniform pressure distributions in the bed. Temperature predictions with the LP model were more accurate at ambient conditions and higher discharge rates, due to greater uniformity in bed temperatures. For the low thermal conductivity carbon porous beds, our study shows that exhaust gas heating can be used as an effective and convenient strategy to improve the discharge characteristics and performance of an ANG system.

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Nomenclature

A	external surface area of the cylinder (m^2)
Bi	Biot number
C_{eff}	effective capacity ($J\ kg^{-1}\ K^{-1}$)
C_{pg}	specific heat capacity of gas ($J\ kg^{-1}\ K^{-1}$)
C_{ps}	specific heat capacity of adsorbent ($J\ kg^{-1}\ K^{-1}$)
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
H	total enthalpy of system (J)
H_{in}	enthalpy input per unit mass ($J\ kg^{-1}$)
K	permeability of the bed (m^2)
m_g	total mass of gas (kg)
$\dot{m}_i$	gas inlet/outlet mass flow rate ($kg\ s^{-1}$)
$\dot{m}_{out}$	outlet mass flow rate ($kg\ s^{-1}$)
M_g	molecular weight ($kg\ mol^{-1}$)
$\mathbf{n}$	unit outward normal
P	pressure (Pa)
P_{cr}	critical pressure (Pa)
P_i	initial pressure (Pa)
P_s	saturated vapour pressure (Pa)
$\overline{P}$	average pressure (Pa)
q	amount adsorbed ($kg\ kg^{-1}$)
$\overline{q}$	average amount adsorbed ($kg\ kg^{-1}$)
Q	discharge flow rate ($l\ min^{-1}$)
Q_s	heat loss at the surface of cylinder (W)
R	universal gas constant
R_p	adsorbent particle radius (m)
t_d	discharge time (min)
T	temperature (K)
T_{cr}	critical temperature (K)
T_i	initial temperature (K)
T_{in}	inlet gas temperature (K)
T_0	reference temperature (K)
T_∞	gas temperature at outlet or exhaust gas temperature for forced convection (K)
$\overline{T}$	average temperature (K)
$\overline{T}_b$	boiling point of methane (K)
$\mathbf{u_g}$	gas velocity ($m\ s^{-1}$)
$\overline{u}_{g,out}$	average velocity of gas at the outlet ($m\ s^{-1}$)
U	internal energy (J)
V_{ads}	volume of adsorbed methane (l)
V_b	volume of adsorbent bed (l)
V_d	discharge volume (l)
V_f	final volume (l)
V_g	volume of gas in gaseous phase (l)
V_{sim}	simulated volume (l)

Greek symbols

α_e	thermal expansion of liquefied gases (K^{-1})
ΔH_a	isosteric heat of adsorption ($J\ mol^{-1}$)
ϵ_b	interparticle porosity
ϵ_p	intraparticle porosity
ϵ_t	total porosity of bed
ρ_g	density of gas ($kg\ m^{-3}$)
λ_{eff}	effective thermal conductivity ($W\ m^{-1}\ K^{-1}$)
λ_g	thermal conductivity of gas ($W\ m^{-1}\ K^{-1}$)
λ_s	thermal conductivity of solid ($W\ m^{-1}\ K^{-1}$)
μ_g	viscosity of gas (Pa s)
$\overline{\rho}_{ads}$	density of liquid methane at boiling point ($kg\ m^{-3}$)
ρ_{ads}	density of adsorbed gas ($kg\ m^{-3}$)
ρ_b	packing density ($kg\ m^{-3}$)
ρ_g	density of gas ($kg\ m^{-3}$)
ρ_s	solid bed density ($kg\ m^{-3}$)
$\eta_d^{(2)}$	discharge efficiency (%) based on depletion pressure of 0 bar
$\eta_d^{(1)}$	discharge efficiency (%) based on depletion pressure of 1 bar

1. Introduction

Natural gas is an attractive alternate fuel for vehicular use, both due to its abundant availability [1] and associated cleaner burning when compared with gasoline. Current technologies use compressed natural gas (CNG) where natural gas is stored at pressures of about 20–24 MPa. CNG is widely used in many cities in Asia, Europe and South America primarily for public transportation vehicles. A CNG based technology involves multistage compression and associated power and safety factors. A promising alternative to CNG is adsorbed natural gas (ANG) technology. In the ANG system, natural gas is stored in an adsorbed state within the microporous adsorbents at a moderate pressure range of 3.5 MPa, which is the line pressure of a natural gas distribution system.

Performance of an ANG system depends on the type of adsorbent and its charging and discharging characteristics [2]. A viable ANG based system hinges on identifying a suitable commercially feasible adsorbent that can meet the United States Department of Energy (DOE) methane storage targets of 180 V/V at STP conditions. Activated carbon based materials have shown to have delivery capacities ranging from 100 V/V on Maxsorb activated carbon [3], 150 V/V on activated carbon fiber [4] to 146 V/V on carbon monoliths [5]. Delivery capacities are based on the volume of gas discharged up to a depletion bed pressure of 0.1 MPa. Since significant bed cooling can occur during desorption, delivery capacities are usually lower than the adsorption capacities. In addition to carbon based adsorbents, metal organic frameworks (MOFs) have also emerged as novel contenders for natural gas storage [6]. In order to design a robust ANG system, it is essential to effectively manage heat effects associated with the charging and discharging process. These temperature changes can range from 40 to 80 K depending on the adsorption capacity of a given material, lowering the charge and discharge capacities. Since heat distribution in adsorption beds is inherently conduction limited, many methods have been attempted to alleviate this problem. These include, changing the flow direction from axial to radial [7,8], use of phase change materials such as salt hydrates and implementing conventional fins and heating jackets for enhancing heat transfer [3,9–11].

The dynamic discharge performance of the ANG system has been studied using simulations [7,11–14] and experiments [7–9,15–19]. Although a continuous discharge flow rate in the ANG system is critical for the success of an onboard application, few studies have been devoted to evaluate the performance with constant outflow conditions [7,17,19,18]. With a few exceptions, Rahman et al. [11] Mota et al. [10] modelling studies reported in the literature, are primarily concerned with 1D models to predict the thermal behaviour in activated carbon beds during constant volumetric outflow conditions [7,13].

In this manuscript we present a combined experimental and modelling study of the discharge characteristics of carbon based adsorbents in a 1.82 l cylinder. We have used a 2D axi-symmetric model as well as a lumped parameter (LP) model to predict the