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Thermal battery for portable climate control

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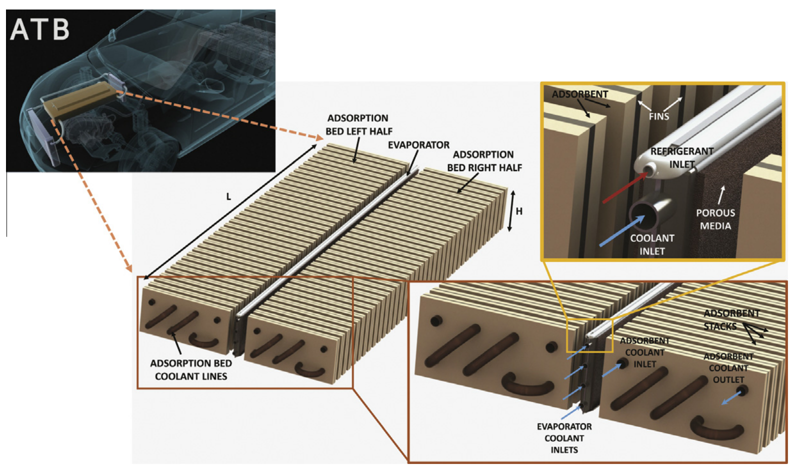
HIGHLIGHTS

- ATB is adsorptive thermal battery delivering both heating and cooling via storage.
- The novel design promotes transport and maximizes ATB performance.
- A general theoretical framework is developed to analyze ATB performance.
- NaX–water is used as the adsorbent–refrigerant pair as a specific case study.
- The effect of key geometric parameters and operating conditions are presented.

GRAPHICAL ABSTRACT



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ABSTRACT

Current technologies that provide climate control in the transportation sector are quite inefficient. In gasoline-powered vehicles, the use of air-conditioning is known to result in higher emissions of greenhouse gases and pollutants apart from decreasing the gas-mileage. On the other hand, for electric vehicles (EVs), a drain in the onboard electric battery due to the operation of heating and cooling system results in a substantial decrease in the driving range. As an alternative to the conventional climate control system, we are developing an adsorption-based thermal battery (ATB), which is capable of storing thermal energy, and delivering both heating and cooling on demand, while requiring minimal electric power supply. Analogous to an electrical battery, the ATB can be charged for reuse. Furthermore, it promises to be compact, lightweight, and deliver high performance, which is desirable for mobile applications. In this study, we describe the design and operation of the ATB-based climate control system. We present a general theoretical framework to determine the maximum achievable heating and cooling performance using the ATB. The framework is then applied to study the feasibility of ATB integration in EVs, wherein we analyze the use of NaX zeolite–water as the adsorbent–refrigerant pair. In order to deliver the necessary heating and cooling performance, exceeding 2.5 kW h thermal capacity for EVs, the analysis determines the optimal design and operating conditions. While the use of the ATB in EVs can potentially enhance its driving range, it can also be used for climate control in conventional gasoline vehicles, as well as residential and commercial buildings as a more efficient and environmentally-friendly alternative.

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Nomenclature

c_{ad}	specific heat of the adsorbent (J/kg K)
c_c	specific heat of the coolant (J/kg K)
c_l	specific heat of the adsorbed phase (J/kg K)
c_m	specific heat of metal in the ATB (J/kg K)
c_p	specific heat (J/kg K)
$c_{p,v}$	specific heat of the vapor phase (J/kg K)
$\dot{C}'''$	volumetric rate of vapor adsorption (mol/m^3 s)
C_b	vapor concentration at the boundary of the stack (mol/m^3)
C_i	initial vapor concentration in the stack (mol/m^3)
C_{eq}	equilibrium concentration of adsorbed phase (mol/m^3)
C_μ	concentration of adsorbed phase (mol/m^3)
$\langle C_\mu \rangle$	spatially averaged concentration of adsorbed phase (mol/m^3)
$C_{\mu b}$	boundary concentration of adsorbed phase (mol/m^3)
d_c	diameter of the coolant pipes (m)
D_μ	intracrystalline vapor diffusivity (m^2/s)
D_v	intercrystalline vapor diffusivity (m^2/s)
E_o	characteristic adsorption energy (J/kg)
e	coolant pipe roughness parameter (m)
f	friction factor for the coolant flow
h_{ad}	enthalpy of adsorption (J/kg)
h_v	enthalpy of vapor phase (J/kg)
H	overall height of the ATB (m)
k	average thermal conductivity of the adsorbent layer (W/m K)
k_c	thermal conductivity of the coolant (W/m K)
$k_\perp$	average out-of-plane thermal conductivity of the stack (W/m K)
$k_\parallel$	average in-plane thermal conductivity of the stack (W/m K)
K	average intercrystalline vapor permeability (m/s)
L	overall length of the ATB (m)
m_{ad}	total dry mass of the adsorbent in the ATB (kg)
m_m	total mass of metal in the ATB (kg)
M	molecular weight of the refrigerant (kg/mol)
N	total number of stacks in each half of the adsorption bed
N_p	number of coolant tubes in one-half of the adsorption bed
p	pressure (Pa)
p_{evap}	operational pressure of the evaporator (Pa)
p_{cond}	operational pressure of the condenser (Pa)
P_p	coolant flow pumping power (W)
p_{sat}	saturation vapor pressure (Pa)
Q	energy exchanged in the form of heat (J)
$\dot{Q}'''$	volumetric heat generation rate (J/m^3)
Q_{ab}	heat supplied to the ATB during process *a*–*b* (J)
Q_{bc}	heat supplied to the ATB during process *b*–*c* (J)
Q_{cd}	heat dissipated by the ATB during process *c*–*d* (J)
Q_{da}	heat dissipated by the ATB during process *d*–*a* (J)
r	radius (m)
r_c	radius of the adsorbent crystal (m)
$\hat{R}$	universal gas constant (J/mol K)
R_c	radius of the coolant lines (m)
Re_c	coolant flow Reynolds number
RP	relative pressure
t	time (s)
t_o	total duration of ATB operation (s)
T	temperature (K)
T_a	temperature at state point '*a*' in the adsorption cycle (K)
T_b	temperature at state point '*b*' in the adsorption cycle (K)
T_c	temperature at state point '*c*' in the adsorption cycle (K)
T_d	temperature at state point '*d*' in the adsorption cycle (K)
T_i	initial temperature (K)
u_v	Darcy velocity for vapor permeation (m/s)
V	specific volume of refrigerant in the adsorbent (m^3/kg)
V_{ad}	total volume of the adsorption bed in the ATB (m^3)
$\dot{V}_c$	volumetric flow rate of the coolant (m^3/s)
V_o	total micropore volume of the adsorbent (m^3/kg)
w_{ad}	total width of the adsorption stack (m)
w_{ev}	total width of the evaporator (m)
w_v	evaporator to adsorption bed spacing (m)
Z_{cond}	thermal impedance due to conduction (K/W)
Z_{conv}	thermal impedance due to convection (K/W)
Z_{cool}	thermal impedance due to flow capacitance (K/W)

Greek symbols

β	structural constant in the D–R equation
δ_{ad}	thickness of a single adsorption layer (m)
δ_c	wall thickness of the coolant lines (m)
δ_m	thickness of the metal substrate (m)
δ_v	interstack spacing (m)
ε	porosity of the adsorption bed
μ_v	dynamic viscosity of the vapor phase (kg/m s)
ω	vapor adsorbed per unit mass of adsorbent (kg/kg)
ω_{ab}	vapor uptake at the end of adsorption (kg/kg)
ω_{cd}	vapor uptake at the end of desorption (kg/kg)
ω_{net}	net vapor uptake, $(\omega_{ab} - \omega_{cd})$ (kg/kg)
ρ	density (kg/m^3)
ρ_{ad}	density of dry adsorbent crystal (kg/m^3)
ρ_c	density of the coolant (kg/m^3)
ρ_l	density of the adsorbed phase (kg/m^3)

1. Introduction

Petroleum consumption in the transportation sector poses several global problems due to high costs, oil security [1,2], emission of greenhouse gases (GHGs) and pollutants [3]. In contrast, biofuels and energy-efficient hybrid electric vehicles (HEVs) or battery powered electric vehicles (BPEVs or EVs) are environmentally friendly and reduce the dependence on oil [4–6]. However, for both gasoline and electrically-driven vehicles, the use of the onboard heating and cooling system gives rise to additional challenges. The power required to operate the air-conditioning system can be significant, which in some cases is greater than the engine power required to move a mid-sized vehicle [7]. Hence, the use of air-conditioning reduces the driving range of gasoline-vehicles and results in higher production of GHGs and pollutants [7–10]. In EVs, the use of a vapor compression cycle (VCC) for cooling and positive temperature coefficient (PTC) heaters for heating results in a significant drain in the electric battery. Consequently, the already limited driving range of EVs is exacerbated by the use of climate control [10], resulting in a 10–65% drop in the driving range [11–13]. Given the importance and widespread use of climate control in the transportation sector, an efficient, mobile heating and cooling strategy is desirable for both electric and gasoline-powered vehicles to improve gas-mileage, driving range and reduce vehicular emissions.

Numerous strategies have been explored to improve the performance of air conditioning systems in vehicles, which include variations in the design of system components and operating conditions, along with the use of alternative refrigerants [14–18]. However, these strategies rely on the availability of significant