



Analytical modeling of oscillatory heat transfer in coated sorption beds

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ABSTRACT

A novel analytical model that considers the thermal contact resistance (TCR) at the interface between the sorbent layer and heat exchanger (HEX) is developed to investigate the oscillatory heat transfer and performance of coated sorption beds. The governing energy equation is solved using an orthogonal expansion technique and closed-form relationships are obtained to calculate the temperature distribution inside the sorbent coating and HEX. In addition, a new gravimetric large pressure jump (GLAP) test bed is designed to measure the uptake of sorption material. Novel graphite coated sorption beds were prepared and tested in the GLAP test bed. The model was successfully validated with the measurements performed in the GLAP test bed. It is found that specific cooling power (SCP) of a sorption cooling system (SCS) enhances by increasing the sorbent thermal diffusivity and decreasing the TCR. For example, SCP of the sorption cooling system (SCS) can be enhanced from 90 to 900 (W/kg) by increasing the sorbent thermal diffusivity from 2.5×10^{-7} to 5.25×10^{-6} (m^2/s) and decreasing the TCR from 4 to 0.3 (K/W). Moreover, the results show that SCP increases by reducing the HEX to sorbent thickness ratio (HSTR). Therefore, the proposed graphite coated sorption beds with high thermal diffusivity and low thickness are suitable for sorption cooling applications.

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1. Introduction

Conventional vapor compression refrigeration systems consume approximately 15% of global electrical energy and have a significant carbon footprint [1]. Sorption cooling systems (SCS), with working pairs such as water and silica gel or CaCl_2 -silica gel, can be driven with low-grade heat, i.e. temperature sources below 100°C , which is used to regenerate the sorbent material. However, commercialization of SCS faces fundamental challenges, including: (i) low specific cooling power (SCP), due to poor heat transfer between sorber bed heat exchanger (HEX) [2–4] and the loose grain or coated sorbent, which ultimately leads to large sizes for SCS; and (ii) low coefficient of performance (COP). Granular packed sorbent bed design offers the advantage of higher mass transfer rates and lower cost of manufacturing; nonetheless, heat transfer rate in packed beds are inherently poor due to the point contacts between HEX and grains as well as to the low thermal diffusivity of the sorbent material [5]. Coated sorbent beds can improve heat transfer rate, as there is a higher conductance between the heat exchanger surface and the sorbent material. However, for thin

coatings (0.1–5 mm), the relative thermal inertia of the HEX metal mass is considerable, which deteriorates the sorption efficiency and SCP. The importance of HEX thermal inertia results from the oscillatory heat transfer inside the sorber beds. Sorber beds need to be cooled down/heated up during sorption/desorption phases because of their exothermic/endothermic nature, and these oscillatory cool down/heat up processes are performed with the heat transfer fluid flowing through the sorber bed HEX. The oscillatory thermal behavior of SCS makes the thermal diffusivity of the sorbent coating and HEX crucially important in determining its performance. Moreover, the thermal contact resistance between the sorbent (for both coated layer and particles) and the HEX surface is key and can be up to 26% of the bulk thermal resistance inside a sorber bed [6,7]. Thus, the heat transfer characteristics of sorber beds have a tremendous impact on the overall performance, SCP and COP of SCS and should be thoroughly investigated.

Mathematical modeling is a primary tool for design and optimization of sorption cooling systems that if used properly in conjunction with experimental studies, can reduce the cost and save time. The simplest approach to study the sorber beds is thermodynamic modeling. These models are fairly simple and cost-effective; however, they can only predict the upper performance limits of a SCS [8–12].

Another method to investigate the sorption beds is to adopt a lumped model, which is based on the assumptions of a uniform

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Nomenclature

A	heat transfer area, m ²
c	specific heat capacity, J/kg K
Fo	Fourier number
g _i	dimensionless heat generation
H	enthalpy, J/kg
Ja	Jacob number
k	thermal conductivity, W/m K
p	pressure, Pa
p ₀	saturation pressure, Pa
Q	cooling energy, J
R _c	dimensionless thermal contact resistance
T	temperature, K
t	time, s
X	eigenfunction
x	coordinate

Greek symbols

α	thermal diffusivity, m ² /s
β	eigenvalue
Γ	gamma function
η	dimensionless coordinate
κ	dimensionless thermal conductivity ratio
μ	dimensionless thermal diffusivity ratio

θ	dimensionless temperature
ρ	density, kg/m ³
τ	cycle time, s
Ω	dimensionless angular frequency of the sorption cycles
ω	sorbate uptake, g/g dry sorbent

Subscripts

0	initial condition
evap	evaporator/evaporative
sorb	sorbent
sorp	sorption

Abbreviations

COP	coefficient of performance
HEX	heat exchanger
HSTR	HEX to sorbent thickness ratio
GLAP	gravimetric large pressure jump
PVP	polyvinylpyrrolidone
SCP	specific cooling power
SCS	sorption cooling system
TCR	thermal contact resistance
TGA	thermogravimetric Analysis

sorbent temperature, uniform sorption of the refrigerant and thermodynamic equilibrium between the solid and gaseous phases. In such models, inter-particle mass transfer and heat transfer resistances are neglected, while the time derivative terms of temperature and sorbate uptake are considered. Energy balance, mass balance and sorption equilibrium equations are solved to acquire the temperature, pressure and sorbate uptake [13–18].

Finally, heat and mass transfer models take into account the variation of sorbent temperature and sorbate uptake with time and space by including convection and diffusion terms in the governing equations. These models solve four governing equations simultaneously: mass conservation, energy balance, momentum equation, and sorption equilibrium. The complexity and nonlinearity of such coupled partial differential equations exclude the possibility of having an analytical solution. Consequently, numerical methods such as finite difference [19–24], finite volume [25–30] and finite element methods [31] are the only feasible approach, but they require high computational time.

In the present model, the temperature and uptake in sorption bed vary with time and space. The governing equations are solved using an orthogonal expansion technique, which is an analytical approach and can generate closed-form relationships [32]. In addition, this model takes into consideration the TCR between sorbent and HEX while the majority of available studies have neglected it. The present analytical model can accurately predict the oscillatory temperature distribution, heat transfer rate and the performance of coated sorption beds considering the TCR at the sorbent-HEX interface.

2. Governing equations

The solution domain consisting of sorbent coating and HEX is shown schematically in Fig. 1. Initially, the sorbent domain is at temperature $T_{1,0}$ and the HEX is at $T_{2,0}$. Continuity of heat flux as well as temperature jump/drop induced by TCR are considered at the interface between the sorbent coating and HEX. The following is the list of assumptions used in the development of the present model:

- The thickness of sorbent and HEX is uniform and sufficiently small compared to the other dimensions; thus, the energy equation can be assumed one-dimensional;
- The outer surface of the sorbent is assumed adiabatic. The convective heat transfer is negligible due to very low operating pressure (1–5 kPa) and the radiative heat transfer is negligible due to low temperature difference between the sorbent and its surrounding (10–20 K);
- Thermophysical properties of the sorbent and HEX are assumed constant;
- Convective effects of the sorbate inside the sorbent coating are negligible.

As such, the energy equation for the sorption layer and HEX can be written as follows.

$$\alpha_i \frac{\partial^2 T_i(x, t)}{\partial x^2} + \frac{\alpha_i}{k_i} G_i(t) = \frac{\partial T_i(x, t)}{\partial t}, \quad x_{i-1} \leq x \leq x_i, t > 0 \quad (1)$$

$$i = 1, 2$$

$$G_i(t) = \begin{cases} \rho_{sorb} H_{sorp} \frac{dw}{dt}, & i = 1 \\ 0, & i = 2 \end{cases} \quad (2)$$

where $i=1$ and $i=2$ represent the sorbent and HEX domains, respectively. The boundary conditions are

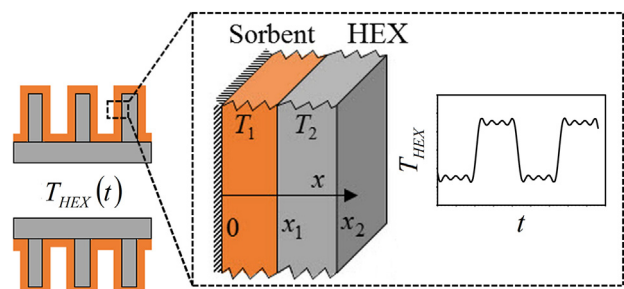


Fig. 1. Schematic diagram of the solution domain consisting of sorbent coating and HEX.

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