Applied Energy 232 (2018) 504–516

Contents lists available at ScienceDirect

Applied Energy

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

Optimum fin spacing of finned tube adsorber bed heat exchangers in an exhaust gas-driven adsorption cooling system

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HIGHLIGHTS

- Adsorption cooling system driven by the exhaust gas for A/C application is modeled.
- Optimum fin spacing of longitudinal and annular finned tube adsorber beds is determined.
- Heat exchangers with annular fins provide higher cooling power than longitudinal fins.
- Adsorption cooling system can decrease fuel consumption and greenhouse emissions.
- Heat and mass transport in porous beds of adsorbent particles is investigated.

ARTICLE INFO

Keywords:
Adsorption cooling system
Waste heat recovery
Optimum fin spacing
Fuel saving
Heat and mass transport
Porous media

ABSTRACT

Adsorption cooling systems (ACS) are considered as potential alternatives to traditional vapor compression air conditioning systems in heavy-duty vehicles. In ACS, adsorber bed heat exchangers (ABHEx) replace compressors and their appropriate design directly impacts the ACS performance. During operation, ABHEx undergo a large temperature swing to derive a refrigerant in ACS and their response time affects the dynamic behavior of ACS. In this study, a detailed three dimensional non-equilibrium model is developed to study the effects of heat and mass transfer in annular and longitudinal finned tube adsorber beds filled with zeolite-13x particles. The effects of fin height and spacing are studied on the system operating parameters to identify an optimum fin geometry. The simulation results show that a decrease in fin spacing leads to a decrease in the coefficient of performance (COP) and an increase in the specific cooling power (SCP), and no optimum value is observed for them in a specific fin spacing. However, variations of the total cooling power (TCP) maximize at a certain fin spacing. For longitudinal finned tube ABHEx, the optimum averaged fin spacing shifts from 5.4 to 6.8 mm for the adsorber beds with 10, 15, and 20 mm fin heights, while the optimum fin spacing of annular finned tube ABHEx changes from 5.0 to 6.4 mm. Furthermore, the results show that under similar dimensions and operating conditions, an ACS with annular finned tube ABHEx provides a 10% higher total cooling power than that with a longitudinal finned tube ABHEx at the optimum fin spacing. Using the ACS with optimized ABHEx in a truck would annually save about 370 L of fuel consumption and decreases greenhouse emissions by up to 738 kg CO_{2e}.

1. Introduction

Conventional vapor compression cooling systems (VCCS) in vehicles add an additional load on engines leading to an increase in fuel consumption and greenhouse gas emissions [1]. Furthermore, synthetic refrigerants, such as Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs) used in VCCS with an annual leak rate of up to 20%, accelerate the global warming and the depletion of the ozone layer [2]. Therefore, sustainable alternatives such as adsorption cooling systems (ACS) have attracted attentions. ACS are thermally-driven systems and operate with a portion of vehicles' waste heat to generate cooling power [3].

In ACS, environmentally friendly refrigerants (adsorbate), such as water, are intermittently desorbed and adsorbed by adsorber beds filled with solid adsorbent materials, such as zeolite and silica gel. Most of these adsorbent materials are non-toxic, non-corrosive and inexpensive

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https://doi.org/10.1016/j.apenergy.2018.10.002
Received 5 July 2018; Received in revised form 17 September 2018; Accepted 2 October 2018

Nomenclature

ABHEx	adsorber bed heat exchanger
C_p	specific heat in constant pressure, J/(kg K)
CH	chamber height, m
CL	chamber length, m
CW	chamber width, m
COP	coefficient of performance
EMCP	equivalent mechanical compressor power, kW
EFC	engine fuel consumption, g/kWh
FH	fin height, m
FN	fin number
FS	fin spacing, m
FSPH	fuel saving per hour of driving, L/h
h	convective heat transfer coefficient, W/(m^2 K)
HTF	heat transfer fluid
k	thermal conductivity, W/(m K)
K_d	bed permeability, m^2
L_v	latent heat of vaporization, J/kg
m	mass, kg
$\dot{m}_g$	mass flow rate, kg/s
Nu	Nusselt number, –
P	pressure, Pa
Pr	Prandtl number, –
Q	heat, J
R_g	gas constant, J/(kg K)
R_u	universal gas constant, J/(mol K)
SCP	specific cooling power
T	temperature, K or °C
TCP	total cooling power
$\vec{u}$	velocity vector, m/s
∀	volume, m^3
VSCP	volumetric specific cooling power
w	average adsorbed amount, $kg_{adsorbate}/kg_{adsorbent}$
w_{eq}	adsorbed phase in equilibrium, $kg_{adsorbate}/kg_{adsorbent}$

Greek symbols

μ	viscosity, (N s)/m^2
ρ	density, kg/m^3
η_c	compressor efficiency

Subscripts

avg	average
b	adsorber bed
cham	chamber
f	fluid
fin	fin
g	gaseous phase
p	particle
t	tube

[4]. In addition to these benefits, ACS operate quietly, and have no vibration and moving parts except valves [5].

The ability of ACS to work with waste thermal energy and the large amount of waste heat available in diesel engines make ACS a suitable choice for the air conditioning system of heavy-duty vehicles. To this end, trucks are the most applicable candidate among other heavy-duty vehicles to use ACS because of long travel distances, space constraints in vehicles, and the cabin cooling demand. Approximately 40% of the fuel energy in a diesel engine is dissipated to the ambient in the form of high temperature exhaust gas at 150–450 °C (tailpipe temperature) [6,7]. In modern diesel engines of heavy-duty trucks, the exhaust gas leaving cylinders can be at temperatures as high as 400–700 °C depending on the engine operating conditions [8].

Despite these advantages, ACS have a lower coefficient of performance (COP) and specific cooling power (SCP) than VCCS. These limitations cause the commercialization of ACS facing more challenges for use in vehicle air conditioning applications. Therefore, recent researches have been focused on increasing the COP and SCP of ACS by improving the characteristics of adsorbate-adsorbent pairs, developing advanced cycles, and optimizing adsorber bed heat exchangers (ABHEx) [9].

Sharafian and Bahrami [10] reviewed several ABHExs used for ACS to find the proper adsorber bed design for vehicle air conditioning application and categorized them into nine different types. They concluded that among the existing ABHExs, finned tube adsorber beds are more suitable according to their higher SCP and COP, and lower adsorber bed to adsorbent mass ratio. However, most of the available off-the-shelf finned tube heat exchangers are not specifically manufactured for ACS applications. Therefore, geometrical characteristics of these heat exchangers should be specifically optimized and sized to get its best performance in an ACS. In this regard, some experimental and numerical studies have been carried out.

Li et al. [11] used a two dimensional quasi-equilibrium model to study the heat and mass transfer of an annular finned tube silica gel module in an attempt to identify the optimum fin pitch and height. Without considering the effect of cycle time, they concluded that the optimum fin spacing occurred when the amount of refrigerant uptake by adsorbent was maximized between consecutive adsorption and desorption processes. This finding was only valid for maximizing the COP but not the SCP.

Niazmand and Dabzadeh [12] numerically investigated the effects of fin parameters and particle diameter on the cycle time, SCP and COP of a two dimensional silica gel/water ACS. Their results showed that the COP was almost constant for the particle diameters ranging from 0.1 to 0.8 mm, whereas the SCP was maximized at the optimum particle diameter of 0.2 mm. The effects of adsorber bed geometrical specifications on the performance of a silica gel-water chiller were examined by three dimensional models for both annular and square finned tube ABHExs [13]. It was shown that the decrease in fin spacing continuously led to an increase in the SCP and there was no optimum value for the fin spacing.

Hong et al. [14] investigated the effect of ten geometrical and operational parameters of a finned tube ACS by using a two dimensional axisymmetric transient model. They found that fin thickness and fin pitch are the most effective parameters on the COP of the system; however, any optimum value for the fin pitch was not presented.

Sharafian et al. [15] experimentally investigated the effects of fin spacing on the temperature distribution of two finned tube adsorber beds with different fin spacing. By comparing the adsorber bed to adsorbent mass ratio and temperature differences between the fins vs. fin spacing, they concluded that an optimum fin spacing of 6 mm is the best suited design for the finned tube adsorber filled with 2–4 mm silica gel particles. It is evident that finding the optimum geometrical characteristics of an ABHEx by using few custom-built adsorber beds is not cost-effective and efficient.

Caglar [16] simulated an adsorber bed with bare pipes and finned tubes with different fin configurations to study the effect of fin design parameters on the heat transfer enhancement. However, the impacts of these parameters on the SCP and COP of ACS were not reported. Rogala [17] studied the effect of fin height and pitch of a flat-tube ABHEx on the performance of a two-bed adsorption chiller using a lumped body model. They showed that optimized fin configurations could increase the SCP of the system by up to 6.3%. Verde et al. [5] developed an analytical model to investigate the effect of geometrical parameters of a