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Effects of adsorbent mass and number of adsorber beds on the performance of a waste heat-driven adsorption cooling system for vehicle air conditioning applications

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ABSTRACT

Waste heat-driven adsorption cooling systems (ACS) are potential replacements for vapor compression refrigeration cycles in vehicle air conditioning applications. However, the bulkiness and heavy weight of ACS are major challenges facing commercialization of these environmentally friendly systems. This study examines the effects of adsorbent mass and the number of adsorber beds on the performance of a FAM-Z02/water ACS under different operating conditions. The experimental results show that reducing the mass of FAM-Z02 from 1.9 to 0.5 kg in a one-adsorber bed ACS increases the SCP by 82% from 65.8 to 119.4 W/kg at cycle time of 20 min. However, the COP reduces by 37% because of the increase in the adsorber bed to adsorbent mass ratio. The results also show that the thermal mass of the evaporator limits the performance of the ACS, especially under short cycle times (8–20 min). A second adsorber bed is added to the one-adsorbed bed ACS test bed to generate continuous cooling in the evaporator. Comparing the performance of one- and two-adsorber bed ACS packed with 0.5 kg of FAM-Z02 particles and cycle time of 20 min shows that the SCP and COP of the two-adsorber bed ACS increase by 28% and 47%, respectively.

1. Introduction

Air conditioning and refrigeration (A/C-R) systems are responsible for using about 30% of the total worldwide energy produced [1]. In the automotive sector, A/C systems of light-duty vehicles consume about 40 billion liters of fuel per year in the U.S. alone [2]. A compressor of a vapor compression refrigeration cycle (VCRC) installed in a typical medium size sedan consumes up to 5–6 kW of the power generated by an internal combustion engine (ICE) to produce the required cooling. This power is sufficient for a 1200-kg sedan to cruise at 56 km/h [2]. Furthermore, about 70% of the total fuel energy released in an ICE is dissipated as a waste heat through the engine coolant and the exhaust gas [3]. Waste heat-driven adsorption cooling systems (ACS) are potential replacements for VCRCs that can significantly reduce fuel consumption and the environmental impacts of A/C systems where low-grade thermal energy is available.

A waste heat-driven ACS uses an adsorbate, such as water or methanol, which is adsorbed and desorbed from the surface of a porous adsorbent, such as zeolite, silica gel, or activated carbon. Most of these materials are non-toxic, non-corrosive, and inexpensive [4], making ACS a safe and environmentally friendly technology. An ACS operates more quietly than a VCRC and is easier to maintain because its only moving parts are valves [5]. However, current ACS have not been commercialized for light-duty vehicles due to their bulkiness and heavy weight. The main challenges facing this technology are low specific cooling power (SCP = cooling energy/(adsorbent mass × cycle time)) and coefficient of performance (COP = cooling energy/input energy) that originate from the low thermal conductivity of adsorbent particles (~0.1–0.4 W/m.K) [6–9] and the low mass diffusivity of adsorbent-adsorbate pairs (~10^{-8}–10^{-14} m^2/s) [7,10].

To overcome these obstacles, different composite adsorbent materials with high thermal conductivity and high adsorbate

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uptake capacity have been developed such as the ones reported in Refs. [11,12]. Besides using a proper adsorbent material, the designs of the adsorber beds, condenser, and evaporator (the main components of an ACS) can significantly affect the SCP and COP of the system. Sharafian and Bahrami [13] conducted a comprehensive literature review on the effects of nine different adsorber bed designs on the performance of an ACS designed for vehicle A/C applications. They identified the SCP, adsorber bed to adsorbent mass ratio (AAMR), and COP as the most influential parameters for evaluating the performance of an ACS. The COP was found to have a lower importance than the SCP and AAMR because the supplied waste heat for regeneration of the adsorber beds was abundant in a vehicle [13]. However, an ACS with a higher COP was preferred. The AAMR represents the dead to active mass ratio and should be minimized for vehicle A/C applications. Comparing more than 66 experiments with different adsorber bed designs reported in the literature showed that finned tube adsorber beds provided the best performance in comparison with other types of adsorber bed designs [13]. Table 1 provides further details on the performance of waste heat-driven ACS with different finned tube adsorber beds and working pairs.

Of the studies cited in Table 1, those with finned tube adsorber beds packed or coated with composite salts in porous matrixes, such as expanded graphite + NaBr [49] and $LiNO_3$-Silica KSK [38–40], and those packed with silicoaluminophosphate AQSOA FAM-Z02 [46] and Sapo-34 [54,55] had the highest SCP values. In a conceptual discussion on the optimal adsorbent for ACS applications, Aristov [12] highlighted the potential improvements in an ACS performance from using composite salts in porous matrixes, but leakage of salt solutions from the host matrixes during adsorption might cause corrosion of metal parts in an adsorber bed and, consequently, emission of non-condensable gases. Also, Okunev and Aristov [57] investigated the importance of adsorbent isobar shape on the SCP of an ACS. Their analysis indicated that with proper selection of an adsorbent material with respect to the operating conditions, the SCP could improve by a factor of 1.5 while other effective parameters, such as the adsorbent particle size, remained unchanged.

Ferroaluminophosphate (AQSOA FAM-Z01), silicoaluminophosphate (AQSOA FAM-Z02), and aluminophosphate (AQSOA FAM-Z05) are synthetic zeolite-based materials with high durability (60,000–200,000 cycles) developed for A/C and dehumidification applications by Mitsubishi Chemical Ltd [58]. These adsorbents have an “S” shaped adsorption isotherm, as shown in Refs. [59–61], which provides quick water adsorption and desorption within a narrow pressure range. Comparing the adsorption isotherms of FAM-Z01, FAM-Z02, and FAM-Z05 indicates that FAM-Z02 provides higher water vapor uptake capacity [59–62] and a broader desorption temperature (75–95 °C). For example, equilibrium water uptake differences of FAM-Z01 and FAM-Z02 at adsorption temperature of 30 °C and water vapor saturation temperature of 15 °C, and desorption temperature of 90 °C and water vapor saturation temperature of 30 °C are 0.185 and 0.254 $kg/kg_{dry\ adsorbent}$, respectively [63–66]. This shows that FAM-Z02 has 37% higher equilibrium water uptake than FAM-Z01 between adsorption and desorption. Therefore, in this study, FAM-Z02 adsorbent is used to pack the adsorber beds. Further details about FAM-Z02 properties including density, heat capacity, and equilibrium uptake rate have been reported in Refs. [60,61].

Sharafian et al. [67] experimentally showed the effects of different finned tube adsorber bed designs packed with 2 mm FAM-Z02 particles with respect to their heat transfer surface area and fin

Table 1
Performance analysis of different finned tube adsorber beds reported in the literature.

Ref. No.	Adsorber bed type and weight	Working pairs	Adsorbent packing method	COP	SCP (W/kg)	AAMR ($kg_{metal}/kg_{adsorbent}$)
[14–16]	Aluminum finned tube, 4.6 kg[a]	Activated carbon/ammonia	Consolidated	0.06[a]	33[a]	5.75[a]
[17]	SS[b] finned tube	Silica gel/methanol	Loose grain	–	30[a]	–
[18–20]	SS cylindrical double finned tube, 31 kg	Zeolite 13X/water	Loose grain	0.38	22.8[a]	5
[21,22]	176-finned tubes, 260 kg	Zeolite 13X/water	Loose grain	0.25	28.5	1.86
[23]	SS finned tube, 3.3 kg[a]	Silica gel + $CaCl_2$(SWS-1L)/water	Loose grain	0.43[a]	23.5[a]	3
[24]	2-bed Aluminum finned tube, 15 kg/bed	AQSOA FAM-Z02/water	Loose grain	0.27[a]	131.5[a]	7.9
[25–27]	2-bed finned tube, 32.7 kg/bed	Silica gel/water	Loose grain	0.43	48[a]	0.654
[28]	SS finned tube	Hydrophobic Y zeolite (CBV-901)/methanol	Coated	0.11[a]	25[a]	3
[29]	2-bed finned tube	Silica gel/water	Loose grain	0.29[a]	35[a]	–
[30–33]	2-bed finned tube	Act. carbon + $CaCl_2$ (1:4)/ammonia	Consolidated	0.19[a]	70.8[a]	–
[34]	Aluminum finned tube, 6.08 kg	Silica gel + $CaCl_2$(SWS-1L)/water	Coated	0.15	137[a]	3.47
[35]	Finned tube	Silica gel + $CaCl_2$/water	Loose grain	0.23	43	–
[36,37]	2-bed Aluminum finned tube, 13.6 kg/bed[a]	Silica gel/water	Loose grain	0.29	158[a]	4.53
[38–40]	Aluminum finned tube, 0.636 kg	$LiNO_3$-Silica KSK/water	Loose grain	0.18[a]	318[a]	1.82
[41,42]	28 finned tube with 2.5 mm fin spacing	Silica gel + LiCl/water	Loose grain	0.41	122	–
[43–45]	2-bed Aluminum finned tube	Silica gel + LiCl/methanol	Loose grain	0.41	76.5	–
		Silica gel/water	Loose grain	0.42	122	
[46]	2-bed Aluminum finned tube, 2.3 kg/bed	AQSOA FAM-Z02/water	Loose grain	0.45	330.2	1.4
[47,48]	8 tubes with Aluminum fins + steel pipes, 40 kg/bed	Expanded graphite + $CaCl_2$/ammonia Expanded graphite + $BaCl_2$/ammonia	Loose grain Loose grain	0.11	7.0	–
[49]	Carbon steel finned tube, 115 kg	Expanded graphite + NaBr/ammonia	Coated	0.35	296	20.9
[50]	4-bed SS shell and Aluminum finned tube	Silica gel/water	Loose grain	0.31	46.5[a]	–
[51]	2-bed finned tube	Expanded graphite + $CaCl_2$/ammonia	Loose grain	0.16	78.5	–
[52]	Aluminum finned tube, 0.16, 0.13, and 0.14 kg	AQSOA FAM-Z02/water	Loose grain	–	2300	1.78 1.71 1.92
[53]	3-bed Aluminum finned tube, 12.4 kg/bed	AQSOA FAM-Z02 + silica gel/water	Coated + Loose grain	–	296	1.85
[54,55]	Aluminum finned tube	Sapo-34/water	Coated	0.24	675	6
			Loose grain	0.4	498	1.96
[56]	2-bed copper finned tube	Zeolite 13X + $CaCl_2$/water	Loose grain	0.16	53	–

[a] These parameters are extracted based on the reported experimental data at $T_{hf,\ i} = 90$ °C, $T_{cf,\ i} = 30$ °C, $T_{coolant,\ i} = 30$ °C, and $T_{chilled,\ i} = 15$ °C. For zeolite 13X/water: $T_{hf,\ i} = 180$ °C.
[b] SS: Stainless steel.