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Critical analysis of thermodynamic cycle modeling of adsorption cooling systems for light-duty vehicle air conditioning applications

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ABSTRACT

Thermodynamic cycle of adsorption cooling systems (ACS) is thoroughly studied under different operating conditions for light-duty vehicles air conditioning applications. Available ACS prototypes installed in vehicles are discussed in detail followed by different ACS thermodynamic cycle modeling. Also, equilibrium uptake and uptake rate of commonly used working pairs in ACS are summarized. The proper ACS thermodynamic cycle with capability of integration with vehicles' Engine Control Unit (ECU) is developed and it is validated against two sets of experimental data reported in the literature. The realistic input data in agreement with light-duty vehicles are introduced to the model as the base-case condition to produce 2 kW cooling power. Sensitivity of ACS specific cooling power (SCP) and coefficient of performance (COP) are studied with respect to the input parameters. According to the results, the SCP and COP of the base-case ACS are maximized at 10–15 min cycle times and adsorption to desorption time ratio (ADTR) of one. In addition, the results indicate that the adsorber bed overall heat transfer conductance and mass have the highest and the lowest effects on the SCP, respectively. Also, the results show that during the operation of ACS, the heating and cooling fluids, coolant fluid and chilled water mass flow rates do not change the SCP and COP after specific values. As a result, variable speed pumps are required to adjust these mass flow rates to reduce feeding pump powers. Finally, the results indicate that the engine coolant cannot provide enough heat for the adsorber bed desorption process under different operating conditions. Therefore, a portion of the exhaust gas of the engine is recommended to be utilized during the desorption process.

Contents

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Nomenclature

A	heat transfer surface area (m^2)
$A/C\text{-}R$	air conditioning and refrigeration
ACS	adsorption cooling system
$ADTR$	adsorption to desorption time ratio
a_i	constants
b_i	constants
c	heat capacity of solid materials (J/kg K)
c_p	heat capacity at constant pressure (J/kg K)
COP	coefficient of performance
D_s	solid-side mass diffusivity (m^2/s)
D_{s0}	pre-exponential constant (m^2/s)
E_a	activation energy (J/mol)
Δh_{ads}	enthalpy of adsorption (J/kg)
ΔT_{LM}	log mean temperature difference (K)
HTS	heat transfer fluid
h_{fg}	enthalpy of vaporization (J/kg)
ICE	internal combustion engine
M	molar mass (kg/mol)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (mbar)
Q_{total}	total heat transfer (J)
$\dot{q}$	heat transfer rate (W)
R_p	average radius of adsorbent particles (m)
R_u	universal gas constant (J/mol K)
SCP	specific cooling power (W/kg dry adsorbent)
ω	adsorbate uptake (kg/kg dry adsorbent)
T	temperature (K)
t	time (s)
τ_{cycle}	cycle time (s)
U	overall heat transfer coefficient (W/m^2 K)
$VCRC$	vapor compression refrigeration cycle

Subscripts

adsorbate	adsorbate
adsorbent	adsorbent particles
bed	adsorber bed
chilled	chilled water
cf	cooling fluid
cond	condenser
coolant	coolant fluid
cooling	cooling process
eq	equilibrium state
evap	evaporator
heating	heating process
hf	heating fluid
i	in
liq.	liquid phase
max	maximum
min	minimum
o	out
sat	saturation
vaporous	vaporous phase

1. Introduction

Vapor compression refrigeration cycles (VCRC) are the most popular air conditioning and refrigeration (A/C-R) systems used in residential and industrial buildings, chemical and process engineering, and the automotive sector. Annually, A/C systems of light duty vehicles in the US consume about 40 billion liters of fuel [1]. To maintain the cabin temperature within the acceptable thermal comfort temperature range, 20–23 °C [2], a compressor of VCRC installed in a typical medium size sedan consumes up to 5–6 kW of the power that the internal combustion engines (ICE) generates. This power is equivalent to the required power for a 1200-kg sedan cruising at 56 km/h [1]. Moreover, approximately 70% of the total fuel energy released in the ICE is wasted through the engine coolant and exhaust gases [3]. A prominent replacement of VCRC is adsorption cooling systems (ACS) in which adsorber beds replace the compressor. ACS take advantage of sorption phenomenon in which a fluid (adsorbate) is adsorbed at the surface of a porous solid material (adsorbent). Common working adsorption pairs used in ACS include: zeolite–water, silica gel–water and activated carbon–methanol. Most of these materials are environmentally friendly, non-toxic, non-corrosive, and inexpensive [4]. Moreover, ACS are quiet and easy to maintain because they do not have any moving parts, except valves [5]. Thus, ACS are ideal candidates for applications where waste-heat or low-grade thermal energy (~100 °C) is available. However, commercialization of ACS faces major challenges; namely: (i) low specific cooling power (SCP), (ii) low coefficient of performance (COP), and (iii) high adsorber bed to adsorbent mass ratio which result in heavy and bulky system. The focus of this study is on light-duty vehicle applications and the following provides the pertinent literature to ACS designed and built for vehicles A/C-R applications.

In 1929, Hulse [6] built the first commercial silica gel–sulphur dioxide ACS and installed it in a freight car refrigeration system to carry fish and meat all over the US. The designed system was able to keep the freezer room temperature as low as −12 °C with minimum moving and control parts, and has the capability of working at car idle time. This ACS consisted of two adsorber beds, an air-cooled condenser and two gas burners to supply high temperature gas for the desorption process. With the advent of compressors and emergence of VCRC, ACS were forgotten for several decades; however, due to VCRC high energy consumption, negative environmental impacts and stringent government emission regulations, ACS have been reconsidered from 1990s. Feasibility of VCRC replacement with ACS in electric vehicles (EVs) was analytically investigated by Aceves [7]. According to his calculations, during a 60 min driving cycle, the A/C system should be able to bring the cabin temperature down from the hot soak (43 °C) to the comfort (25 °C and 60% relative humidity) conditions within the first 15 min. As a result, Aceves' calculations showed that the maximum required cooling power is 2 kW and to keep the cabin temperature constant, the A/C system should continuously supply 1.5 kW cooling power. Finally, Aceves concluded that the mass of VCRC could be up to 20% lighter than that of ACS. It should be noted that, in Aceves' analysis, the COP of 2.2 was assumed for the vehicles' VCRC; however, the COP of vehicles' VCRC is between 1.0–1.6 in real applications [8–10]. Suzuki [3] assessed the possibility of using the ACS for automobile A/C applications and studied the effects of adsorber bed overall heat transfer conductance, UA (W/K), on the SCP of zeolite–water ACS. Suzuki reported that the engine coolant at the inlet of the radiator and the engine exhaust gas at the outlet of the piston compartment were at 95 °C and 400–600 °C, respectively; and these temperatures were enough for regeneration of the adsorber beds. Suzuki, also, mentioned that the power generated in a compact vehicle with a 2000 cc ICE were about 10.8 and 35–50 kW at the idle and city driving (60 km/h) conditions, respectively [3]. As such, one can conclude that the