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Assessment of adsorber bed designs in waste-heat driven adsorption cooling systems for vehicle air conditioning and refrigeration

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ABSTRACT

Adsorber bed design strongly affects the performance of waste-heat driven adsorption cooling systems (ACS) for vehicle air conditioning and refrigeration (A/C–R) applications. Adsorber beds should be specifically sized for vehicle A/C–R considering the limitations of mobile applications. However, there is no conclusive evidence on what type of adsober bed is proper for vehicle applications. To evaluate the performance of ACS, specific cooling power (SCP), adsorber bed to adsorbent mass ratio, and coefficient of performance (COP) are introduced and their order of importance are assessed. To investigate the available studies in the open literature, desired SCP of 350 W/kg dry adsorbent and adsorber bed to adsorbent mass ratio of less than one are calculated for a 1-ton-of-refrigeration, 2-adsorber bed, silica gel–water ACS. According to these criteria, previous studies are summarized into nine groups with respect to their adsober beds and consequently, finned tube adsorber bed design is selected among the existing designs. Finally, optimization of fin spacing and fin height, and enhancing thermal conductivity of adsorbent material by adding metal wool inside the finned tube adsorber bed are proposed as the practical solutions to increase heat and mass transfer rates within the adsorber bed.

Contents

1. Introduction

Refrigeration systems consume a considerable amount of energy to produce cooling power in domestic and industrial applications such as ice-making [1–3] and food industries [4–6], vaccine protection [7–9], and air conditioning applications [10–13]. Vapor compression refrigeration cycles (VCRCs) are the most popular type of refrigeration systems in which different refrigerants such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs) [14] are used. Ozone depletion and global warming resulting from such refrigerants are direct environmental impacts of VCRCs. An ideal refrigeration system should use a refrigerant which has favorable thermodynamic properties and be noncorrosive, nontoxic,

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Nomenclature

COP	coefficient of performance
c_p	specific heat capacity at constant pressure, (J/kg/K)
Δh_{ads}	enthalpy of adsorption, (J/kg)
HEX	heat exchanger
h	enthalpy, (J/kg)
m	mass, (kg)
Q	total heat transfer, (J)
SCP	specific cooling power, (W/kg dry adsorbent)
SS	stainless steel
T	temperature, (K)
t	time, (s)
VSCP	volumetric specific cooling power, (W/m^3 adsorber bed)

Greek symbols

τ_{cycle}	cycle time, (s)
ω	adsorbate uptake, (kg adsorbate/kg dry adsorbent)

Subscripts

bed	adsorber bed
cond	condenser
evap	evaporator
iba	isobaric adsorption
ibd	isobaric desorption
ic	isosteric cooling
ih	isosteric heating
sat	saturation
sorbent	adsorbent

non-flammable, and environmentally benign [15]. Therefore, development of green, sustainable refrigeration systems which utilize environmentally friendly refrigerants is of great importance.

The negative impacts of air conditioning and refrigeration (A/C–R) systems become more pronounce in automotive and transportation applications where a VCRC compressor is powered by mechanical energy from the internal combustion engine (ICE). Current A/C–R systems significantly increase fuel consumption and greenhouse gas production. The U.S. annually consumes about 40 billion liters of fuel for heating, ventilation, and air conditioning (HVAC) systems of light duty vehicles [16]. A VCRC compressor can add up to 5–6 kW peak power draw on a vehicle's engine, the equivalent power required for a 1200-kg sedan cruising at 56 km/h [16].

In an ICE vehicle, almost 70% of total fuel energy is dissipated through the ICE coolant and exhaust gas in the form of waste heat [16]. To retrieve the waste heat and reduce the negative impacts of VCRCs, an alternative solution is adsorption cooling systems (ACS) in which adsorber beds replace the compressor. A portion of ICE waste heat is sufficient to run an ACS to meet the A/C–R needs of a vehicle [17]. ACS, also, can be applied in natural gas vehicles (NGVs) similarly to the gasoline-powered vehicles because the exhaust gas of the engine is available. However, in hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) the exhaust gas of the engine is not available continuously. The required heat to regenerate the adsorber beds can be supplied from a heat storage tank and/or the electric motor and battery cooling systems. In the case of electric vehicles (EVs), similarly, the waste heat energy can be supplied from the electric motor and battery cooling systems. As such, proper implementation of ACS in vehicles has the potential to significantly reduce fuel consumption and minimize the carbon footprint of vehicles.

ACS work based on the sorption phenomenon in which a fluid (adsorbate) is adsorbed at the surface of a solid material (adsorbent). Most popular working pairs used in ACS include zeolite–water, silica gel–water and activated carbon–methanol. These materials are environmentally friendly, non-toxic, non-corrosive, and inexpensive [18]. Moreover, ACS are quiet and easy to maintain [19] as there is no moving part, except valves, in these systems. Thus, ACS are ideal candidates for a variety of applications especially where waste-heat or low-grade thermal energy is available. However, commercialization of ACS faces major challenges; namely: (i) low specific cooling power (SCP) and (ii) low coefficient of performance (COP) that result in heavy and bulky A/C–R systems which make them impractical for vehicle A/C–R applications [20]. The origin of the ACS low performance is low thermal conductivity of adsorbent materials due to high porosity and thermal contact resistance between the adsorbent particles, for example, thermal conductivity of zeolite 13X, silica gel–$CaCl_2$ and activated carbon are 0.1, 0.12 and 0.3 W/m/K, respectively [21–23]. As a result, heating and cooling of ACS adsorber beds are time consuming processes. As such, design and optimization of an adsorber bed with improved heat and mass transfer characteristics, and low adsorber bed to adsorbent mass ratio can effectively increase the SCP and COP of ACS [24–26].

In this paper, an in-depth assessment of available adsorber bed design of waste-heat driven ACS is presented with a focus on vehicle A/C–R applications. The previous studies are classified based on the ACS working pairs, cooling capacity, cycle time, COP, SCP, and adsorber bed to adsorbent mass ratio. Based on these data, the effects of different adsorber bed designs are investigated on the SCP, adsorber bed to adsorbent mass ratio and COP to identify the best adsorber bed designs suitable for vehicle A/C–R applications. Finally, several practical solutions and remedies are proposed to improve the performance of ACS.

2. Adsorption versus absorption

Adsorption is, in general, the adhesion of ions or molecules of gases, liquids or dissolved solids to a solid surface [27]. Adsorption phenomenon is an exothermic process in which molecules of a liquid or gas, called adsorbate, accumulate on a solid surface, called adsorbent [28,29]. Adsorbents are porous materials with ability to take up several times of their volume of gases or liquids. The terms “adsorption” and “absorption” are usually assumed to be the same, but they are, in essence, completely different physical phenomena. In the adsorption process, molecules of gas or liquid adhere on the surface of the solid, whereas in the absorption process, molecules of gas or liquid penetrate into the solid or liquid phase.

3. Thermodynamic cycle of ACS

ACS work based on two main steps: heating–desorption–condensation and cooling–adsorption–evaporation. Using these steps, the ACS produces evaporative cooling power intermittently. To produce continuous cooling power, the solution is to use more than one adsober bed. Fig. 1a depicts the schematic of a 2-adsorber bed ACS. The main components of an ACS consist of adsorber beds, condenser, expansion valve, and evaporator. Therefore, the ACS is similar to the VCRC, except that the adsorber beds replace the compressor.