IX Minsk International Seminar "Heat Pipes, Heat Pumps, Refrigerators, Power Sources",
Minsk, Belarus, 7-10 September, 2015

NOVEL EXPANSION AND CONTROL VALVES DESIGN FOR TWO-BED ADSORPTION COOLING SYSTEM

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Abstract

In this study, two novel ideas for the expansion valve and control valves of an adsorption cooling system (ACS) for vehicle air conditioning applications are suggestedto reduce the weight and parasitic power consumption of the system. A check valve with cracking pressure of 3.5-7 kPa is proposed for the expansion valve and a combination of low-cracking pressure check valves and solenoid valves with an innovative arrangement is proposed for the control valves to heat up and cool down the adsorber beds. The proposed innovative designs can reduce the total mass of the ACS up to 10.5 kg (12%) and the parasitic power consumption of the control valves by 50%. The operating range of these new designs is investigated on a two-adsorber bed silica gel/$CaCl_2$-water ACS. The results show that the expansion valve and control valves operate effectively under heating and cooling fluid inlet temperatures of 70-100°C and 30-40°C, respectively, and coolant and chilled water inlet temperatures of 30-40°C and 15-20°C, respectively.

KEYWORDS

Expansion valve, control valve, adsorption cooling system, vehicle air conditioning.

INTRODUCTION

Waste heat-driven adsorption cooling systems (ACSs) are potential energy efficient replacements for vapor compression refrigeration cycles (VCRC) in vehicle's air conditioning (A/C) applications. Approximately 70% of the total fuel energy released in an internal combustion engine (ICE) is wasted as heat that is dissipated through the engine coolant and exhaust gas [1]. An ACS can use this waste heat to provide cooling in vehicles and drastically reduce their fuel consumption and carbon-footprint.

An ACS uses an adsorbent-adsorbate working pair, where an adsorbate, such as water or methanol, is adsorbed and desorbed from the surface of an adsorbent, such as zeolite, silica gel, or activated carbon, in a thermally driven cycle. Most of these materials are non-toxic, non-corrosive, and inexpensive [2]makingan ACS a safe and environmentally friendly technology. This system operates more quietly than a VCRC and is easier to maintain because its only moving parts are valves [3]. However, current ACSsare not commercially available for vehicle applications, specifically light-duty vehicles, because of their large foot-print and heavy weight which are due to the low thermal conductivity of adsorbent materials and low mass diffusivity of adsorbent-adsorbate pairs. These properties result in a low coefficient of performance (COP = cooling energy / input energy) and low specific cooling power (SCP = cooling energy / (adsorbent mass × cycle time)). In mobile applications, the mass of the system is crucial, which makes the SCP and the adsorber bed to adsorbent mass ratio (AAMR), i.e., the dead to active mass ratio, the two most important parameters in amobile ACS design.

There are several successful ACSs installed in mobile applications where the weight and footprint of the ACS were not problematic such as the ones reported in Refs.[4–6]. For light-duty vehicle A/C applications, de Boer et al.[7] built and installed a two-adsorber bed silica gel-water ACS with 2-kW cooling power for a compact car. In their setup, each adsorber bed was filled with 3 kg of silica gel with the AAMR of 4.2 kg metal/kgadsorbent. The 86 kg total mass of their system exceeded the 35 kg limit set by the car manufacturer [7]. From the data reported in Ref. [7], one can conclude that the mass of the two adsorber beds loaded with adsorbent material was 31.2 kg which makes only 36% of the total mass of the system. The condenser, evaporator, expansion valve, piping and control valves made up the remaining 64% of the ACS total mass.In the present study, two ideas are proposed for the expansion and control valves of an ACS for vehicle A/C applications to simplify the control system, and reduce the total mass and its parasitic power consumption.As a proof-of-concept demonstration, a two-adsorber bed silica gel/$CaCl_2$-water ACS was designed and builtto investigate the operating ranges of the expansion and control valves under different operating conditions.

EXPERIMENTAL STUDY

A two-adsorber-bed ACS equipped with four temperature control systems (TCS) to control the adsorption, desorption, condensation, and evaporation temperatures was designed and built. A schematic of our ACS system along with photos of the system components are shown in Fig.1a-c. Valves V1-V4 shown in Fig.1awere installed before and after the adsorber beds to control the adsorption and desorption processes, and eight valves (V5-V12) were installed on the TCS_{HF} and TCS_{CF} to intermittently heat up and cool down adsorber beds 1 and 2. Silica gel/$CaCl_2$ adsorbent material was prepared with chromatography-grade commercial silica gel with irregular-shaped grains (0.5–1.0 mm) and average pore diameter of 5.7 nm (SiliaFlash N60, Silicycle Inc.) with 30 wt% $CaCl_2$. Two heat exchangers, as shown in Fig.1d, were designed and built based on the results of Sharafian et al.[8] to be packed with the silica gel/$CaCl_2$ adsorbent. Type T thermocouples (Omega, model #5SRTC-TT-T-36-36) with accuracy of ±0.1°C and pressure transducers with 0-34.5 kPa operating range (Omega, model #PX309-005AI) and ±0.4 kPa accuracy were used to monitor and record the temperature and pressure variations in each component of the ACS versus time.

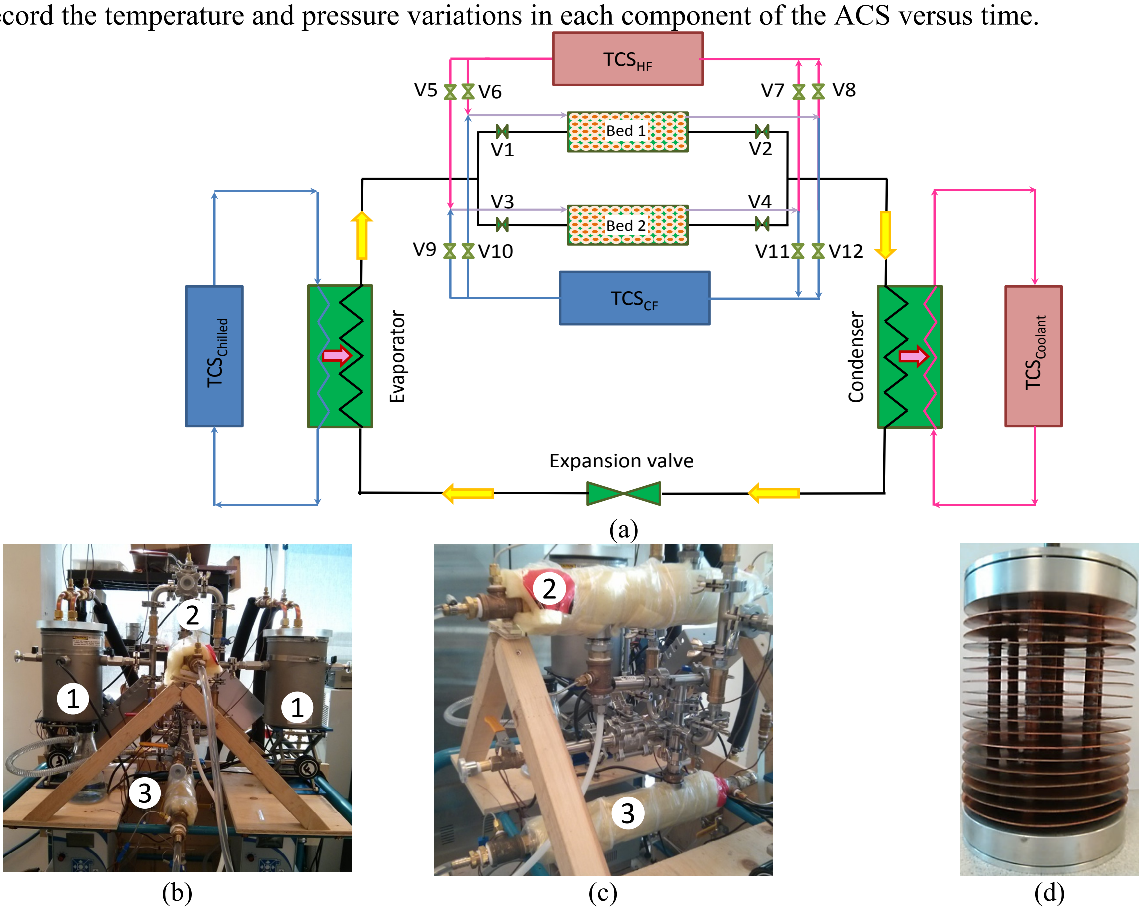
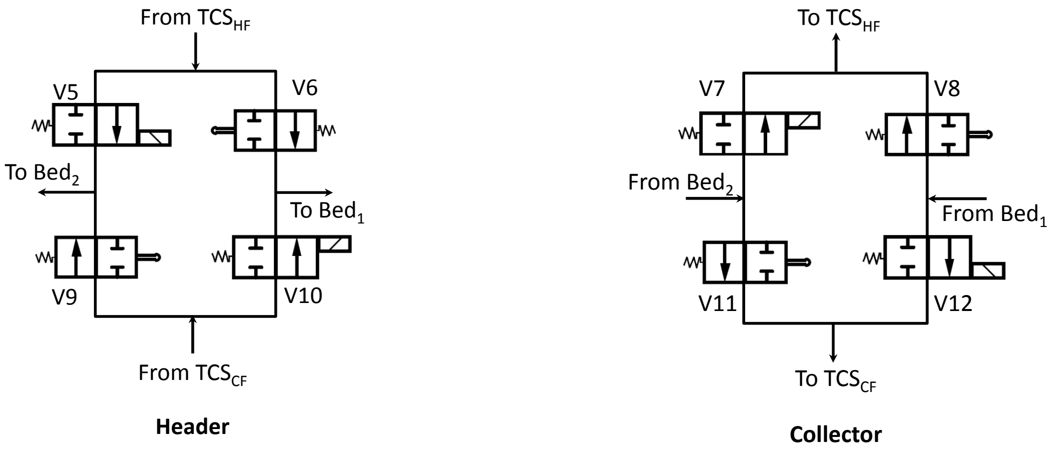


Fig.1. (a) Schematic of a two-adsorber bed ACS, (b) and (c) ACS components: 1- adsorber beds, 2-condenser, and 3-evaporator, and (d) custom-built heat exchanger located inside the adsorber beds.

Four check valves, V1-V4, installed between the adsorber beds and the condenser, and adsorber beds and the evaporator must have a low-cracking pressure. The ACS uses water as the refrigerant and operates between 1 and 8 kPa, therefore any pressure drop above 0.5 kPa between the adsorber beds and the condenser or theadsorber beds and the evaporator reduces the system performance. In this study, the check valves have a cracking pressure of less than 250 Pa (Generant, model #DCV-375B-S), have no power consumption, and are durable and inexpensive. To control the heating and cooling of the adsorber beds, eight solenoid valves, V5-V12 with a maximum operating temperature of 120°C (StcValve, model #2W160-1/2-3-V with 14 W power consumption and #2WO160-1/2-3-V with 30 W power consumption) and a total power consumption of 176 W were installed. The solenoid valve arrangements for the heat transfer fluid header and collector are displayed in Fig.2.



(a) (b)

Fig.2. Solenoid valve arrangements in (a) the header and (b) collector of the two-adsorber bed ACS.
: normally opened, : normally closed.

As shown in Fig.2, solenoid valves V5, V7, V10, and V12 are normally closed and solenoid valves V6, V8, V9, and V11 are normally open. To desorb adsorber bed 1, heating fluid comes from TCS_{HF}, enters the header, passes through valve V6, and goes to adsorber bed 1, as shown in Fig.2a, and then returns from adsorber bed 1, passes through valve V8, and returns to TCS_{HF}, as shown in Fig.2b. For the adsorption process in adsorber bed 2, cooling fluid comes from TCS_{CF}, passes through valve V9, and enters adsorber bed 2. Then, it returns from adsorber bed 2, passes through valve V11, and returns to TCS_{CF}. When the solenoid valves are not energized, TCS_{HF} and TCS_{CF} are connected to adsorber beds 1 and 2, respectively. When the solenoid valves are energized, the flows of heating and cooling fluid are switched, and TCS_{HF} and TCS_{CF} are connected to adsorber bed 2 and 1, respectively. With this design, valves V1-V8 are controlled with onlya relay switch, which in turn is controlled automatically using a LabVIEW program, and the power consumption of valves V1-V8 for one cycle reduces by 50% from 176 W to 88 W. Also, check valves V1-V4 operate automatically, without power consumption, actuated by the pressure gradients between the adsorber beds, and the condenser and evaporator. The total mass of the eight solenoid valves and four check valves is about 7 kg (8 × 0.815 kg + 4 × 0.115 kg). If electrically or pneumatically actuated ball valves were used, the total mass of eight valves and four check valves would be 17.5 kg (8 × 2.130 kg + 4 × 0.115 kg) which is 10.5 kg (2.5 times) heavier than the design in this study.

The expansion valve of a refrigeration system prevents the vaporous refrigerant in the condenser from flowing to the evaporator, and creates a pressure difference between the condenser and evaporator thatis set by the refrigerant saturation pressure. Therefore, the expansion valve of an ACS that uses water as the refrigerant differs from those of designed for conventional VCRCs that use commercial refrigerants such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs). Among ACS experiments for stationary applications, a reverse U-bend tube was often used as the expansion valve such as the one reported in Ref. [9]. The problem associated with a reverse U-bend tube in an ACS thatuses water as the refrigerant is its fixed height. To create a pressure drop of 5 kPa between the condenser and evaporator, the height of such a reverse U-bend should be about 50 cm which is not practical for light-duty vehicle A/C applications and limits the operating range of the ACS. To resolve the issue of U-bend tube for mobile applications and design an expansion valve for a wide range of operating conditions, in this study, a check valve (Generant, model #CV-250B-S-1) with a cracking pressure of 3.4-6.9 kPa is proposed.Fig.3 shows the positions of the condenser and evaporator, and the expansion valve located between them.

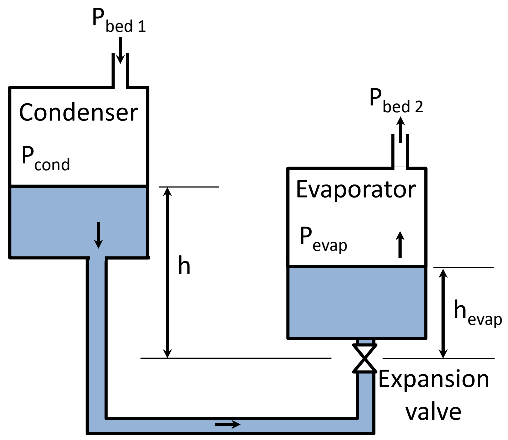


Fig.3. Schematic of the expansion valve for the mobile ACS.

The condensed refrigerant is accumulated at the outlet of the condenser and before the expansion valve. As such, the hydrostatic pressure balance for the liquid refrigerantbetween the condenser and evaporator can be used to relate P_{cond} and P_{evap} to $P_{cracking}$as follows:

$$P_{\mathrm{cond}} - P_{\mathrm{evap}} - \rho g h_{\mathrm{evap}} + \rho g h > P_{\mathrm{cracking}} \quad (1)$$

Equation (1) shows that the expansion valve connects the condenser to the evaporator only if the sum of the left-side terms become larger than the cracking pressure of the check valve,P_{cracking}. As such, the term ρghin Eq. (1), created by the accumulation of liquid refrigerant at the outlet of the condenser,guarantees that no vaporous refrigerant passes through the expansion valve. Such a compact expansion valve can effectively operate in a vehicle where operating conditions vary significantly and vibrations are abundant. The other specifications of the designed ACS and the operating conditions are summarized in

Table 1.

DATA ANALYSIS

By measuring the chilled water inlet and outlet temperatures and mass flow rate, given in

Table 1, the evaporation heat transfer rate is calculated as follows:

$$\dot{q}_{\mathrm{evap}}(W) = \dot{m}_{\mathrm{chilled}}\, c_{p,\mathrm{chilled}} (T_{\mathrm{chilled},i} - T_{\mathrm{chilled},o}) \quad (2)$$

The total evaporation rate is calculated by time averaging the heat flow given in Eq. (2):

$$Q_{\mathrm{evap}}(J) = \int_{0}^{\tau_{\mathrm{cycle}}} \dot{q}_{\mathrm{evap}} dt \quad (3)$$

where τ_{cycle} is the cycle time.

Table 1. Specifications and operating conditions of the ACS built in this study.

Parameter	**Changed values**
Working pairs	Silica gel/$CaCl_2$-water
Mass of adsorbent per bed (kg)	1.15
Metal mass of adsorber bed (kg)	2.8
Adsorber bed heat transfer surface area, A_{bed}, (m^2)	0.235
Adsorber bed heat transfer coefficient, U_{bed}, (W/m^2K)	20.0
Heating fluid mass flow rate to adsorber bed (kg/s)	0.06 (4.1 L/min of silicone oil)
Cooling fluid mass flow rate to adsorber bed (kg/s)	0.06 (4.1 L/min of silicone oil)
Heat capacity of silicone oil (kJ/kgK)	1.8
Metal mass of condenser (kg)	1.9
Condenser heat transfer surface area, A_{cond}, (m^2)	0.1444
Condenser heat transfer coefficient, U_{cond}, (W/m^2K)	250
Coolant water mass flow rate to condenser (kg/s)	0.036 (2.16 L/min of water)
Metal mass of evaporator (kg)	1.9
Evaporator heat transfer surface area, A_{evap}, (m^2)	0.072
Evaporator heat transfer coefficient, U_{evap}, (W/m^2K)	250
Chilled water mass flow rate to evaporator (kg/s)	0.02 (1.2 L/min of water)
Heating fluid inlet temperature (°C)	90
Cooling fluid inlet temperature (°C)	30
Coolant fluid inlet temperature (°C)	30
Chilled water inlet temperature (°C)	15
Cycle time, τ_{cycle}, (min)	30

Equation(4) gives theSCP of ACS:

$$SCP(W/kg) = \frac{Q_{\text{evap}}}{m_{\text{adsorbent}}\tau_{\text{cycle}}} \tag{4}$$

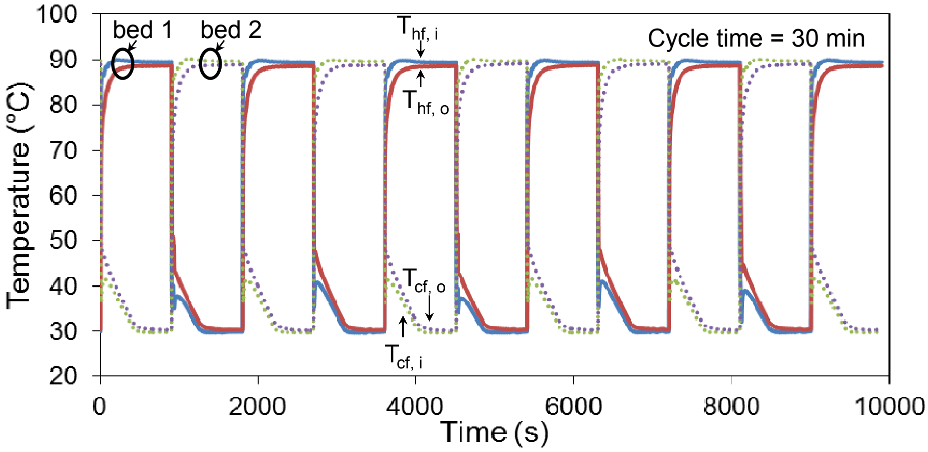
where $m_{\text{adsorbent}}$ is the total mass of adsorbent material in two adsorber beds.

RESULTS AND DISCUSSION

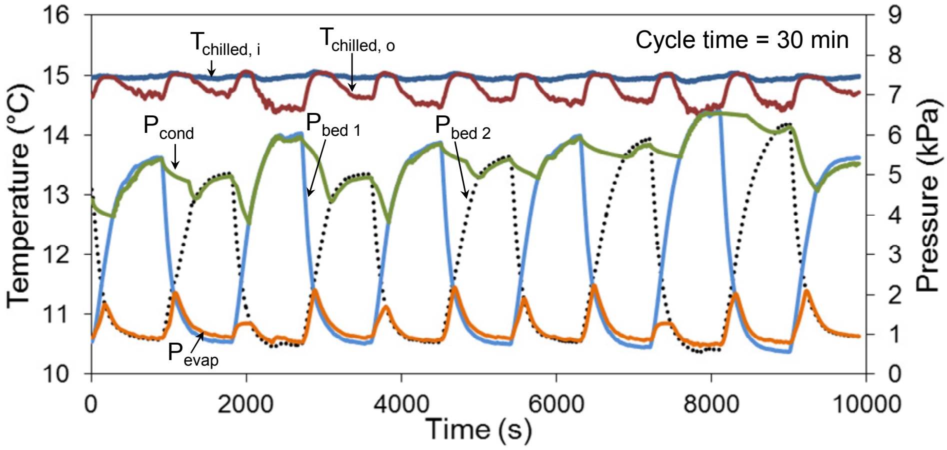
Base-case operating condition

Fig.4 shows the performance of the ACS with the new expansion valve and control valves at the base-case operating conditions summarized in

Table 1. Fig.4a shows the temperatures of the heating and cooling fluids before and after adsorber beds 1 and 2 as they are alternately heated and cooled fordesorption and adsorption, respectively. The pressures of the adsorber beds, $P_{\text{bed},1}$ and $P_{\text{bed},2}$, corresponding to desorption and adsorption are shown in Fig.4b. Also shown in Fig.4b are the pressuresinthe adsorber beds as they vary between the condenser and evaporator pressures, P_{cond}andP_{evap}. It can also be seen from Fig.4b that whenever one of the adsorber beds undergoes the adsorption process, it is automatically connected to the evaporator via valves V1 or V3, seeFig.1a, and the chilled water outlet temperature, $T_{\text{chilled},o}$, reduces because of refrigerant evaporation inside the evaporator. It can also be seen in Fig.4b that the expansion valve creates the required pressure difference between the condenser and evaporator under the base-case operating conditions.



(a)



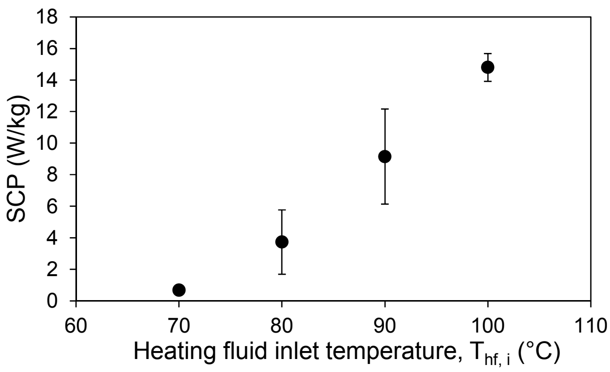
(b)

Fig.4. ACS performance under the base-case operating conditions summarized in

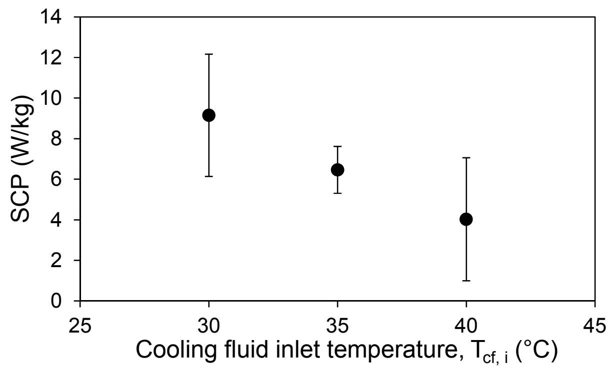
Table 1. (a) Inlet and outlet temperatures of heating and cooling fluids pumped to the adsorber beds, and (b) operating pressures of the adsorber beds, condenser and evaporator, and chilled water inlet and outlet temperatures in the evaporator.

Parametric study

Fig.5 shows the effects of heating and cooling fluid inlet temperatures on the SCP of the ACS. As shown in Fig.5a:



(a)



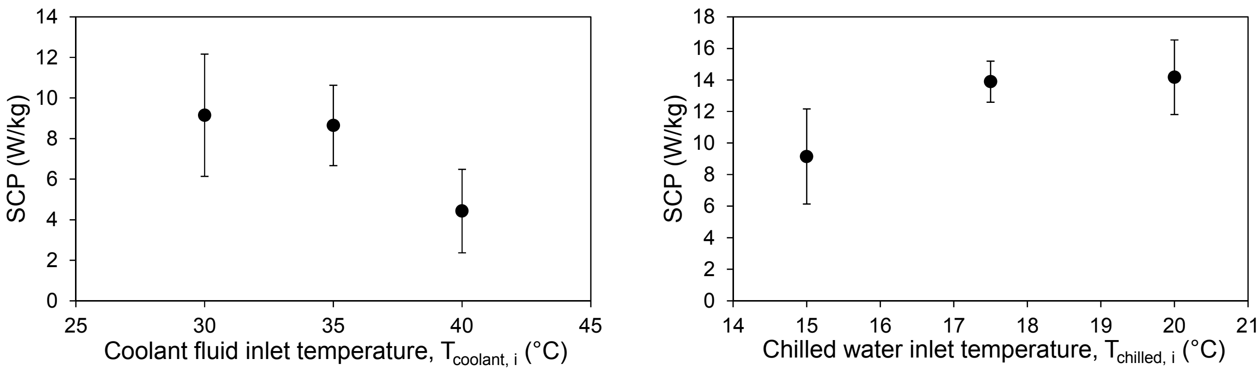
(b)

Fig.5. Effects of (a) heating and (b) cooling fluids inlet temperatures to the adsorber beds on the SCP of the ACS.

- Increasing the heating fluid inlet temperature to the adsorber beds from 70°C to 100°C increases the SCP from 0.7 W/kg to 14.8 W/kg.
- Increasing the temperature of the heating fluid to the adsorber beds during desorption increases the heat transfer rate to the adsorbent material and, consequently, the rate of desorption of the refrigerant (adsorbate) from the adsorbent material increases, and more refrigerant is desorbed.
- Accordingly, the drier adsorbent material adsorbs more adsorbate from the evaporator during the adsorption process. Thus, higher cooling power (or SCP) is generated.
- In contrast, Fig.5b shows that by increasing the cooling fluid inlet temperature from 30°C to 40°C, the SCP reduces from 9.2 W/kg to 4.0 W/kg because the higher adsorbent temperature during the adsorption process reduces the uptake capacity of the adsorbent. This clearly shows a competing trend which should be considered in the design of ACS.

The effects of the coolant fluid inlet temperature circulated in the condenser on the SCP of the ACS are shown in Fig.6a. The SCP of ACS decreases when the coolant fluid inlet temperature increases because of the increase in the condenser pressure which results in a lower refrigerant condensation rate. Therefore, within a constant cycle time, lower refrigerant is desorbed from the adsorbent material and the adsorption capability of the adsorbent material during the adsorption process reduces.

Fig.6b demonstrates the effects of the chilled water inlet temperature flowing through the evaporator on the SCP of the ACS. Increasing the chilled water inlet temperature from 15°C to 20°C, increases theSCP of the ACS from 9.2 W/kg to 14.2 W/kg, i.e., a 54% increase, because the adsorbate uptake capability of the adsorbent material increases with theincreasing the pressure during the adsorption process.



(a) (b)

Fig.6. Effects of (a) coolant fluid and (b) chilled water inlet temperatures on the SCP of ACS.

From Fig.5 and Fig.6, it can be concluded that the expansion valve and control valves proposed for the mobile ACS can operate reliably within a wide range of operating conditions.

CONCLUSION

In this study, a new design for the expansion valve and control valves of a mobile ACS were proposed and tested on a two-adsorber-bed silica gel/$CaCl_2$-water ACS. The performance of system was experimentally investigated under different operating conditions. The results showed that the expansion valve and control valves operated effectively in the system while the weigh of the system was reduced up to 10.5 kg (12%) and the parasitic power consumption of the control valves was reduced by 50%.

Acknowledgement

The first author thanks to the LAEC members, Dr. Claire McCague, postdoctoral fellow, and Ms. Cecilia Berlanga, a co-op student, for preparing the silica gel/$CaCl_2$ required to run the experiments. Also, the authors gratefully acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) through the Automotive Partnership Canada Grant No. APCPJ 401826-10.

Nomenclature

c_p	heat capacity at constant pressure (*J/(kg.K)*)
$\dot{m}$	mass flow rate (*kg/s*)
Q_{total}	total heat transfer (*J*)
$\dot{q}$	heat transfer rate (*W*)
ρ	density (*kg/m*^{3})
SCP	specific cooling power (*W/kg dry adsorbent*)
T	temperature (*K*)
τ_{cycle}	cycle time (*s*)
Subscripts	
chilled	chilled water
cf	cooling fluid
cond	condenser
coolant	coolant fluid
cooling	cooling process
evap	evaporator
heating	heating process
hf	heating fluid
i	in
o	out

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