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Performance Study of Adsorption Cooling System Driven by Waste Heat from Automobile Engine

*Khairul Habib**
Nurul Afiqah Kamaruzzaman
Department of Mechanical Engineering,
Universiti Teknologi Petronas,
32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia
**khairul.habib@utp.edu.my*

ABSTRACT

*Adsorption cooling system driven by waste heat from automobile engine driven out through radiator is used as an alternatives means to drive adsorption cooling system. Air conditioning of lightweight vehicle has been considered in term of energy savings and environmental issues. This article presents an instantaneous modelling and performance analysis of the waste heat from automobile engine driven two-bed adsorption chiller employing water and silica gel as refrigerant and adsorbent, respectively. The effects of adsorption/desorption cycle time, regeneration and cooling water temperature on the performance are reported in terms of specific cooling capacity (SCC) and coefficient of performance (COP). Results indicate that the chiller is able to produce SCC of 15 kW and a COP of 0.5, even when the low-temperature (between 70°*C *and 90°C) heat source from engine waste heat is available. However, improvement is still needed on the coefficient of performance.*

Keywords: *Adsorption cooling system; Waste heat; Cooling capacity; Automobile engine.*

Introduction

Increase in population density around the globe and costly standard of living have affected energy savings in space cooling. Thus, environment-friendly applications are now on the front burner among the research community. Carbon-based gases that are released into the environment from the engine of

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a vehicle and synthesized refrigerant employed in the classical vapour-compression refrigeration cycles (VCRC) have been the prominent sources of pollutants to the surrounding [1]. VCRC is still recognized as the most prominent refrigeration and air conditioning systems because of its performance compared to others techniques [2]. However, the researchers acclaimed that when these systems are put to use, it leads to a significant consumption of energy in conjunction with its effluents that causes environmental pollution.

In the current context, the conceptualization has support cooling by adsorption technique which makes it an alternative to VCRC. Indeed, the adsorption cooling cycle possess is supported by reported studies because it employs organic material and water as refrigerants with low potential of global warming potential (GWP) [3-4], ammonia [5], methanol [6], ethanol [7] etc. In addition, the energy harvested from the sun or the waste heat energy from car or truck engine or heat energy released from the industrial sector could be used to drive the adsorption chiller. Thus, the sun, waste heat from engine and industry act as the driving force. The exhaust gases released from the automobile engine usually constitutes about 60% to 70% of all energy expended by an internal combustion engine (ICE) in the process of energy conversion [8].

There are quite a number of researches and studies on investigating the adsorption cooling system for the automotive sector and most of them are currently at the stage of developing suitable mathematical computations. In recent time, developments are directed to the time-dependent models. These give an accurate information on the behaviour of the transient processes of heat and mass transfer regarding the adsorbent bed. A classical example is when the source of heat is changing, which is similar to the applicable case in an automobile engine. Many researchers utilize zeolite/H_2O as an adsorbent-refrigerant pair [8-11] with a high magnitude of temperature from the heat source. It has been reported that silica gel/H_2O adsorption chiller which is driven released waste heat from the automobile engine. This takes place with a desorption temperature of 80°C to 90°C. Thus, it could be efficiently used to provide a cooling load in automobile sector [12].

In the present investigation, the performance of silica gel/H_2O based adsorption chiller has been analyzed which is driven by engine waste heat from the radiator. A parametric study has been done using MATLAB simulation.

Description of the Adsorption Cooling Cycle

The present study on cooling by adsorption system comprises of sorption Bed 1 and sorption Bed 2 which are directly linked to a condenser and an evaporator. The condenser is connected to the radiator and the evaporator is connected to the cabin. The system also comprises of three loops of secondary water: The order of Cooling Water Loop is the condenser follow by the bed, while Heating Water Loop would heat the bed and the Chilled Water Loop would provide the needed heat by the refrigerant at the region around the evaporator of the system. The operation of the two beds is in contra-phase order. This is to give room for the continuation of useful effect. Thus, if a bed is in cooling mode, the other bed would be in the regeneration condition. This is depicted in Fig.1 when the heating process takes place in Bed 1, it will desorb the water vapour. The cooling water is first sent to the condenser from the radiator and then through the valves to Bed 2. The evaporator would receive the condensate then travels into it through the expansion valve. The chilled water circuit is directly connected to the evaporator.

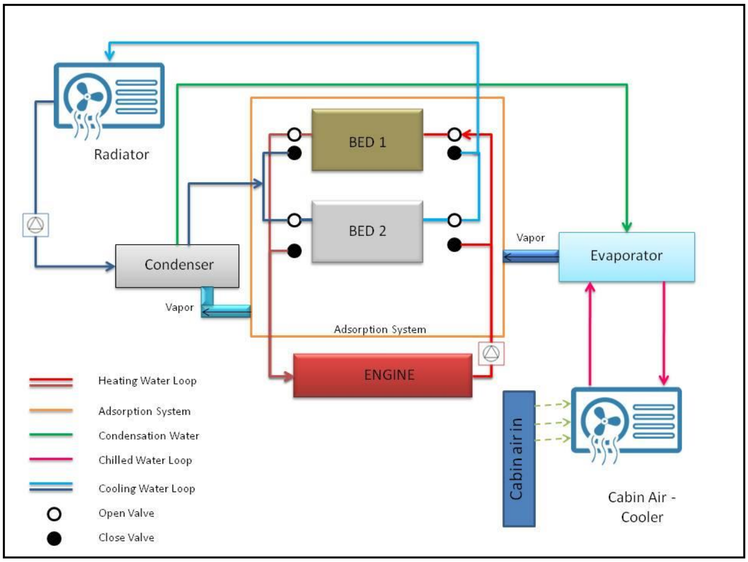

Figure 1. Schematic diagram of the cooling system by adsorption process

Mathematical Modelling

Equation (1) is a modification of the Freundlich model, which is used to determine the silica gel/H_2O pair equilibrium uptake [3].

$$q^* = \alpha(T_a)(P_R)^{\beta(T_a)} \tag{1}$$

where,

$$P_R = \frac{P_s(T_r)}{P_s(T_a)}$$

$$\alpha(T_a) = \alpha_0 + \alpha_1(T_a) + \alpha_2(T_a)^2 + \alpha_3(T_a)^3$$

$$\beta(T_a) = \beta_0 + \beta_1(T_a) + \beta_2(T_a)^2 + \beta_3(T_a)^3$$

The numerical values of quantities α_0 to α_3 and β_0 to β_3 of the experimental data were evaluated by using the least square fit approach [13]. The governing equation for the rate of desorption or adsorption by the linear driving force kinetic model is of form in Eq. (2).

$$\frac{dq}{dt} = k_s a_v \left(q^* - q\right) \tag{2}$$

where,

$$k_s a_v = \frac{15 D_s}{R_p^2} \tag{3}$$

$$D_s = D_{so} \exp\left(-\frac{E_a}{RT}\right) \tag{4}$$

The energy balance of the sorption bed of silica gel/H_2O cycle based on the lumped parameter approach to adsorption and desorption is expressed in form of relationship in Eq. (5).

$$C_{HX} \frac{dT_{bed}}{dt} = m_{a,HX} \frac{dq_{bed}}{dt} \Delta h_{ad} - \left(\frac{\dot{m}_{v,l}}{N_{HX}}\right) C_v \left(T_{bed} - T_e\right) + \dot{Q}_{heat/cool} \tag{5}$$

The term on the LHS of Eq. (5) represents the quantity of heat needed to cool or heat the bed as the case may be. The first term of RHS denotes the heat due to desorption or adsorption process while the second term of the equation refers to the sensible heat energy needed to raise the vapour heat energy from the evaporation temperature to the bed temperature when adsorption process is taken place. Furthermore, the third term of RHS describes the overall quantity of heat energy taken from the heating water or released to the cooling water depending on the bed current process. Equation (5) is applicable for both the desorption and adsorption situations. However, the second term of RHS needs to be neglected in desorption mode, as the temperature of the desorbed vapour is assumed to be similar to the temperature of the bed.

The heat transfer $Q_{\text{heat/cool}}$ is evaluation has been obtained by the correlation which is based on effectiveness- NTU formula (Eq. 6).

$$\dot{Q}_{heat/cool} = \varepsilon_{HX}\dot{m}_{w,HX}C_w\left[\alpha\left(T_{w,i,HX} - T_{bed}\right) + \left(1-\delta\right)\left(\frac{T_{w,o,HX} - T_{bed}}{1-\varepsilon_{HX}}\right)\right] \quad (6)$$

where the δ parameter represents the temperature change weighting coefficient. Thus, the difference in temperature of the inlet and outlet water and the bed. The effectiveness of the adsorbent bed heat exchanger is computed by expression in Eq. (7).

$$\varepsilon_{HX} = 1 - \exp\left(-\frac{UA_{total,HX}}{\dot{m}_{w,HX}C_w}\right) \quad (7)$$

Therefore, the heat energy balance equation for the vapour region in the vicinity of the condenser tube could be determined by expression in Eq. (8). This is based on the fact that the refrigerant enters from the desorber bed as the vapour at an elevated temperature while the pressure remains constant. Thus, the same situation in the condenser is observed,

$$\dot{Q}_{con} = \dot{m}_{con}\left[C_v\left(T_{con,i} - T_{con}\right) + \Delta h_{st}\left(T_{con}\right)\right] \quad (8)$$

As water enters the evaporator region in the liquid phase with high pressure and temperature, the energy balance equation of the refrigerant is as stated in the following expression.

$$\dot{Q}_e = \dot{m}_e\left[\Delta h_{st}\left(T_e\right) - c_w\left(T_{con,o} - T_e\right)\right] \quad (9)$$

System Performance

The specific cooling capacity (SCC) could be obtained at the evaporator in the following form:

$$\dot{Q}_c = \dot{m}_{w,c}C_w\int_0^{t_{cycle}}\left(T_{c,i} - T_{c,o}\right)dt \quad (10)$$

The driving heat source could be obtained with the desorber (bed connected with condenser) expression presented in Eq. (11).

$$\dot{Q}_{rg} = \dot{m}_{hotw} C_w \int_{0}^{t_{cycle}} \left(T_{hot,i} - T_{hot,o}\right) dt \tag{11}$$

The system coefficient of performance (COP) has been determined using relationship in Eq. (12).

$$COP = \frac{\dot{Q}_{rg}}{\dot{Q}_c} \tag{12}$$

Results and Discussion

Time-Based Response of The Chiller

The temporal histories of the system component are presented in Figure 2. Components such as desorber, adsorber, condenser and evaporator profile were achieved by using a mathematical model presented in the modelling section. Table 1 shows the necessary rated conditions for adsorption cycle. The values of the symbols used in the simulation of the present study are provided in a detailed format in a reported study [3]. The values employed in run the simulation of the proposed model are presented in Table 2.

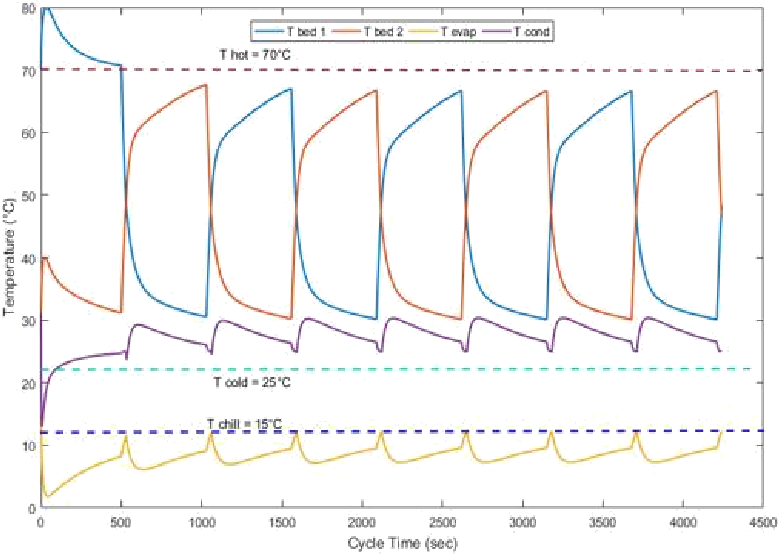

Figure 2. The temperature profiles for the adsorption cooling system components

Cycle Time of Adsorption/Desorption Processes

The outcome of the simulation achieved for cooling capacity and COP variations with adsorption/desorption cycle time for silica gel/H_2O cycle are shown in Fig. 3. It could be observed that for a proposed cycle, the highest specific cooling capacity achievable is in the neighbourhood of 14 kW over cycle times range between 480 s and 520 s. Therefore, it has been observed that the COP increases with a corresponding increase in the adsorption/desorption cycle time.

Table 1 The rated condition for the proposed adsorption cooling system

Hot H_2O (Inflow)		Cooling H_2O (Inflow)		Chilled H_2O (Inflow)	
Temperature (°C)	Flow rate(kg/s)	Temperature (°C)	Flow rate(kg/s)	Temperature (°C)	Flow rate(kg/s)
70	1.28	25	1.37	15	1.25

Table 2. Values adopted for simulation

Symbols	Silica gel/H_2O	Unit
m_a	40	kg
UA_{bed}	3500	W/K
UA_{eva}	4870	W/K
UA_{con}	15330	W/K
m_{con}	24.28	kg
m_{eva}	12.45	kg
$C_{p,a}$	960	J/kg-K
Δh_{sh}	2.8×10^6	J/kg

Driven Heat Source Temperature

In Figure 4, as the heat energy source temperature is changing between the range of 70°C and 90°C, there is a drop in the value of COP after 70°C while the SCC increases with temperature. The trend is observed due to the increment in the value of temperature, the ability to adsorb the water vapour is improving, then the effect of the specific cooling capacity would increase in magnitude.

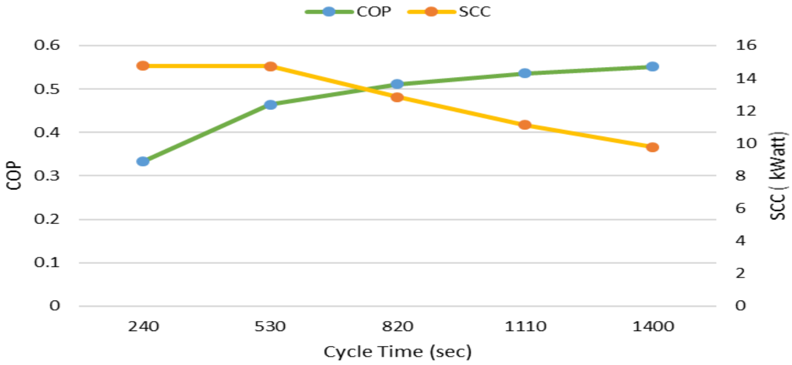

Figure 3. The variation of Cycle Time with SCC and COP

Temperature of Cooling Water Inlet

From the profile presented in Figure 5, as varying the cooling water inlet temperature rise from 20°C to 35°C. The trend for both graphs is observed to be decreasing as shown below. Thus, as the adsorption temperature decreasing, the ability to adsorb the water vapour is increasing. This situation contributes to the high amount of refrigerant that is being adsorbed as well as desorbed at every cycle.

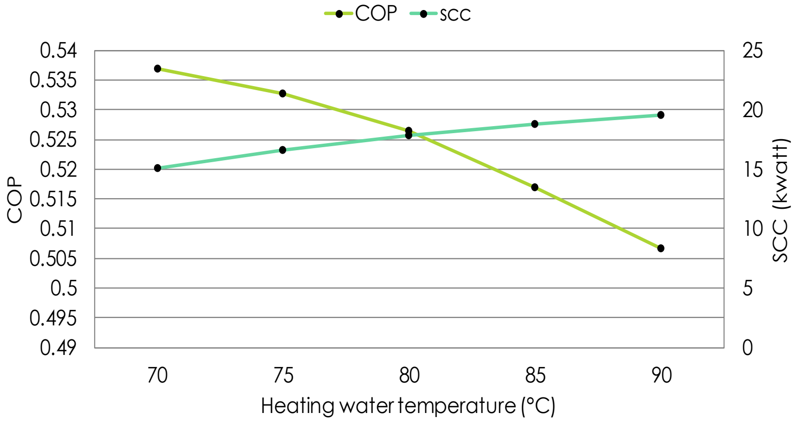

Figure 4. The variation of regeneration temperature with SCC and COP

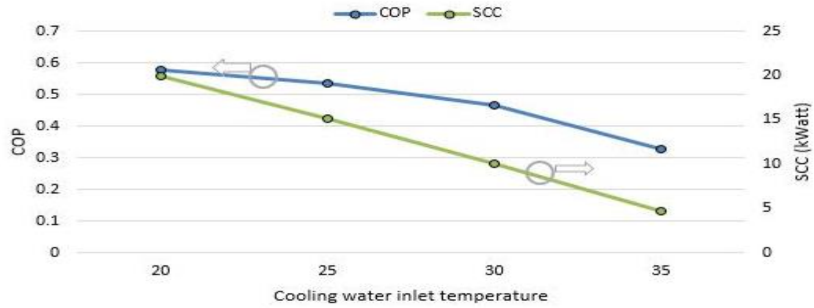

Figure 5. Profile of the Coefficient of Performance and Specific Cooling Capacity versus Cooling Water Inlet Temperature of the system

Conclusion

In this study, a theoretical investigation was conducted on an adsorption chiller that is driven by automobile engine waste heat using silica gel/H_2O. MATLAB tool has been used to develop an optimized non-equilibrium instantaneous model for the system. The results showed that the system could be able to produce an SCC in the neighbourhood of 15 kW while a COP of about 0.5 could be obtained when the driving heat source temperature in between 70°C to 90°C. Finding of the present study could be useful in the designing of an adsorption cooling system driven by engine waste heat in the automobile sector.

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Nomenclature

Symbols

α_0	coefficient, kg (dry adsorbent in kg)$^{-1}$
α_1	coefficient, kg (dry adsorbent in kg, K)$^{-1}$
α_2	coefficient, kg (dry adsorbent in kg, K^2)$^{-1}$
α_3	coefficient, kg (adsorbent in kg, K^3)$^{-1}$

β_0	coefficient
β_1	coefficient, K^{-1}
β_2	coefficient, K^{-2}
β_3	coefficient, K^{-3}
A	area, m^2
C	specific heat capacity, $J\ kg^{-1}\ K^{-1}$
COP	Performance
D_s	coefficient of surface diffusion, $m^2\ s^{-1}$
D_{so}	constant for pre-exponential, $m^2\ s^{-1}$
$k_s a_v$	mass transfer coefficient, s^{-1}
P_R	pressure ratio
q	quantity of refrigerant adsorbed, $kg\ kg^{-1}$
q^*	equilibrium uptake ratio, $kg\ kg^{-1}$
Δh_{sh}	isosteric heat of adsorption/desorption, $J\ kg^{-1}$
SCC	specific cooling capacity, kW
T	temperature, K
t	time, s
U	coefficient of heat transfer, $W\ m^{-2}\ K^{-1}$

Subscripts

a	adsorber
bed	adsorbent bed
c	chilled H_2O
con	condenser
d	desorber
e	evaporator
hot	hot H_2O
i	system inlet
o	system outlet
r	refrigerant
s	saturation
a	adsorbent

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