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Performance Study of Activated Carbon – Hydrofluoro Olefin based Adsorption Cooling System

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Abstract. In this study, a dynamic behavior of a two bed adsorption chiller has been analyzed using highly porous activated carbon of type Maxsorb III as adsorbent and hydrofluoro olefin [R1234ze (E)] as refrigerant. R1234ze(E) has a low global warming potential (GWP) and zero ozone depletion potential (ODP). A parametric study has been presented where the effects of adsorption/desorption cycle time, cooling water inlet temperature and regeneration temperature on the performance are reported in terms of cooling capacity and coefficient of performance (COP). This chiller can be driven by the waste heat of internal combustion engine and hence it is applicable in automobile air conditioning.

Introduction

In the field of mobile air conditioning (MAC), R134a is the most commonly used refrigerant until now although it has a very high value of GWP. It has been decided from the MAC Directive of the European Union that of refrigerants having global warming potential (GWP) below 150 should be used in all new car models from January 2011 and in all new cars from 2017 [1]. Therefore, it has become essential to replace R134a with an environmental-friendly refrigerant which has the potential to deliver similar or better system performance compared to the R134a system. Generally, the efficiency of internal combustion engines installed in vehicles is around 40% and the remaining 60% is rejected by exhaust cooling the engine. This waste heat could be used as the driving heat source for adsorption cooling system.

The performance of adsorption cooling systems employing various adsorbent-refrigerant pairs such as silica gel–water [2], zeolite-water [3], activated carbon-ethanol [4] etc. has been investigated. But all these systems possess some drawbacks such as low cooling capacity, low COP, toxicity, requirement of high pressure etc. Hydrofluoro Olefins i.e. R1234ze(E) and R1234yf are newly synthesized refrigerants that have zero ozone depletion potential (ODP) and very low global warming potential (less than 10). It is expected that these refrigerants would be an ideal replacement in the field of mobile air conditioning systems. Tanaka et al. [5] measured thermo-physical properties of hydrofluoro olefins

From the above perspective, the present study deals with the transient analysis of a two-bed activated carbon (AC) – R1234ze(E) adsorption cooling cycle. This cycle will be powered by process waste heat or waste heat from the automobile engine. A cycle simulation computer program of the novel adsorption cooling system is developed to analyze the cooling capacity and coefficient of performance (COP) variations by varying adsorption/desorption cycle times, regeneration temperatures and cooling water inlet temperatures.

Working principle of AC- R1234ze(E) adsorption cooling cycle

Figure 1 shows the schematic diagram of the two bed adsorption cooling cycle which consists of a condenser, an evaporator, two sorption beds filled with activated carbon. The details of the adsorption cooling system have been presented by Chua et el. [2].

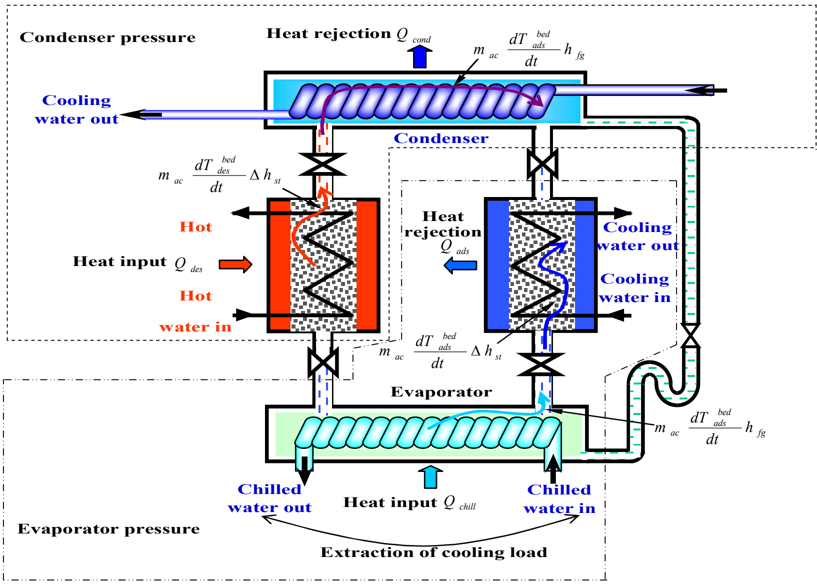

Figure 1: Schematic diagram of two bed adsorption chiller [2].

Mathematical modeling

Adsorption isotherms

Tóth model is used to estimate the equilibrium uptake of AC-R1234ze(E) cycle [6].

$$x = x_0 \frac{kP}{\left[1+(bP)^t\right]^{\frac{1}{t}}} \tag{1}$$

$$k = k_0 \exp\left(\frac{\Delta h_{st}}{RT}\right) \tag{2}$$

Adsorption kinetics

The rate of adsorption or desorption is governed by the linear driving force model [7].

$$\frac{dx}{dt} = 15 D_{so} \frac{\exp\left(-\frac{E_a}{RT}\right)}{R_p^2}\left(x^* - x\right) \tag{3}$$

Adsorption and desorption energy balance

Using the lumped approach for the adsorption bed, which comprises activated carbon, the heat exchanger fins and tubes, the energy balance equation is given by [2],

$$\left[m_{ac}C_{p,ac} + m_{ac}C_p^{ref}x^{ref} + m_{Al}C_{p,Al} + m_{Cu}C_{p,Cu}\right]\frac{dT^{ref}_{ads/des}}{dt} = \delta m_{ac}\left\{h_g\left(P^{ref}_{eva/cond}, T^{ref}_{ads/des}\right) - h_g\left(T^{ref}_{eva/cond}\right) + \Delta h^{ref}_{st}\right\}\frac{dx^{ref}_{ads/des}}{dt} +$$
$$\dot{m}_w C_{p,w}\left(T^{ref}_{w,in,ads/des} - T^{ref}_{w,o,ads/des}\right) \tag{4}$$

The outlet temperature of the source is to be modeled by the log mean temperature difference (LMTD) method and it is given by,

$$T_{w,o,bed}^{ref} = T_{bed}^{ref} + \left(T_{w,in,bed}^{ref} - T_{bed}^{ref}\right)\exp\left[-\frac{(UA)_{bed}^{ref}}{\left(\dot{m}C_p\right)_w}\right] \tag{5}$$

Evaporator energy balance
The evaporator energy balance of adsorption cycle can be expressed as [2]:

$$\left[m_{eva}^{ref}C_{p,eva} + m_{hex}C_{p,Cu}\right]\frac{dT_{eva}^{ref}}{dt} = -\delta\left\{h_g\left(P_{eva}^{ref}, T_{ads}^{ref}\right) - h_g\left(T_{eva}^{ref}\right) + h_{fg}^{ref}\right\}m_{ac}\frac{dx_{ads}^{ref}}{dt} + \left(\dot{m}C_p\right)_{chill}\left(T_{chill,in} - T_{chill,o}\right) \tag{6}$$

The water outlet temperature can be expressed as,

$$T_{chill,o} = T_{eva}^{ref} + \left(T_{chill,in} - T_{eva}^{ref}\right)\exp\left[-\frac{(UA)_{eva}^{ref}}{\left(\dot{m}C_p\right)_w}\right] \tag{7}$$

Condenser energy balance
The condenser energy balance of adsorption cycle can be expressed as [2]:

$$\left(m_{cond}^{ref}C_{p,cond} + m_{hex}^{ref}C_{p,Cu}\right)\frac{dT_{cond}^{ref}}{dt} = -\delta\left\{h_g\left(P_{cond}^{ref}, T_{des}^{ref}\right) - h_g\left(T_{cond}^{ref}\right) + h_{fg}^{ref}\right\}m_{ac}\frac{dx_{des}^{ref}}{dt} + \dot{m}_w C_{p,w}\left(T_{w,in,cond}^{ref} - T_{w,o,cond}^{ref}\right) \tag{8}$$

The condenser outlet temperature can be expressed as:

$$T_{w,o,cond}^{ref} = T_{cond}^{ref} + \left(T_{w,in,cond}^{ref} - T_{cond}^{ref}\right)\exp\left[-\frac{(UA)_{cond}^{ref}}{\left(\dot{m}C_p\right)_w}\right] \tag{9}$$

Cooling Capacity and coefficient of performance
The cooling capacity is obtained at the evaporator of adsorption cycle.

$$Q_{eva}^{cycle} = \frac{1}{t_{cycle}}\int_0^{t_{cycle}}\left(\dot{m}C_p\right)_w\left(T_{chill,in} - T_{chill,o}\right)dt \tag{10}$$

The coefficient of performance (COP) of adsorption cycle can be expressed as:

$$COP = \frac{\int_0^{t_{cycle}}(\dot{m}c_P)_{chill}\left(T_{chill,in} - T_{chill,o}\right)dt}{\int_0^{t_{cycle}}(\dot{m}c_P)_{des}\left(T_{h,in} - T_{h,o}\right)dt} \tag{11}$$

Results and discussion

Chiller transient response

Figure 2 shows the chiller temporal histories for all the components (adsorber, desorber, evaporator and condenser) by using the mathematical model presented herein. Table 1 depicts the rated conditions for adsorption cycle. The values of the symbols used in the present simulation model are furnished in the reference [2]. It can be seen from Fig. 2, the AC-R1234ze(E) based adsorption chiller is able to reach from transient to nearly steady state within three half cycles or 1900s, where adsorption/desorption cycle time is taken as 480 s and switching time is taken as 50s.

Table 1: Rated conditions

Hot water inlet		Cooling water inlet		Chilled water inlet	
Temperature (°C)	Flow rate (kg/s)	Temperature (°C)	Flow rate (kg/s) (ads+cond)	Temperature (°C)	Flow rate (kg/s)
85	1.0	30	(1.0+1.0)	14	0.5
Adsorption/desorption cycle time: 480s			Switching time: 50s		

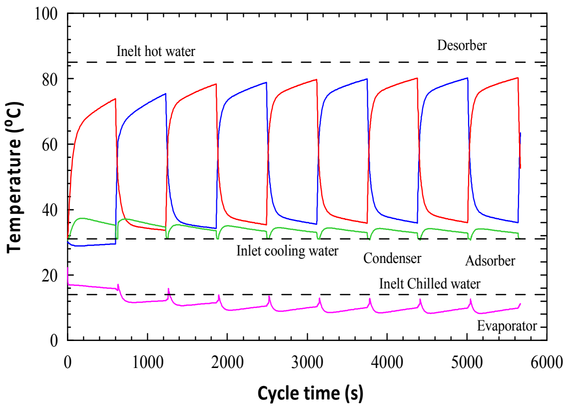

Figure 2: Temperature profiles for various components of AC-R1234ze(E) cycle at rated conditions

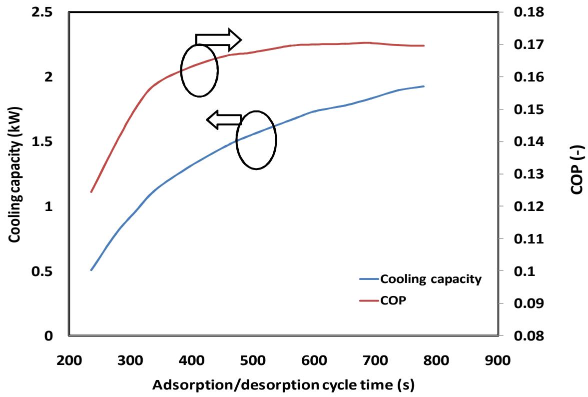

Figure 3: Effects of adsorption/desorption cycle time on cooling capacity and COP

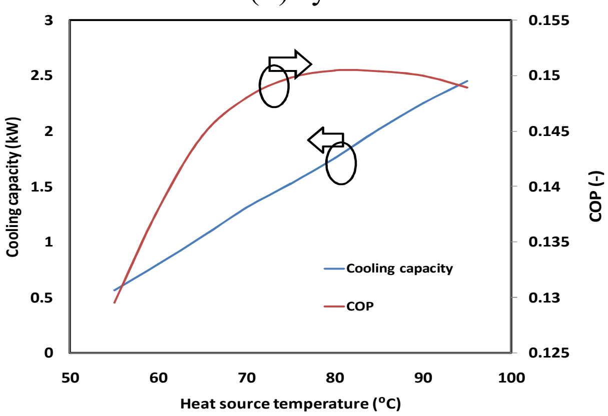

Figure 4: Effects of regeneration temperature on cooling capacity and COP

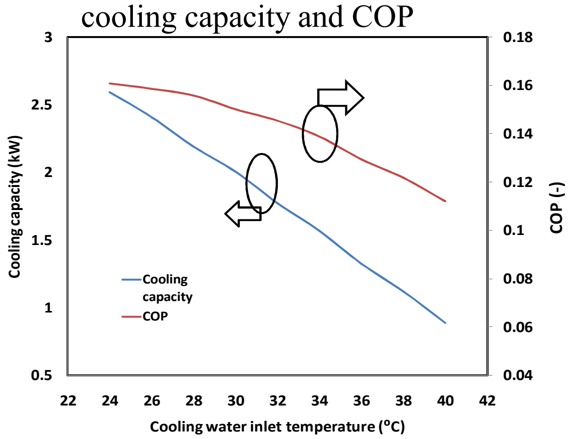

Figure 5: Effects of cooling water inlet temperature on cooling capacity and COP

Adsorption/desorption cycle time

The simulated results of cooling capacity and COP variations with adsorption/desorption cycle time for AC- R1234ze(E) cycle are shown in Fig. 3. From the Fig. 3, it is observed that for AC-R1234ze(E) cycle, the highest cooling capacity is around 1.5 kW for cycle times between 480 and 520s. From the Fig. 3 it is noted that the COP increases uniformly with the increase of adsorption/desorption cycle time and after reaching a certain value (around 480 s) it becomes steady.

Regeneration temperature

Figure 4 shows the effects of heat source temperature on cooling capacity and COP for AC-R1234ze(E) cycle. From Fig. 4, it is noticeable that the cooling capacity increases linearly from 0.6

to 2.5kW with heat source temperature varies from 55 to 95ºC. The optimum COP value is around 0.145 for AC- R1234ze(E) system when the regeneration temperature is between 80 to 85ºC.

Cooling water inlet temperature

The effects of cooling water inlet temperature on cooling capacity and COP for AC- R1234ze(E) cycle is illustrated in Fig. 5. It is observable from Fig. 5 that the cooling capacity decreases linearly from 2.5 to 1kW with cooling water inlet temperature varies from 24 to 40ºC.

Conclusion

The paper investigates the transient analysis of a two-bed activated carbon (AC)-R1234ze (E) based adsorption cooling cycle. The proposed adsorption system is well suited for waste heat powered room air conditioning applications. The prime advantage of R1234ze (E) is that it has very low GWP as well as zero ODP compared to R134a. The present study seems to be promising for automobile air conditioning applications.

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