Study on two stage activated carbon/HFC-134a based adsorption chiller

K Habib[1]*, M Amin B A Majid[1] and Shaharin Anwar B Sulaiman[1]

[1]Mechanical Engineering Department, Universiti Teknologi PETRONAS
Bandar Seri Iskandar, 31750 Tronoh, Perak Darul Ridzuan
Malaysia

*E-mail: khairul.habib @petronas.com.my

Abstract. In this paper, a theoretical analysis on the performance of a thermally driven two-stage four-bed adsorption chiller utilizing low-grade waste heat of temperatures between 50°C and 70°C in combination with a heat sink (cooling water) of 30°C for air-conditioning applications has been described. Activated carbon (AC) of type Maxsorb III/HFC-134a pair has been examined as an adsorbent/refrigerant pair. FORTRAN simulation program is developed to analyze the influence of operating conditions (hot and cooling water temperatures and adsorption/desorption cycle times) on the cycle performance in terms of cooling capacity and COP. The main advantage of this two-stage chiller is that it can be operational with smaller regenerating temperature lifts than other heat-driven single-stage chillers. Simulation results shows that the two-stage chiller can be operated effectively with heat sources of 50°C and 70°C in combination with a coolant at 30°C.

1. Introduction

Due to the severity of the ozone layer destruction in the atmosphere, a central challenge in cooling science today is the development of freon-free refrigeration and air-conditioning systems, which occurs partly due to the production and utilization of CFCs and HCFCs in refrigeration. Heat driven adsorption cooling systems seem to be an alternative option as these systems do not utilize electricity as the driving heat sources and mainly non-toxic and environmentally friendly refrigerants. Several heat-pumping and refrigeration applications have been studied using various adsorbent and refrigerant pairs. Some representative examples are silica gel-water [1], zeolite-water [2] activated carbon-ammonia [3], activated carbon-methanol [4] etc. Most of the adsorption cooling cycles require medium and/or high temperature heat sources to act as the driving sources. However, many researchers reported that silica-gel/water and activated-carbon (AC)/methanol adsorption cooling systems can be driven by heat of relatively low, near-ambient temperatures, so that the waste heat below 100°C can be recovered and used [5-6].

This study deals with the utilization of unexploited, near ambient temperature between 50°C and 70°C as the driving heat source with a cooling source of 30°C, and presents the theoretical analysis of a two-stage advance adsorption cooling system where activated carbon (Maxsorb III) and HFC-134a are used as adsorbent-refrigerant pair. Temperature profiles of all the system components (adsorber,

---

[1] Khairul Habib.

desorber, condenser and evaporator) have been investigated. The influences of heat transfer fluid temperature and flow rate as well as the cycle time on the system performance in terms of cooling load and COP are determined theoretically.

2. Working principle of two-stage adsorption cooling cycle

Figure 1 shows the conceptual Dühring diagram (P-T-x) of a conventional and an advanced two-stage adsorption chiller. For practical utilization of renewable energy heat sources such as solar energy, an advanced (two stage) adsorption cooling system is presented here. The operation of this cycle is based on reducing the temperature left of adsorbent ($\Delta T_{reg} = T_{cond} - T_{eva}$) into two smaller temperature lifts. The refrigerant pressure is therefore rises into two progressive pressure steps from the evaporator pressure to the condenser pressure. To achieve this condition an additional two sorption elements are added to the conventional system as shown in Figure 2. The two-stage four bed adsorption cooling system then comprises of six heat exchangers, namely, a condenser, an evaporator and two pairs of sorption elements (SEs). The details of the working principle of two-stage adsorption cycle have been described elsewhere [5].
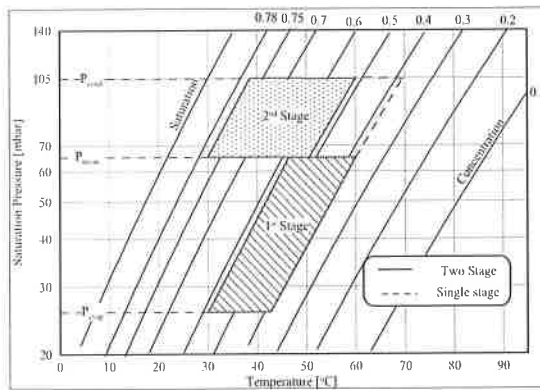

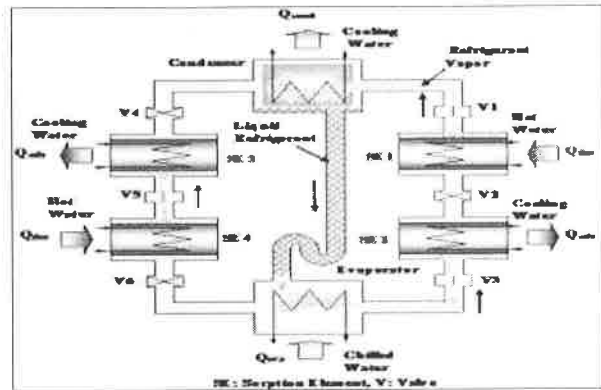**Figure 1**. Conceptual Dühring diagram of two-stage adsorption chiller

Figure 2. Schematic diagram of two-stage adsorption chiller.

3. Mathematical modelling

3.1. Adsorption isotherms

Dubinin-Astakhov (D-A) model, which is expressed by Eq. (1), is used to estimate the equilibrium uptake of the AC/HFC-134a

$$W = W_0 \exp\left[-\left\{\frac{RT}{E}\ln\left(\frac{p_s}{p}\right)\right\}^{n}\right] \tag{1}$$

Saha et al. [7] measured the adsorption characteristics of AC-R134a pair and obtained the numerical values of W_0, E and n as 1.66 x 10^{-3} m^3/kg, 82.9 x 10^3 J/kg and 1.3, respectively.

3.2. Adsorption kinetics

In the current adsorption chiller model, the rate of adsorption or desorption is governed by the Fickian diffusion model [8].

3.3. Isosteric heat of adsorption

The isosteric heat of adsorption for AC-R134a has been expressed elsewhere. [9]

3.4. Adsorption or desorption energy balances

The adsorption bed comprises activated carbon, the heat exchanger fins and tubes, and the energy balance equation is given by [10],

$$\left[m_{ac}C_{p,ac} + m_{ac}C_p^{ref}x^{ref} + m_{Al}C_{p,Al} + m_{Cu}C_{p,Cu}\right]\frac{dT_{bed}^{ref}}{dt} = \delta m_{ac}Q_{st}^{ref}\frac{dx_{bed}^{ref}}{dt} +$$

$$\dot{m}_w C_{p,w}\left(T_{w,in}^{ref} - T_{w,out}^{ref}\right) - \lambda m_{ac}C_{p_v}\left(T_{ads} - T_{eva}\right)\frac{dx}{dt} \tag{2}$$

The outlet temperature of the source is sufficiently accurate to be modelled by the log mean temperature difference (LMTD) method and it is given by:

$$T_{w,out,bed}^{R134a} = T_{bed}^{R134a} + \left(T_{w,in,bed}^{R134a} - T_{bed}^{R134a}\right)\exp\left[-\frac{(UA)_{bed}^{R134a}}{\left(\dot{m}C_p\right)_w}\right] \tag{3}$$

Similarly, the energy balance equations of the evaporator, condenser and cooling capacity and COP can be expressed [10].

4. Results and discussion

4.1. Chiller transient response

Figure 3 shows the chiller temporal histories for the reactor beds (adsorber/desorber heat exchangers), evaporator and condenser for the two-stage cycle where hot water temperature has been chosen as 60 °C along with a coolant at 30 °C. The values used in the present simulation are shown in Table 1 [11]. The chilled water inlet temperature is taken as 14 °C. It can be observed from Figure 3 that the adsorption cycle in two-stage operation is able to reach from transient to nearly steady state within 1800 s.

4.2. Heat source temperature

Figure 4 indicates the effects of regeneration temperature on cooling capacity for both single stage and two-stage cycles with a fixed cooling water inlet temperature at 30°C. It is visible from Figure 4 that cooling capacity increases linearly from 0.6 to around 8 kW as the hot water inlet temperature is increased from 45 to 80°C. As observed in Figure 4, the two stage cycles gives comparable cooling capacities when the hot water inlet temperature is between 60 and 70°C. However, when the hot water inlet temperature is less than 55°C, the two-stage cycle could still be operated, a region that could not be reached by the single stage.
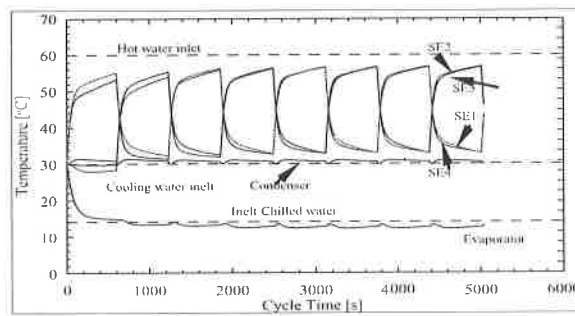

Figure 3. Temperature profiles of different components of AC-HFC 134a cycle at rated conditions
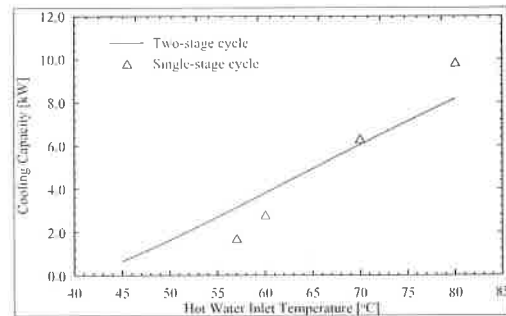
Figure 4. Effect of cooling capacity on heat source temperature.

Figure 5 shows the change of COP of single-stage and two-stage system with the hot water inlet temperature. Being operated by the lower range of inlet hot water temperature, it is expected that the COP of the two stage cycle is lower. The superiority of two-stage cycle is again demonstrated when the inlet hot water temperature is lower than 55°C.
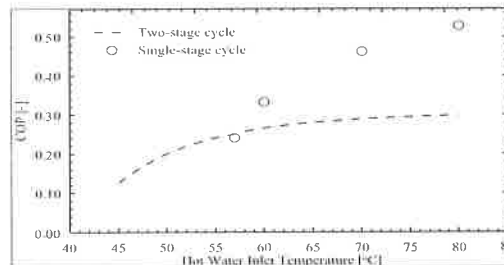

Figure 5. Effects of COP on heat source temperature.

5. Conclusions

The main advantage of the AC/HFC-134a based two-stage adsorption chiller is that it can operate even when the driving heat source temperature is low (typically between 55 to 70°C). The simulation results show that the single-stage chiller is superior when the heat source temperature is relatively higher (above 75°C). However, when the regeneration temperature is at or below 55°C, the two-stage chiller could still be operated, a region that could not be reached by single-stage chiller.

Acknowledgements

References

[1]　Chua H T, Ng K C, Malek A, Kashiwagi T, Akisawa A and Saha B B 1999 *Int. J. Refrig.* **22** 194

[2]　Wang D C, Xia X X and Wu J Y 2006 *Energ. Conv. Manage.* **47** 590

[3]　Miles D J and Shelton S V 1996 *Appl. Therm. Eng.* **16** 389

[4]　Anyanwu E E and Ezekwe C I 2003 *Energ. Conv. Manage.* **44** 2879

[5]　Saha B B, Akisawa A and Kashiwagi T 2001 *Renew. Energ.* **23** 93

[6]　Ferreira Leite A P and Daguenet M 2010 *Energ. Conv. Manage.* **41** 1625

[7]　Saha B B, Habib K, El-Sharkawy I I and Koyama S 2009 *Int. J. Refrig.* **32** 1563

[8]　Habib K, Saha B B, Rahman K A, Chakraborty A, Koyama S and Ng K C 2010 *Int. J. Refrig.* **33** 706

[9]　El-Sharkawy I I, Saha B B, Koyama S and Srinivasan K 2007 *Int. J. Heat and Mass Trans.* **26** 902

[10]　Habib K, Saha B B and Chakraborty A, El-sharkawy I I and Koyama S 2008 *Eng. Science Reports Kyushu Univ.* **30** 383