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Investigation of Cascading Adsorption Refrigeration System with Integrated Evaporator-Condenser Heat Exchanger Using Different Working Pairs

H.J. Dakkama[a,b,c,*], A. Elsayed[a,d], R.K. Al-Dadah[a], S.M. Mahmoud[a], P. Youssef[a]

[a]*School of Mechanical Engineering, University of Birmingham, United Kingdom, B15 2TT*
[b] *Engineering Technical College –Baghdad, Middle Technical University, Baghdad, Iraq*
[c]*The Higher Committee for Education Development in Iraq*
[d]*Mechanical Engineering Department, Alexandria University, Egypt.*

Abstract

This paper investigates the performance of various adsorbent/refrigerant working pairs in a cascaded adsorption system using Simulink/Matlab software. The cascaded system consists of two pairs of adsorber beds, condenser, evaporator and an integrated condenser/evaporator heat exchanger, forming upper and bottoming cycles. Four combinations of working pairs were investigated: ATO-Ethanol + Maxsorb/R507A, Maxorb/R134a + Maxorb/Propane and ATO/Ethanol + Maxorb/Propane and Maxorb/R134a + Maxsorb/R507A. The latter case was used for validation and as a reference point for assessing the performance of the investigated working pairs in term of COP and cooling capacity. Results showed that the Maxorb/R134a + Maxorb/Propane combination gives a higher enhancement compared to reference one with up to 30.0% and 30.1% for the COP and cooling capacity, respectively. ATO/Ethanol + Maxorb/Propane combination is the cheapest but with lower performance.

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Keywords: Adsorption; Cascading; Working Pairs; Freezing; Simulink;

1. Introduction

Adsorption cooling is an environmental benign technology where waste heat is utilized to drive cooling systems. However, one of their drawbacks is the low coefficient of performance [1]. System cascading is one of the adsorption system improvement techniques that were reported to enhance the COP by 60% and 50% of intermittent and two beds cycles [2 - 4]. Different working pairs have been utilized by researchers including Maxsorb/R134a+Maxsorb/R507A (evaporation / desorption temperature = -10ºC / 70ºC) [5], Zeolite-water+AC-methanol (evaporation / desorption temperature = -10ºC / 275ºC and 110 ºC) [6], zeolite-13X /water+SWS-2L/water [7], manganese chloride/ammonia+barium chloride/ammonia (evaporation / desorption temperature = 15C /90 & 160ºC) [8].

*Corresponding author. Tel.: +447405794147
E-mail address: hjd231@bham.ac.uk.

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However, no clear comparison available in literature regarding selection of working pairs suitable for low evaporating temperature and low desorption temperature where low temperature heat sources can be used. Therefore, this work investigates four combinations of adsorbent/refrigerant pairs namely, ATO-Ethanol & Maxsorb-R507A, Maxorb-R134a & Maxorb-Propane and ATO-Ethanol & Maxorb-Propane and Maxorb-R134a & Maxsorb-R507A. Such pairs have been reported to have good adsorption characteristics and suitable for low temperature cooling thus can produce energy efficient adsorption system for ice making [5,10,11,14]. Simulink software package has been utilized to solve the differential system of equations representing the cascaded adsorption system linked with Refprop package to utilise the thermo physical properties of different fluids.

Nomenclature

A	area	U	overall heat transfer coefficient, [W/m2/K]
Cp	Specific heat, [kJ/kg/K]	x	instantaneous uptake, [kg_{ref}/kg_{ads}]
COP	coefficient of performance, [_]	**Subscript:**	
Dso	pre-exponetial constant, [m2/s]	AC	Activated carbon (adsorbent)
Ea	activation energy, [kJ/kg]	ads	Adsorption
Fp	particle shape factor [_]	Al	Aluminum
h	enthalpy, [kJ/kg]	bed	Adsorber bed
ksav	overall mass transfer coefficient, [1/s]	cond	Condenser
m	characteristic energy of the system, [kJ/kg]	Cu	Copper
$\dot{m}$	mass flow rate, [kg/s]	des	Desorption
n	heterogeneity parameter, [_]	evap	Evaporator
Q	heat power, [kW]	g	gas
Qst	isostric heat of adsorption, [kJ/kg]	heating	Heating at desorption and switching time
R	universal gas constant=8.314, [J/mol/K]	hot	Hot heat transfer source
Rp	adsorbent particle radius, [m]	in	inlet
T	temperature, [K]	ref	Refrigerant (adsorbate)
t	time, [sec]	w	Water

2. Simulink Modelling for Cascading Adsorption Refrigeration System

Simulink has been utilized to model transient operation of cascaded adsorption system. The differential equations 1-12 have been solved using integral blocks to determine condensation, evaporation, desorption, adsorption temperatures and cyclic uptake of refrigerants in upper and bottoming cycles using different working pairs. Table 1 lists the constants required for equations 1-2 and Figure 1 shows a flow chart of the cascaded adsorption system model developed in Simulink.

Equilibrium uptake [9]:

$$x_{eq} = x_o \exp\left(-\left(R.T \ln(P_s / P)/m\right)^n\right) \quad (1)$$

Adsorption-desorption rate [10, 13]:

$$dx/dt = \left(F_p D_{so} / {R_p}^2\right) \times \exp\left(-E_a/(RT)\right) \times \left(x_{eq} - x\right) \tag{2}$$

Heat balance for adsorber/ desorber:

$$\left(m_{AC}\left(C_{p\,AC} + C_{p_{ref}}.x\right) + m_{Al}.C_{p\,Al} + m_{Cu}.C_{pCu}\right)\frac{dT_{ads/des}}{dt} = \delta m_{AC}\left[h_g\left(P_{evap/cond}, T_{ads/des}\right) - h_g\left(T_{evap/cond}\right) + Q_{st}\right]\frac{dx_{ads/des}}{dt} + \dot{m}_{w,ads/des} C_{p_w}\left(T_{w,in,ads/des} - T_{w,out,ads/des}\right) \tag{3}$$

The outlet heat transfer fluid from adsorber /desorber:

$$T_{w,out,ads/des} = T_{bed} + \left(T_{w,in,bed} - T_{bed}\right)\exp\left(-(UA)_{bed}/\left(\dot{m}.C_p\right)_w\right) \tag{4}$$

Heat balance for condenser:

$$\left(m_{ref}.C_{p_{ref}} + m_{Cu}.C_{p_{Cu}}\right)\frac{dT_{cond}}{dt} = -\delta m_{AC}\left[h_g\left(P_{cond}, T_{des}\right) - h_g\left(T_{cond}\right) + h_{fg}\right]\frac{dx_{des}}{dt} + \dot{m}_{w,cond} C_{p_w}\left(T_{w,in,cond} - T_{w,out,cond}\right) \tag{5}$$

The outlet heat transfer fluid from condenser:

$$T_{w,out,cond} = T_{cond} + \left(T_{w,in,cond} - T_{cond}\right)\exp\left(-(UA)_{cond}/\left(\dot{m}.C_p\right)_w\right) \tag{6}$$

Heat balance for evaporator:

$$\left(m_{ref}.C_{p_{ref}} + m_{Cu}.C_{p_{Cu}}\right)\frac{dT_{evap}}{dt} = -\delta m_{AC} h_{fg}\frac{dx_{ads}}{dt} - \delta m_{AC} C_{p_{ref}}\left(T_{cond} - T_{evap}\right)\frac{dx_{des}}{dt} + \dot{m}_{Brine} C_{p_{Brine}}\left(T_{Briein,in} - T_{Brine,out}\right) \tag{7}$$

The outlet heat transfer fluid from evaporator:

$$T_{Brine,cond} = T_{evap} + \left(T_{Brine,in} - T_{bed}\right)\exp\left(-(UA)_{evap}/\left(\dot{m}.C_p\right)_{brine}\right) \tag{8}$$

Heat balance for integrated Evaporator-condenser:

$$\left(m_{ref}.C_{p_{ref}} + m_{Cu}.C_{p_{Cu}}\right)\frac{dT_{cond/evap}^{bottom/upper}}{dt} = -\delta m_{AC}\left[h_g\left(P_{cond}, T_{des}\right) - h_g\left(T_{cond}\right) + h_{fg}\right]_{bottom} \frac{dx_{des}^{bottom}}{dt} - \delta m_{AC}\left[h_g\left(P_{evap}, T_{ads}\right) - h_g\left(T_{evap}\right) + h_{fg}\right]_{upper}\frac{dx_{ads}^{upper}}{dt} \tag{9}$$

The cooling capacity of system:

$$Q_{evap}^{Bottom} = \left(1/t_{cycle}\right)\dot{m}_{Brine} C_{p\,Brine}\int_0^{tcycle}\left(T_{Brine,in} - T_{Brine,out}\right)dt\Big|_{Bottom,cycle} \tag{10}$$

The consumed heat during preheating and desorption process:

$$Q_{heating}^{Upper/\,Bottom} = \left(1/t_{cycle}\right)\dot{m}_{w,hot}C_{p_{w,hot}}\int_0^{tcycle}\left(T_{hot,w,in}-T_{hot,w,out}\right)dt\Big|_{Upper/\,Bottom} \quad (11)$$

The coefficient of performance of the system:

$$COP = Q_{evap}^{Bottom}/\left(Q_{heating}^{Upper}+Q_{heating}^{Bottom}\right) \quad (12)$$

Table.1. Empirical parameters of adsorption isotherm [5,10,11,14]

	E_a(J/mol)	R_p(m)	F_p.D_{so}/R_p^2	D_{so}(m^2/s)	x_o(kg/kg)	n	F_p	k_{sav}(1/s)
Maxsorb-Ethanol:	40276.718	95×10-6	7175.344	_	1.12934	2.3169	_	_
ATO-Ethanol:	47830	365.1×10-6	187423.9	_	0.4368	2.3169	_	_
Maxsorb-Propane:	_	_	_	_	0.96	1.220.	_	006395
Maxsorb-R134a:	7332.69	36×10-6	_	1.44×10-1	2.22	1.29	9.8596	_
Maxsorb-R507A:	7547.24	36×10-6	_	3.41×10-11	2.05	1.34	9.8596	_

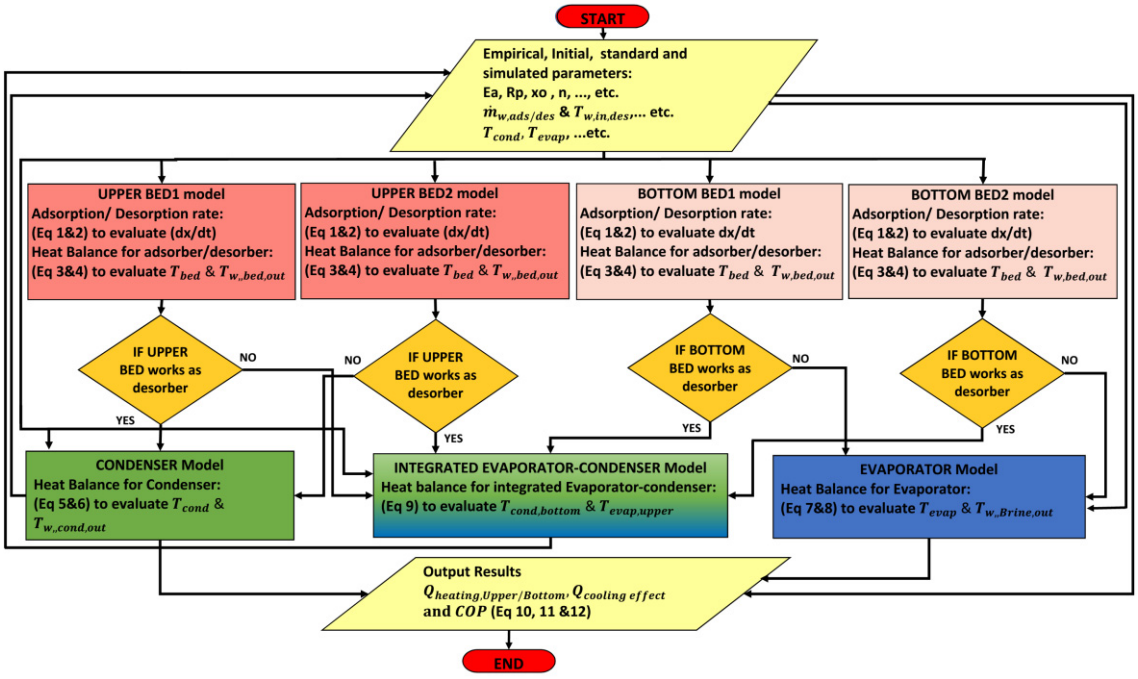


Fig.1. Flow chart of cascading ice-making system model developed in Simulink

3. Validation of the Simulink Model and Results

The model has been validated using Habib et al. [5] with testing condition summarized in Table 2 using Maxsorb/R507a in the bottom cycle and Maxsorb/R134a in the upper cycle. Figure 2 shows the good agreement in the predicted temperature profile with ±6% deviation in the evaporator temperature, ±2.7 in the condenser temperature, ±3.6 upper bed temperature and ±1.3 bottom bed temperature. Figure 3 compares the cooling load of the four working pair combinations showing that the highest cooling capacity is produced by Maxsorb-R134 & Maxsorb-Propane with up to 1.8kW at cycle time of 350seconds. ATO-Ethanol & Maxsorb-Propane and ATO- Ethanol & Maxsorb-R507A produced similar

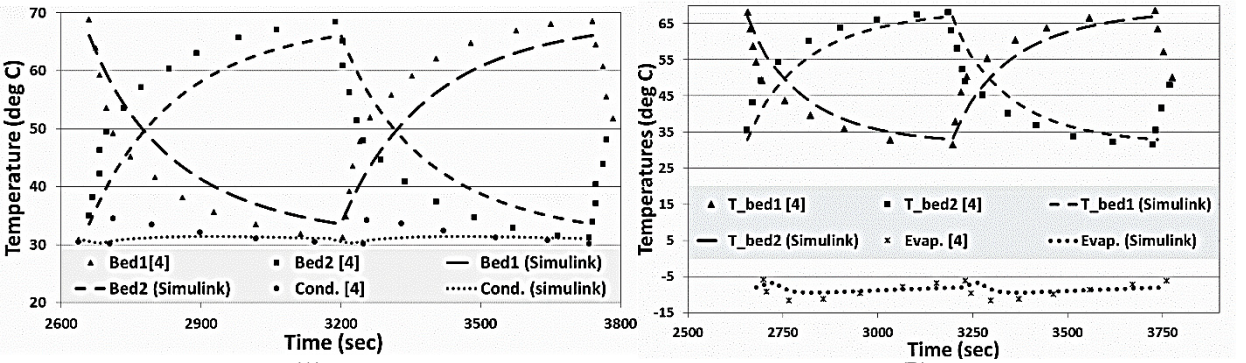
cooling output at all cycle times except for 1800 seconds cycle time. Also Figure 3 shows that as the cycle time increases, the cooling output decreases for all the working pairs. The Maxsorb-R134a & Maxsorb-Propane system produced lowest brine temperature of -11.7°C with highest cooling capacity of 1.8kW and COP up to 0.088. This could be explained by the high latent heat of evaporation of Propane compared to R507A and high pressure of R134a compared to ethanol that enables it to penetrate in the adsorbent pores quickly. Figure 4 compares the COP of the cascaded system with the various adsorption pair combinations showing that Maxsorb-R134 & Maxsorb-Propane produces the highest COP values among all combinations used. However, as the cycle time decreases, the COP decreases.

Table.2. Initial and standard values, as given in [4]

Symbols	Value	Units	Symbols	Value	Units
$\dot{m}_{w,ads/des/cond}$	0.3	kg/s	$(UA)_{evap}$	4770	W/K
$\dot{m}_{Brine}$	0.1	kg/s	$(UA)_{cond}$	15300	W/K
$T_{w,in,des}$	70	°C	m_{AC}	50	kg
$T_{w,in,des/cond}$	30	°C	$m_{ref,cond/evap}$	25/13	kg
$T_{Brine,in}$	-5	°C	Half cycle time	540	sec
$(UA)_{bed}$	3500	W/K	Switching time	50	sec

Conclusion

An investigation of efficient working pairs for low temperature cooling adsorption cascaded system has been made. Simulink Matlab software has been used to model the dynamic operation of adsorption chiller. Results showed Maxsorb/R134a+Maxsorb/Propane has better performance to other tested working pairs due to the high latent heat of propane and high pressure of R134a.



(A) (B)

Fig.2.Validation of Temperatures trends with Habib's work of: (A) of Maxsorb-R134a cycle (B) Maxsorb-R507A

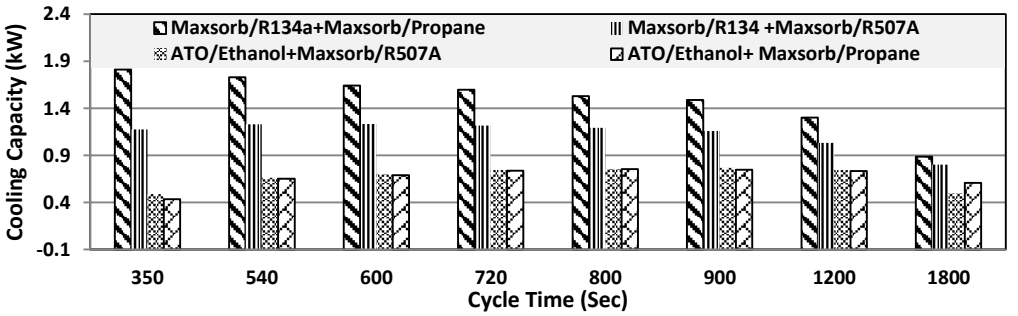


Fig.3. The effect of cycle time on the cooling capacity for different working pairs

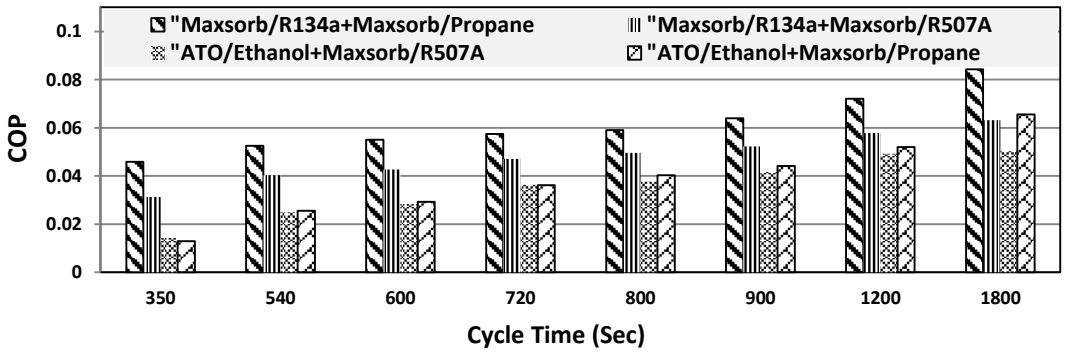


Fig.4. The effect of cycle time on the COP for different working pairs

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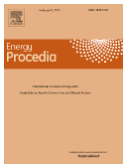

Biography

Hassan Dakkama is currently a second year PhD student in Mechanical Engineering at the University of Birmingham. His research is focused on adsorption refrigeration systems. He previously completed the B.Sc. in Air Conditioning & Refrigeration specializing (2001-2005) and M.Sc. study in Solar and Renewable Energy (2005-2008) both from Iraq.