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Theoretical Study on the performance of adsorption refrigeration cycle using activated carbon – ethanol working pair

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Abstract

This study presents a lumped parameter modeling for one-bed, condenser, and evaporator of adsorption cooling system that uses activated carbon (AC)/ethanol as working pair. Pressure profile and evaporator temperature of the adsorption/desorption bed are presented. The simulation results showed the effect of cooling water inlet temperature, chilled water inlet temperature, and hot water inlet temperature (regeneration temperature) on the Coefficient of Performance (COP) and Specific Cooling Power (SCP) of adsorption refrigeration system. It is found that the COP and SCP increase with decreasing the cooling water inlet temperature. The minimum evaporator temperature reaches about 7 ºC at cooling water inlet temperature of 17 ºC achieving a maximum COP and SCP of 0.33 and 340 W/kg, respectively under adsorption/desorption cycle time of 1050 s. Increasing in the chilled water temperature leads to an increasing in the COP and SCP. It is found that increasing hot water inlet temperature decreasing COP and increasing SCP of the system.

Nomenclature

A	Area (m^2)	$\dot{m}$	mass flow rate (kg/s)
C_p	specific heat capacity (J /kg.K)	P	pressure (Pa)
D	exponential constant (K^{-1})	P_{sat}	saturated pressure (Pa)
Dso	pre-exponential constant ($m^2\ s^{-1}$)	U	overall heat transfer coefficient ($W/m^2.K$)
E_a	activation energy ($J\ kg^{-1}$)	x	instantaneous uptake (kg /kg)
H	enthalpy ($J\ kg^{-1}$)	X	equilibrium uptake (kg/kg)
$k_s a_v$	mass transfer coefficient (s^{-1})	x_0	maximum uptake (kg/kg)
M	mass (kg)	dH_{st}	isosteric heat of adsorption (J/kg)

Subscripts

AC	activated carbon	cond	Condenser
ads	Adsorption	cu	Cubber
In	Inlet	chin	Inlet chilled water
out	Outlet	chout	Outlet chilled water
evap	Evaporator	w	Water
b	bed	SCP	Specific cooling power
COP	Coefficient of performance	ART	Adsorption refrigeration tube

Introduction

Refrigeration and air conditioning needs are appreciably developing because of the growth in people's living standards further to the dramatically growth of industries. A lot of refrigeration techniques were developed during the last few decades. The traditional refrigeration systems such as vapor compression system are widely used, but it consume a huge amount of electrical power, in addition to air pollution and ozone layers depletion due to using of refrigerants such as CFC and HCFC. Therefore, alternative refrigeration techniques became very much needed. Especially for people living in remote areas that lack electricity, so people cannot preserve their food and store vaccine. Accordingly, new technology such as Adsorption refrigeration system (ARS) has more interest in development in last two decades. That is because of the sorption system is quit (no moving parts), cheap to maintain and environmentally friend [1]. Adsorption refrigeration system is thermally driven refrigeration system, which can be powered by solar energy as well as waste heat. Adsorption systems mainly use a natural working fluid called adsorbate such as ammonia, water, ethanol and methanol. And use solid which called adsorbent such as zeolite, silica gel and activated carbon. Habib et al. [2] investigated a various types of adsorption refrigeration pairs such as activated carbon-methanol, activated carbon fiber-ethanol and silica gel-water. Their work showed that AC- ethanol pair has the highest adsorption uptake, but Silica gel-water pair has the highest COP values when regeneration temperature is below70 ºC. Shmroukh et al [3] also studied the adsorption refrigeration systems working pairs. They divided the working pair types in to two categories classical and modern working pairs. Classical such as zeolite/water, silica-gel/water and activated-carbon/methanol, and modern working pairs such as activated carbon-R134a. the study investigate that the maximum adsorption capacity for the classical working pairs was 0.259 kg/kg for activated carbon/methanol pair and that for the modern working pairs was 2 kg/kg for maxsorb III /R- 134a pair. A lot of researches such as [4,5] studied the adsorption refrigeration cycle for different pairs. Astina et al [6] investigated the adsorption refrigeration system using AC- ethanol as working pair. It found that Ethanol-AC pair can be operated with the heat source temperatures 90 ºC and 100 ºC for different heat sink temperature 20 ºC, 25 ºC and 30 ºC and The maximum adsorption capacity is 0.302 kg/kg. Khanam et al [7] analyzed the effect of adsorption heat exchanger design on increasing the performance of adsorption refrigeration system, it found that the optimum cycle time is 800S, and the equivalent evaluated specific cooling power (SCP) and coefficient of performance (COP) were found to be 488 W/kg and 0.61, respectively. From the above view, the present study deals with the performance study of one-bed, AC-ethanol adsorption system. A cycle simulation computer program of the one -bed AC–ethanol system is established to study the cooling capacity and COP variations by changing heat transfer fluid (hot and cooling water) inlet temperatures and regeneration bed temperature. Miyazaki et al [8] studied one bed adsorption refrigeration system using on AC powder – ethanol as working pair. In this study they enhance the setting time for the four cycle processes to achieve the highest SCP, it found that to the desorption time must be less than the adsorption time to achieve the highest SCP and it is expected that the COP will be 0.48 and SCP will be 140 W/kg for conditions 80ºc, 30ºc, 14ºc for hot water, cooling water and chilled water, respectively. TSO et al [9] investigated the enhancement of COP of adsorption refrigeration cycle driven by waste heat and using activated carbon impregnated by soaking in sodium silicate solution and then in calcium chloride solution, it study the effect of the temperature of inlet hot water, chilled water, inlet cooling water and cycle time on the coefficient of performance and SCP of the cycle, it is found that high SCP 380 W/kg, COP 0.65 can be obtained by using hot water temperature of 85 ºC, inlet cooling water 30 ºC and inlet chilled water 14 ºC. Marzia et al [10] studied heat and mass transfer model of adsorber bed with finned tube using activated carbon-ethanol as working pair. The results are validated with experimental result at [11]. It's evaluated a COP and SCP of 0.51 and 426.09 W/kg respectively. Uddin et al [12] diagnostically explored the performance of a perfect adsorption compression system and discussed the energy saving possible for the proposed system looking at the traditional system under same working condition. Miyazaki et al [13] reviewed the performance of original double evaporator compose three-bed adsorption chiller for cooling application and discovered critical change of system performance more than two-bed single stage chiller. Bouzid et al [14] studied a simulation of the adsorption kinetics of ethanol onto parent Maxsorb III and the two chemically improved activated carbons (H2–Maxsorb III and KOH–H2–Maxsorb III). The examination of every one of these parameters intends to discover an improvement strategy permitting to trade off the two impacts of diffusion and adsorption which could be enemy with a specific end goal to expect systems and systems conditions to improve effectiveness. Sahin et al [15] analyzed the adsorption refrigeration system bed by using CFD modeling to discuss the impacts of the changes in fin geometry on heat transfer and pressure drop at the bed. It detected that insertion the fin tube at downstream region affects heat transfer completely. Abdel Aziz et al [16] investigated the adsorption refrigeration tube uses the activated carbon – ethanol as working pair experimentally, and design the configuration of ART. It presented an investigation for different shapes and numbers of fins. It's found that charcoal- 4 zigzag fins has the highest COP=0.635 followed by charcoal – aluminum slices and charcoal- 4 straight fins, the charcoal- 4 zigzag fins accomplished an increase in SCP equal to 103.5%. In the present work, the adsorption cooling system performance is analyzed by a lumped modeling. The mathematical model takes into consideration the heat and mass transfer characteristics in the adsorbent bed, and energy balance in both evaporator and condenser. The main goal in this work is to improve the overall heat transfer coefficient through the bed with proper insertion fins and to study this effect on the pressure variations inside the adsorber.

Description of adsorption cooling system

The schematic of one bed adsorption cooling system is shown in Fig. 1 and Fig. 2 shows Clapeyron diagram for adsorption thermodynamic cycle [18]. The cycle consists of three heat exchanger, evaporator (evap), condenser (cond) and adsorber (bed).

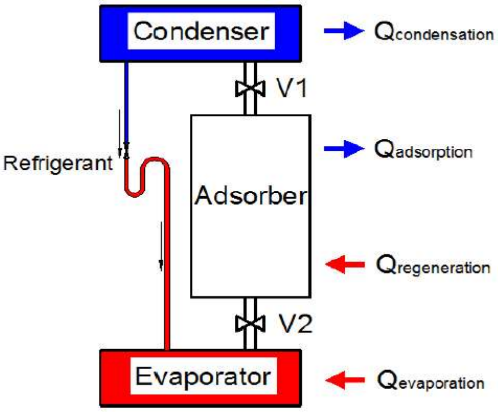

Figure 1 Schematics of one-bed adsorption cooling system.[17]

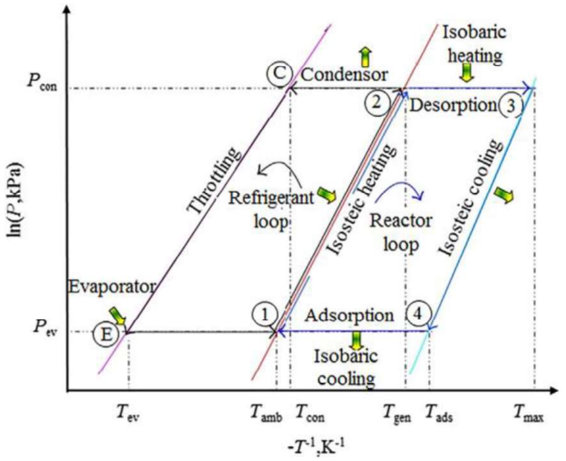

Figure 2.Clapeyron diagram of adsorption refrigeration cycle [18]

The cycle has four modes, Mode A, B, C, and D. In mode A, valve V1 is closed and V2 is opened, in this mode adsorption-evaporation process takes place. Refrigerant (ethanol) in evaporator is evaporated at evaporation temperature and P_{evap} by taking heat (Q_{evap}) from chilled water then released heat to cooled water inlet to the adsorber. The evaporated ethanol is adsorbed by activated carbon, at which cooling water removes the adsorption heat. In mode B both valves V1 and V2 are closed and the concentration in the adsorber is still constant at an equilibrium level (isosetric heating). In mode C valve V1 is opened while V2 is closed, in this mode the condenser and the bed are in desorption-condensation process which takes place at condenser pressure (P_{cond}). The desorber is heated to a desorbed temperature by hot water provided from a hot water tank. Refrigerant (ethanol) in condenser is cooled down and condensed at (T_{cond}) and reject heat Q_{cond} to the cooling water. The condensed ethanol returns back to the evaporator. The main assumptions are the system is well insulated, the pressure difference between the bed and the evaporator or condenser is neglected, and the pressure and temperature are constant throughout each heat exchanger.

Mathematical model

The equilibrium uptake of activated carbon/ethanol pair is given by the equation developed by Dubinin-Astakhov (D-A) [19,20].

$$x = x_o \exp\left[-D\left(T \ln \frac{P_{st}}{P} \right)^n \right] \qquad (1)$$

x	Is the concentration of adsorbed adsorbate, (kg/kg)
P	Is the system adsorption pressure, (Pa)
x_o	Is the theoretical maximum adsorption capacity, (kg/kg)
T	Is the temperature of adsorbent, (K)
D	Is a constant that depends on the adsorbent micro structure
n	Is a parameter introduced to achieve a better fit with experimental data

x_o, D, and n are determined from the experimental work

The saturation pressure (P_{st}) for ethanol is estimated using the following equation:

$$\ln(P_{st}) = -4.4114 + 8.7650\times10^{-2}\times(T+273) - 6.3182\times10^{-4}\times(T+273)^2 + 3.9958\times10^{-6}\times(T+273)^3 - 1.4340\times10^{-8}\times(T+273)^4 + 2.0359\times10^{-11}\times(T+273)^5 \qquad (2)$$

$$\frac{\partial x}{\partial t} = k_s a_v (X^* - X) \qquad (3)$$

$$k_s a_v = F_o \frac{D_S}{{R_p}^2} \qquad (4)$$

$$D_s = D_{so} e^{-E_a/RT} \qquad (5)$$

Energy balance equation for the adsorption bed

The energy balance equation for the adsorption bed by using the lumped approachs given by [20]:

$$(m_{hex} c_{st} + m_a C_a)\frac{dT}{dt} + m_a X\, C_{eth}\frac{dT}{dt} = \delta m_a \Delta H_{ads}\frac{dx}{dt} + \delta(1-\emptyset) m_a C_{evap}\frac{dx}{dt}(T_e - T) + \dot{m}_w C_{pw}\left(T_{j,in} - Tj,out\right.$$

where δ called tha flag and $\delta = 0$ During switching and $\delta = 1$ During adsorption- desorption cycle. J represents the cooling and heating source. $\emptyset=0$ during adsorption *and* $\emptyset=1$ during desorption.

The outlet temperature of the heat transfer fluid (water) is estimated by using the logarithmic mean temperature difference technique.

$$\frac{T_{j,out}-T}{T_{j,in}-T} = \exp\left(-\frac{UA}{m^{\cdot}{}_{w}C_{pw}}\right) \qquad (7)$$

Energy balance equation for the condenser

The condenser is a heat exchanger which cooled by water and it condenses the refrigerant (ethanol) which desorbed during desorption process and comes back to the evaporator.

$$M_C C_{cu}\frac{dT_c}{dt} = \left(m_a C_{evap}\frac{dx_{des}}{dt}(T_C - T_b) - m_a\frac{dx_{des}}{dt}L + m^{\cdot}{}_{cw}\, C_w(T_{cin} - T_{cout})\right)dL \qquad (8)$$

LMTD for the condenser:

$$\frac{T_{C,out}-T_C}{T_{C,in}-T_C} = \exp\left(-\frac{UA_C}{m^{\cdot}{}_{w}C_{pw}}\right) \qquad (9)$$

Energy balance Equation for the evaporator

Energy balance Equation for the evaporator can be expressed as

$$(m_eC_{cu} + m_{eth}C_{eth})\frac{dT_e}{dt} = \Big(-m_a\frac{dx_{des}}{dt}L - m_a\frac{dx_{des}}{dt}C_{eth}\big(T_c - T_{evap}\big) + m^{\cdot}{}_{chw}C_{pw}(T_{chi} - T_{chout})\Big)(1 - \qquad (10)$$

LMTD for the evaporator:

$$\frac{T_{Ch,out}-T_e}{T_{Ch,in}-T_e} = \exp\left(-\frac{UA_e}{m^{\cdot}{}_{w}C_{pw}}\right) \qquad (11)$$

In the current model the linear driving force equation (LDF) is used to investigate the adsorption and desorption processes. Table (1) shows the parameters which used in the model.

Table 1: Properties of activated carbon powder and specification of adsorber [21]

Parameter	Symbol	Value
Mass of adsorbent (kg)	m_a	0.5
Isosetric heat of adsorption (kJ/kg)	ΔH_{ads}	947
Latent heat of ethanol, kJ/kg	L	846
Mass of evaporator, kg	m_e	2
Mass of condenser, kg	m_c	15.2
Cooling water mass flow rate, kg/s	$m^{\cdot}{}_{ww}$	0.0
Specific heat of stainless steel, kJ/kg.K	C_{st}	0.5
Specific heat of activated carbon, kJ/kg.K	C_a	0.9
Specific heat of ethanol, kJ/kg.K	C_{eth}	2.46
Fiber radius, m	R_P	1.7E-4
Constant depend on pair type	F_O	15
Universal gas constant, J/mole.K	R	8.314
Specific heat of water, kJ/kg.K	C_{Pw}	4.18
Inlet cooling water temperature, ºC	$T_{c,in}$	25
Inlet chilled water temperature, ºC	$T_{ch,in}$	25

Parameters such as Coefficient of performance (COP) and Specific cooling power (SCP) are used to evaluate the adsorption refrigeration system and are given by:

$$COP = Q_{evap}/Q_{in}$$

(12)

$$SCP = Q_{evap}/m_a$$

(13)

Results and Discussion

A cyclic simulation run is performed to study the performance of adsorption refrigeration cycle. The main purpose of this simulation is studying the effect of operating conditions on SCP and COP of the system. The operating conditions for the adsorption/desorption cooling system are conducted for the range of cooling water inlet temperature, chilled water inlet temperature, and hot water inlet temperature between (17 - 32 ºC), (10 - 25 ºC), and (60 - 100 ºC), respectively.

Inlet cooling water temperature

The inlet cooling water temperature to the adsorber has a significant effect on the adsorption refrigeration system that provides a favorable effect on the adsorption process and COP. In this simulation it varies from 17 ºC to 32 ºC for cycle time 1050s (adsorption and desorption). Based on this, decreasing the cooling water inlet temperature has only minor effects on the adsorber pressure as shown in Fig. 3 and hence the performance of the system. During the isosetric process no effect is observed for cooling water inlet temperature. It is noticed that the pressure profile is replicated after a cycle time of 1050 s. When the inlet cooling water temperature to the adsorber decreases from 17 ºC to 32 ºC then the adsorber bed is cooled down and the pressure inside the adsorber reduces and consequently, the adsorbate inside the evaporator evaporates efficiently. As a result of evaporation, the evaporator temperature drops from 18 ºC to 7 ºC and cooling occurs when the cooling inlet temperature decreases from 32 ºC to 17 ºC, respectively as shown in Fig. 4. The COP variations against the operating time during a cycle are shown in Fig. 5 for different cooling water inlet temperature. It is found that the COP increases with operating time during adsorption process and approached to a maximum value of 0.32 after 600 s for cooling water inlet temperature 17 ºC and then remains constant till the end of adsorption. This is because the adsorbent adsorbs more ethanol vapor from the evaporator at low cooling water inlet temperature. The lowest value of COP is obtained at high value of inlet cooling water temperature of 45 ºC due to the lowest adsorption capacity as shown in Fig. 6. Figure 7 shows that as the cooling water inlet temperature to the adsorption bed decreases, the SCP increases and more cooling effect is obtained because a more ethanol vapor is adsorbed by the bed at this low temperature.

Hot water inlet temperature

Figure 8 shows the simulation results of dynamic pressure profile in the adsorption bed for different generation temperatures. Adsorption pressure takes place at 0.2 kPa while the desorption pressures are 3.6 kPa, 3.2 kPa, 2.8 kPa, 2.05 kPa, 1.45 kPa, and 1.0 kPa at generation temperatures 100 ºC, 95 ºC, 90 ºC, 80 ºC, 70 ºC, and 60 ºC, respectively. There is a suddenly decrease and increase of pressure during the isosetric precooling and preheating processes. This is because more ethanol vapor is desorbed at the higher generation temperature causing high pressure profile. If the hot water inlet temperature is higher than a certain value (e.g. 65 oC), no change is observed in the value of COP as shown in the Fig. 9. On other hand, Fig. 10 shows that the SCP increases continuously with the hot water inlet temperature. The SCP of the adsorption cooling system increases greatly though the COP decreases a bit with increasing in hot water inlet temperature as shown in Figs. 9 and 10. The SCP and COP reach 315 W/kg and 0.286 at 100 ºC hot water inlet temperature.

Chilled water inlet temperature

Figure 11 and 12 show the effects of chilled water inlet temperature on the COP and SCP of the cooling system, respectively. It is found that the COP and the SCP of the cooling system are improved by about 1% and 0.3% when the chilled water inlet temperature increases 15 ºC. It can be noticed that the chilled water inlet temperature have a minor effects on the performance of the cooling system.

Overall heat transfer coefficient

Figure 13 shows a variation of the dynamic pressure profile of the adsorption/desorption bed against the operating time for different values of overall heat transfer coefficient (UA). The improvement in the overall heat transfer coefficient (UA) is carried out by insertion of conductive fins in the adsorbent. The effect of UA on the bed system pressure is studied at same working conditions and cycle time. The bed system pressure various strongly with the overall heat transfer coefficient during desorption process and slightly during the adsorption process. At high value of UA (5 kW/K), the adsorption/desorption bed pressure range is high (0.2 – 3.65 kPa) with about 3.45 kPa while for low value of UA (0.01), the pressure range is (0.2 – 1.8 kPa). The improvement in the UA value is the most important parameter for an adsorption cooling system that can improve the performance and at same operating conditions.

Conclusion

A simulation modeling of adsorption refrigeration system with activated carbon-ethanol working pair is provided to study the performance of this cooling system in terms of coefficient of performance (COP), specific cooling power (SCP), and profile pressure of the system. The maximum COP and SCP (0.33 and 340 W/kg) are obtained from the simulation results when the cooling inlet temperature, the hot water inlet temperature, and the chilled water inlet temperature are 17 ºC, 100 ºC, and 25 ºC, respectively. The performance design of the cooling system for a modified adsorbent bed and operating conditions is modeled by using a lumped system.

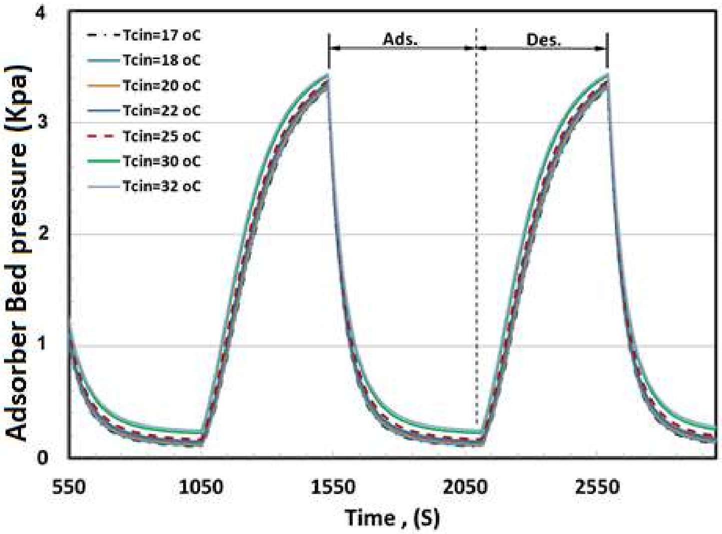

Fig. 3: Pressure profile in ART adsorber bed under the cycle time of 1,050 s for different cooling water temperatures into the adsorber.

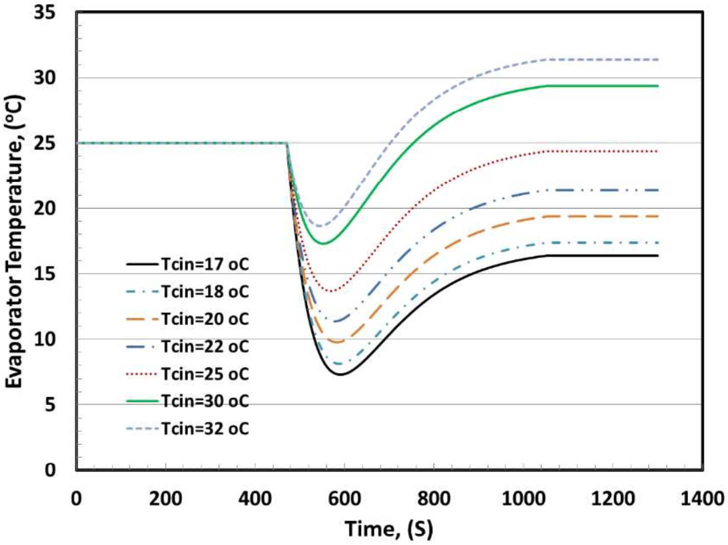

Fig. 4: Evaporator temperature variations with operating time for different inlet cooling water temperatures.

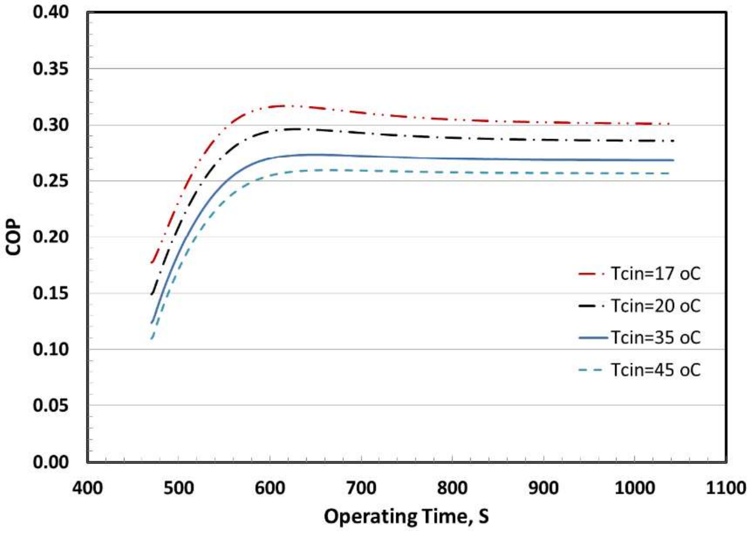

Fig. 5: COP variations against operating time for different cooling water inlet temperatures.

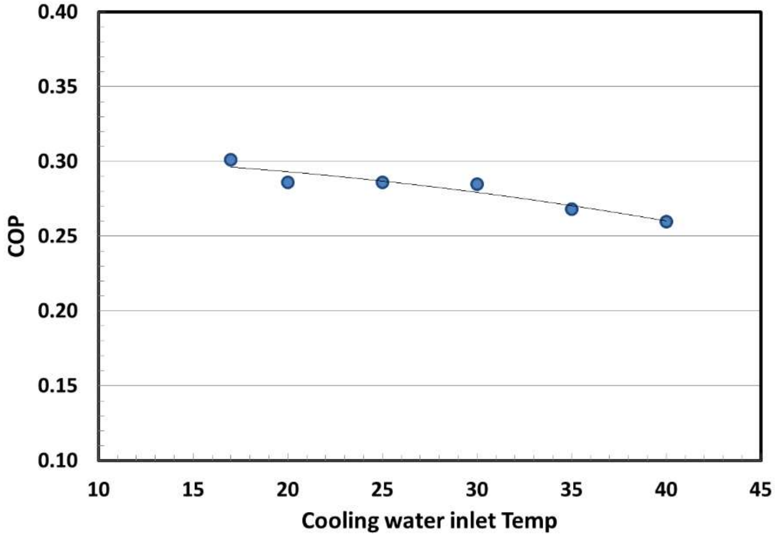

Fig. 6: Effect of cooling water inlet temperature on COP

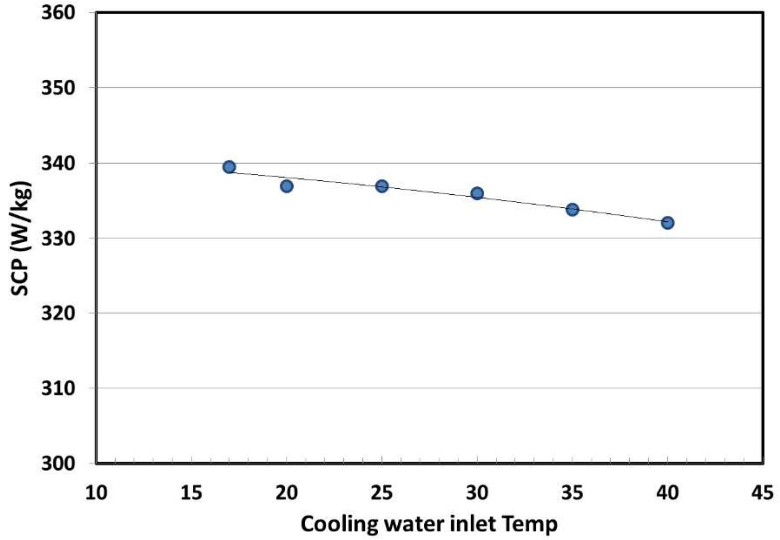

Fig. 7: Effect of cooling water inlet temperature on SCP

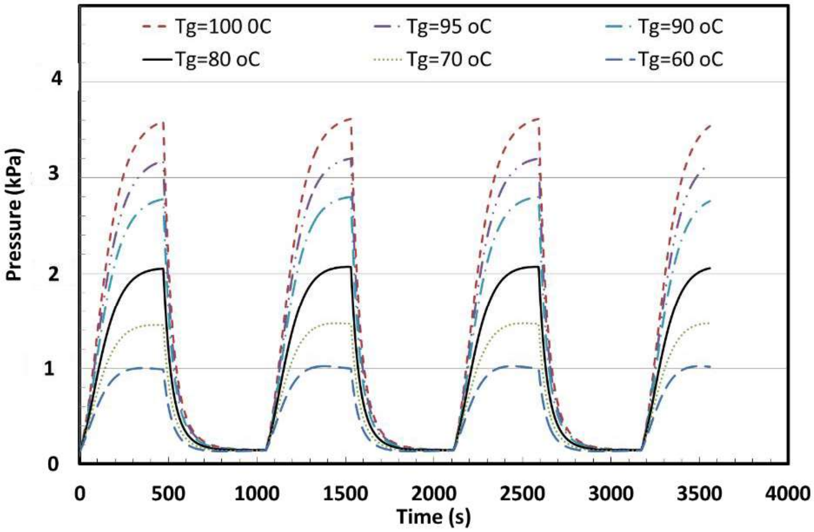

Fig. 8: Bed pressure variations with operating time for different hot water inlet temperatures.

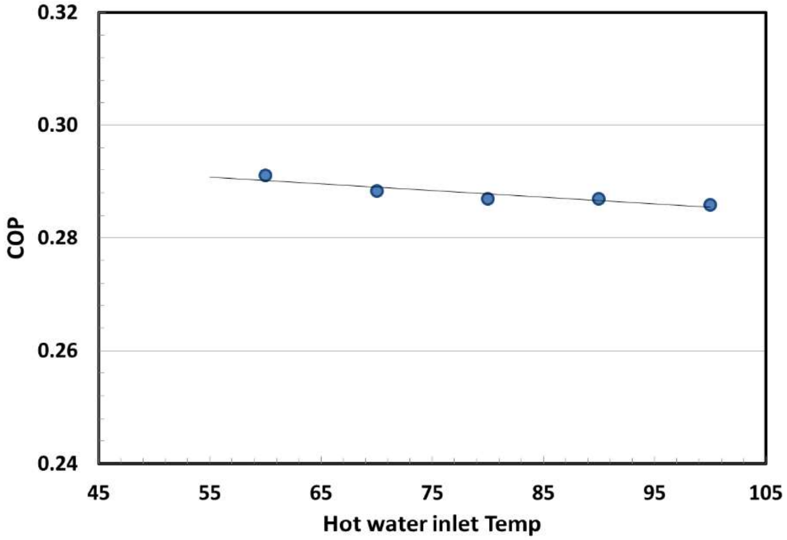

Fig. 9: Effect of hot water inlet temperature on COP

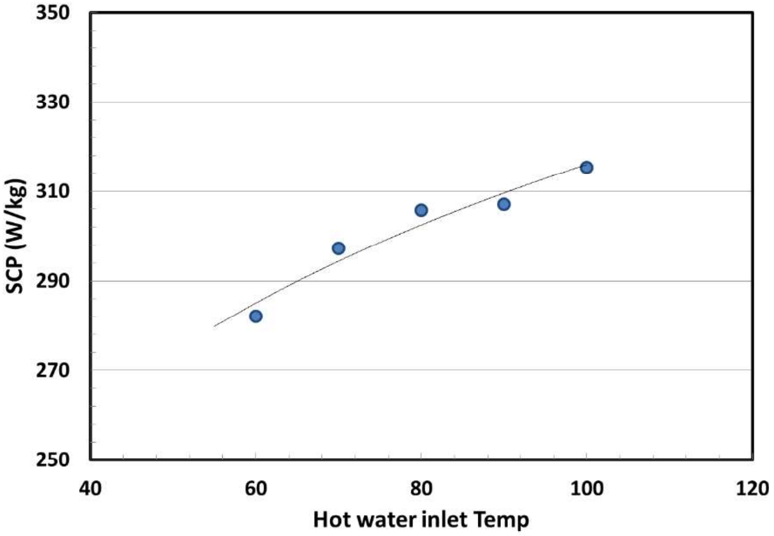

Fig. 10: Effect of hot water inlet temperature on SCP

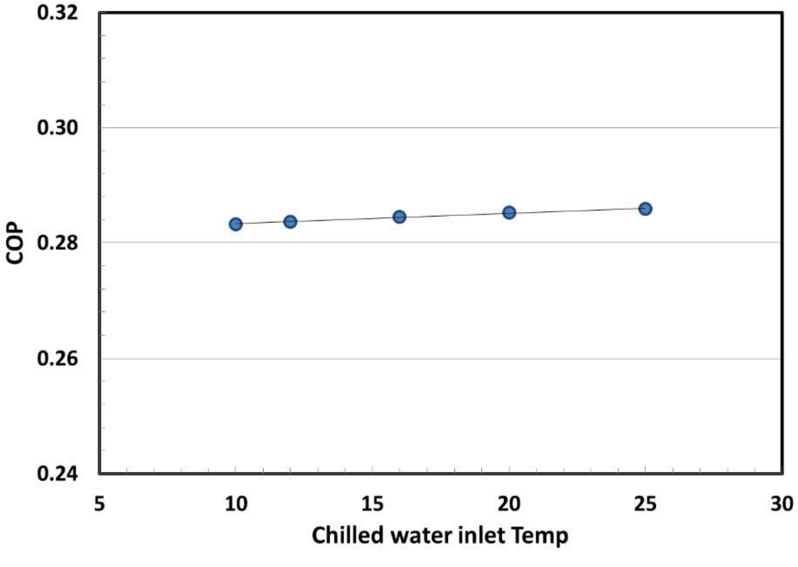

Fig. 11: Effect of chilled water inlet temperature on COP

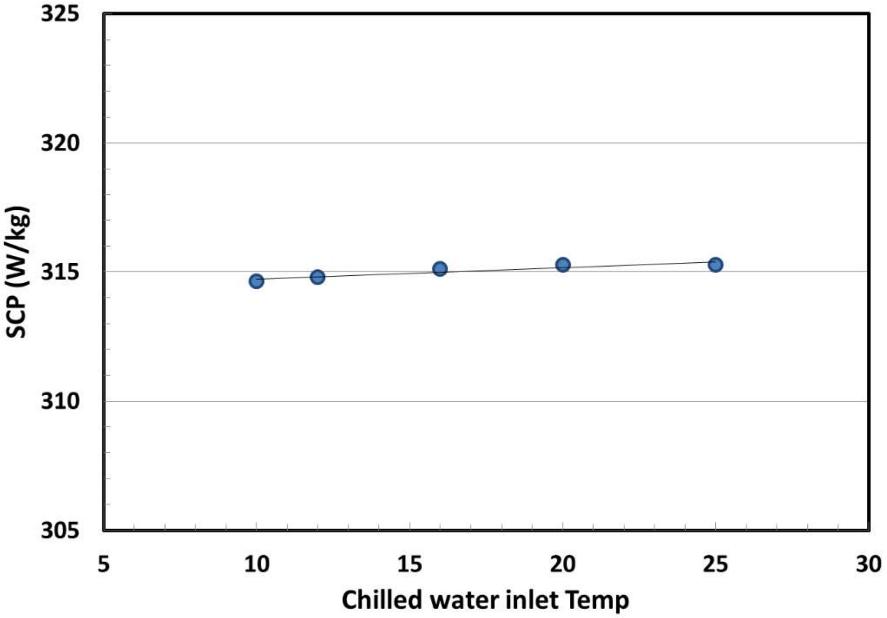

Fig. 12: Effect of chilled water inlet temperature on SCP

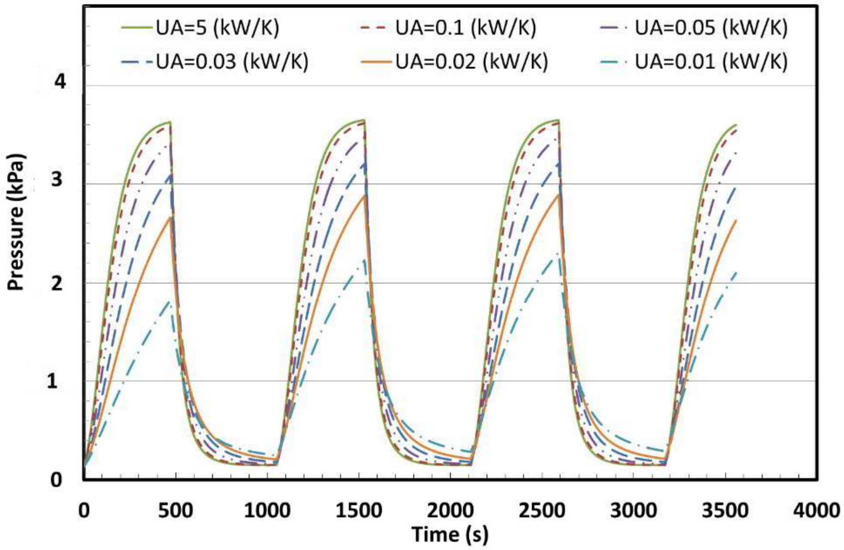

Fig. 13: Bed pressure variations with operating time for different overall heat transfer coefficients through the bed.

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