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Hui Tong Chua

*National University of Singapore*

Anutosh Chakraborty

*National University of Singapore*

Xiao Lin Wang

*National University of Singapore*

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# AN ADSORPTION CHILLER DRIVEN BY THERMOELECTRICITY

Hui Tong Chua<sup>1,\*</sup>, Anutosh Chakraborty<sup>1,‡</sup> and Xiaolin Wang<sup>1,+</sup>

<sup>1</sup>Department of Mechanical Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260, Singapore. Tel no.: (65)68746627, Fax no.: (65)67791459, E-mail id:

\*mpecht@nus.edu.sg, ‡ engp1424@nus.edu.sg, +mpewx@nus.edu.sg

## ABSTRACT

A thermoelectrically driven adsorption chiller that symbiotically combines adsorption and thermoelectric cooling devices has been developed. The seemingly low efficiency of each cycle individually is overcome by an amalgamation with the other. In this paper, we have proposed an improved design of a thermo-electrically driven adsorption cooling cycle, which makes use of the effects of regenerative condenser and additional thermoelectric devices to improve the chiller coefficient of performance. The virtues of this improved designs are; (a) scale independence, amenable to chiller miniaturization and system compactness; (b) lack of moving parts; (c) comparatively higher COP; and (d) the use of non-toxic environmentally-friendly materials.

## 1 INTRODUCTION

The development of thermoelectrically driven miniaturized adsorption chiller, which is compact, nearly free of moving parts, efficient in converting input electricity to cooling power, capable of high cooling densities in Watt per square centimeter, and free of toxic and environmentally-harmful substances, is a challenge in the arena of miniaturized cooling technology. The thermoelectrically driven adsorption chiller regeneratively combines the operation of thermoelectric devices with that of an adsorption chiller. The thermoelectric devices powered by a DC power source, absorb heat from the adsorber (cold bed) and regeneratively pump the heat to the desorber (hot bed) of the adsorption chiller. The regenerative pumping action of the thermoelectric devices sustain the adsorption-induced evaporation of the working fluid from the evaporator and the desorption of working fluid from the desorber. An air-cooled condenser condenses the desorbed working fluid and returns it to the evaporator via a needle valve. In our previous papers (Gordon et al., 2002 and Ng et al., 2002), the miniaturized electro-adsorption chiller has been described briefly and show how a unique union of the adsorption and thermoelectric chillers can produce a device that could provide active and high density cooling effect. In this paper an improved design and the current status of a thermoelectrically driven adsorption chiller is presented.

## 2 A THERMOELECTRICALLY DRIVEN ADSORPTION CHILLER CYCLE

The thermoelectrically driven adsorption chiller, otherwise known as the Electro-Adsorption Chiller (EAC) where the thermoelectric cooler is thermally cascaded with the batch processes of an adsorption chiller is shown in Figure 1. The thermoelectric modules are attached to the adsorbent beds in a thermally conductive but electrically non-conductive manner. The batch cycle of an electro-adsorption chiller comprises two time intervals, namely the switching time interval and the operation time interval. During the operation, the supply of DC power to thermoelectric-device would produce hot and cold junctions. The heat produced at the hot junction drives the desorption of refrigerant from the adsorbent in the desorber while the cooling effect from the cold junction enhances the adsorption of refrigerant by the adsorbent in the adsorber. During the heating and cooling of the beds, small electromagnetic valves (with off/on control) ensure that no refrigerant flows into or out of the beds. A timed controller activates the opening of the valves after adequate heat transfer, so that heated refrigerant from the desorber is released to a condenser for heat rejection to the environment and vaporized refrigerant is fed to the adsorber from the evaporator which in turn cools the load of interest. The roles of the adsorber and desorber must be reversed to complete the adsorption operation cycle. This is accomplished by reversing the polarity of voltage supplied to the thermoelectric-device. What was formerly the cold junction become the hot junction and vice versa. Simultaneously, pairs of switching valves for the adsorption chiller would switch their roles with desorbed refrigerant being directed to the condenser (which is at a high vapor pressure) and adsorbed vapor supplied from the evaporator (which is at a low vapor pressure). During the switching time interval, the vapor in the bed which is being heated is thermally compressed so that its pressure approaches that of the condenser. Concomitantly, the

vapor in the bed which is being cooled is thermally de-compressed so that its pressure approaches that of the evaporator. During the same time interval, the throttling valve connecting the condenser to the evaporator is isolated. During the operation time interval, the desorber is connected to the condenser so that adsorbate is desorbed from the desorber and condensed in the condenser. Simultaneously, the adsorber is connected to the evaporator so that refrigerant is evaporated from the evaporator and adsorbed in the adsorber. In the meantime, the throttling valve serves to throttle the condensate flow from the condenser to the evaporator and maintains the pressure difference between the two compartments.

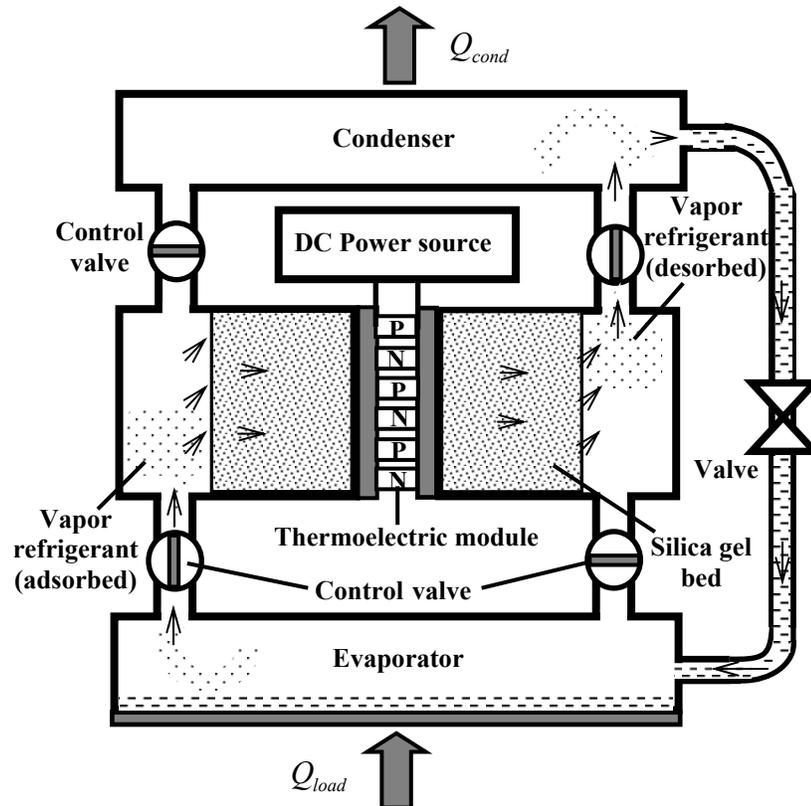


Figure 1: Schematic showing the principal components and energy flow of the electro-adsorption chiller (Here  $Q_{load}$  = heat absorbed from surface,  $Q_{cond}$  = heat removed to the environment)

### 3 MATHEMATICAL MODELING

The energy balance equations for the thermoelectric, the adsorber, the desorber, the condenser and the evaporator can be solved, but the boundary conditions depend on the heat and mass exchanges among them. All the modeling equations are based on experimentally confirmed relations, as well as on measured material properties.

#### 3.1 Adsorption thermodynamics

The silica-gel water pair is considered because it is the most promising pair for most adsorption cooling applications. The vapor uptake shows a saturation phenomenon of adsorbate uptake, a more accurate model for the isotherms would be the Tóth's equation (Tóth, J., 1971) which is given as

$$q^* = \frac{K_o \exp\{\Delta H_{ads} / (RP)\} P}{\left[1 + \{K_o / q_m \exp\{\Delta H_{ads} / (RP)\} P\}^n\right]^{1/n}} \quad (1)$$

where  $q_m$  denotes the monolayer capacity and  $n$  is the dimensionless Tóth's constant. The adsorption isotherm parameters and the isosteric heats of adsorption for the two grades (type RD and type A) of (silica gel+ water) system have been reported in one of our previous paper (Chua et al., 2002).

### 3.2 Thermoelectric

The transient one-dimensional energy balance equation for a thermoelectric couple of constant cross-section area  $A_{TE}$  and length  $L$  as a function of time  $t$  and position  $x$  ( $0 \leq x \leq L$ ) is given by [Rowe, 1995]:

$$\frac{\partial T_{TE}(x,t)}{\partial t} = \frac{\lambda_{TE}}{w_{TE}c_{p,TE}} \frac{\partial^2 T_{TE}(x,t)}{\partial x^2} + \frac{\rho_{TE}J^2}{w_{TE}c_{p,TE}} + \frac{J}{w_{TE}c_{p,TE}} \frac{\partial(\Gamma T_{TE}(x,t))}{\partial x} \quad (2)$$

Hence, the Thomson coefficient ( $\Gamma$ ) is defined by  $\frac{d\alpha_{te}}{d(\ln T)}$ . The heat fluxes at the boundaries (i.e., the boundary conditions on the derivatives of  $T_{TE}$ ) depend on the properties and operation of the sorption beds. The properties of thermoelectric material such as  $\lambda_{TE}$ ,  $\alpha_{TE}$  and  $\rho_{TE}$  do not vary with temperature. So equation (2) becomes

$$\frac{\partial T_{TE}(x,t)}{\partial t} = \frac{\lambda_{TE}}{w_{TE}c_{p,TE}} \frac{\partial^2 T_{TE}(x,t)}{\partial x^2} + \frac{\rho_{TE}J^2}{w_{TE}c_{p,TE}} \quad (3)$$

### 3.3 Adsorber and desorber

The transient energy balance of the bed (Gordon et al., 2002) accounts for heat conduction at the interface with the thermoelectric chiller; sensible heating of the silica gel, water and heat exchanger; heat generation or removal due to adsorption or desorption; Peltier effect; and switching control:

$$\left[ M_{sg}c_{p,sg} + M_{HX}c_{p,HX} + (Mc_p)_{connect} \right] \frac{dT_{bed,i}}{dt} + M_{sg}q_{bed,i} \left( c_{p,g}(P_1, T_{bed,i}) + \frac{\Delta H_{ads}}{T_{bed,i}} - \frac{\Delta H_{ads}}{v_g} \frac{\partial v_g}{\partial T} \right) \frac{dT_{bed,i}}{dt} = M_{sg} \frac{dq_{bed,i}}{dt} \left[ \delta \{ h_g(T_{evap}) - h_g(P_{evap}, T_{bed,i}) + \Delta H_{ads} \} + (1-\delta)\Delta H_{ads} \right] - N_{TE}\alpha_{TE}IT_L - N_{TE}\lambda_{TE}A_{TE} \frac{\partial T_{TE}}{\partial x} \Big|_{x=0} \quad (4)$$

Here the value of the switching function  $\delta$  depends on the processes in the bed.  $\delta$  would be 1 for adsorption and 0 for desorption. For the regeneration step (when the bed interacts with the condenser) the energy balance is described as follows:

$$\left[ M_{sg}c_{p,sg} + M_{HX}c_{p,HX} + (Mc_p)_{connect} \right] \frac{dT_{bed,j}}{dt} + M_{sg}q_{bed,j} \left( c_{p,g}(P_1, T_{bed,j}) + \frac{\Delta H_{ads}}{T_{bed,j}} - \frac{\Delta H_{ads}}{v_g} \frac{\partial v_g}{\partial T} \right) \frac{dT_{bed,j}}{dt} = M_{sg} \frac{dq_{bed,j}}{dt} \left[ (1-\theta) \{ h_g(T_{cond}) - h_g(P_{cond}, T_{bed,j}) + \Delta H_{ads} \} + \theta\Delta H_{ads} \right] + N_{TE}\alpha_{TE}IT_H - N_{TE}\lambda_{TE}A_{TE} \frac{\partial T_{TE}}{\partial x} \Big|_{x=L} \quad (5)$$

The value  $\theta$  depends on adsorption or desorption. During desorption  $\theta$  equals to 1 and the value of  $\theta$  is 0 during adsorption.

### 3.4 Condenser and evaporator

The energy balance equation for the condenser includes sensible heat transfer from both liquid condensate and vapor adsorbate; heat generation by condensation; heat transfer to the ambient; and switching control. It can be given by (Ng et al., 2002)

$$\left[ (Mc)_{cond} + M_{cond}^{refr}c_{cond}^{refr}(T_{cond}) \right] \frac{dT_{cond}}{dt} - \sigma h_f(T_{cond})M_{sg} \frac{dq_{des}}{dt} = \sigma M_{sg} \frac{dq_{des}}{dt} \left[ \delta(1-\gamma)h_f(T_{cond}) - \delta h_g(T_{cond}, P_{cond}) - (1-\delta)h_g(T_{cond}) \right] - (UA)_{cond}(T_{cond} - T_{air}) \quad (6)$$

where subscript  $f$  denotes the fluid phase and superscript  $refr$  indicates refrigerant. The overflow control  $\gamma$  is zero when the heat exchange surface area on the vapor side of the condenser is saturated; otherwise it has a value of unity.

Similarly the energy balance equation for the evaporator taking into account switching control is given by

$$\left[ (Mc)_{evap} + M_{evap}^{refr} c_{evap}^{refr} (T_{evap}) \right] \frac{dT_{evap}}{dt} - \sigma h_f (T_{evap}) \frac{dM_{evap}^{refr}}{dt} = -\sigma \{ (1-\delta)(1-\gamma) h_f (T_{cond}) M_{sg} \frac{dq_{des}}{dt} + M_{sg} \frac{dq_{ads}}{dt} \left[ (1-\delta) h_g (T_{ads}, P_{evap}) + \delta h_g (T_{evap}) \right] \} - (UA)_{evap} (T_{evap} - T_{load}) \quad (7)$$

where  $\frac{dM_{evap}^{refr}}{dt} = M_{sg} \left[ (1-\delta)(1-\gamma) \frac{dq_{des}}{dt} - \frac{dq_{ads}}{dt} \right]$  (8)

The net Coefficient of Performance of thermoelectrically driven adsorption chiller is given by,

$$COP_{net} = \frac{\tau Q_{evap}}{\int_0^t I(t) V dt} \quad (9)$$

At long cycle time  $\tau$ , current  $I$  becomes constant.

#### 4 DEVICE PROTOTYPE AND SIMULATION RESULTS

The thermoelectrically-driven adsorption chiller set-up (bench-top model) as shown in Figure 2, is mainly comprised of two reactors (adsorber and desorber), condenser and evaporator. The heat exchanger containing silica-gel as shown in Figure 3 is placed between the top and the base plates of the reactor. The carbon sheet ensures the good thermal conductance between the plate and heat exchanger. The reactors are designed to have enough vapor space, so that the working refrigerant could be diffused into the adsorbents. The pictorial view of heat exchangers and the reactor are shown in Figure 4. The pressures in the two reactors are measured with two calibrated BOC Edwards Active Strain Gauge (accuracy  $\pm 0.2\%$  full scale, stability 0.2% full scale, temperature range operation  $-20$  to  $90$  °C, response speed 5 ms, full scale pressure range 0-1000 mbar). The temperatures in the two reactors are measured with 400-series NIST-Traceable Thermister probes (operating temperature  $-80$  °C to  $200$  °C, error =  $\pm 0.2$  °C). The thermister probe for the reactor is designed to be in direct contact with the silica gel so that a more representative adsorbent temperature could be obtained.

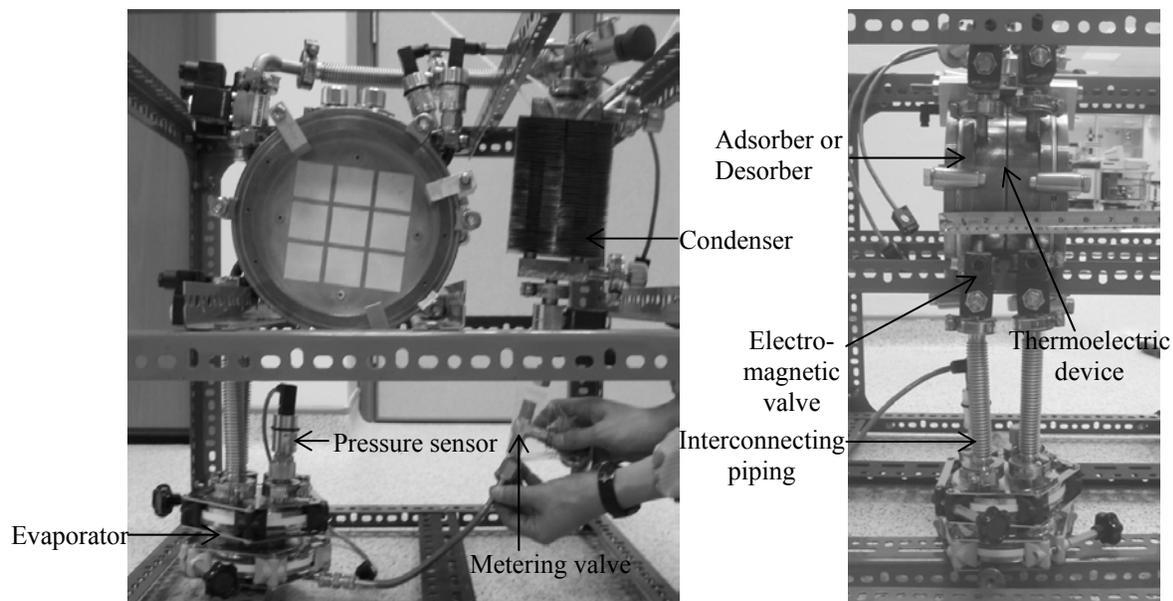


Figure 2: The bench-top prototype of the thermoelectrically-driven adsorption chiller

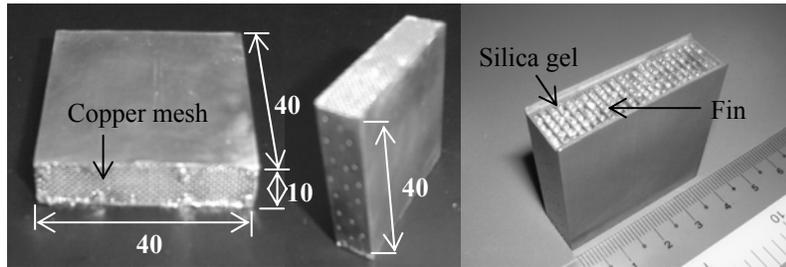


Figure 3: The pictorial view of heat exchanger (all dimensions are in mm)

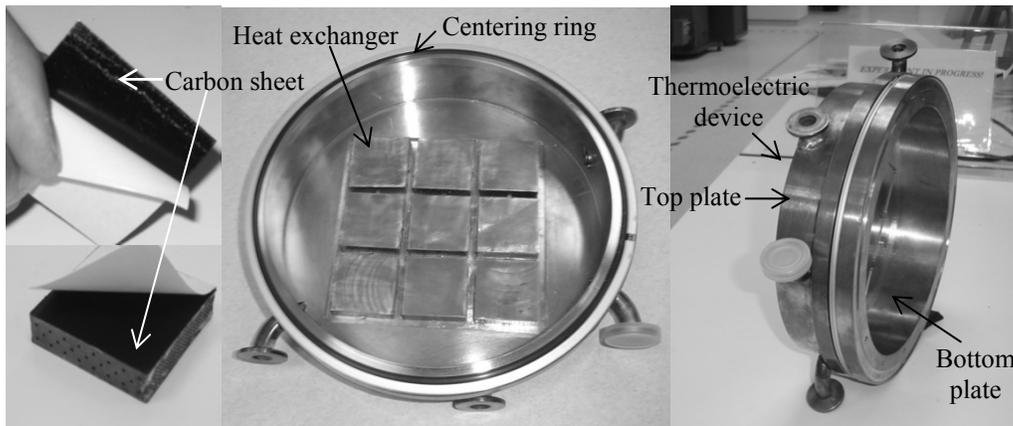


Figure 4: The pictorial view of the adsorber / desorber

Thermoelectric devices are placed between two reactors. All other inter-connecting piping (SS 316), stainless steel vacuum fittings, vacuum-rated electro-magnetic valves (mini angle valve, solenoid actuated, service life = 2000000 cycles) and metering valve are chosen to ensure good conductance during evacuation. The copper foam is attached to the base of evaporator with high vacuum rated S-bond material. The heater is placed at the outer side of evaporator to provide direct heating.

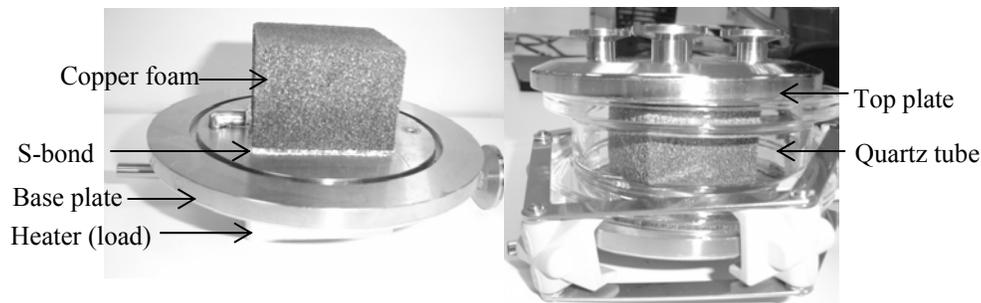


Figure 5: the pictorial view of the evaporator

Figure 6 (temperature profile) shows the thermoelectrically driven adsorption chiller responses at constant terminal voltage in terms of the temporal history of adsorber bed, desorber bed, condenser, evaporator and load temperatures. During the first part of the adsorption or desorption process, the adsorber bed temperature decreases and the

desorber temperature increases. After 220 s, the temperature of the adsorber and desorber is nearly equal to the cold junction and hot junction temperature, suggesting that the heat transfer has been accomplished.

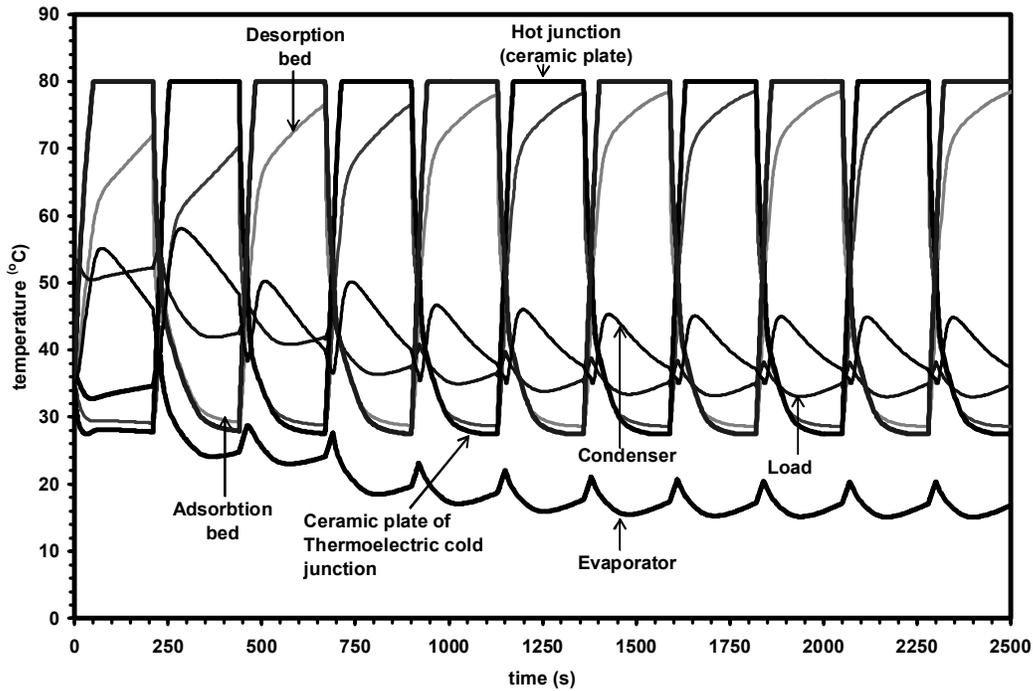


Figure 6: Temperatures of the principal components as functions of time from initial start-up through cyclic steady-state.

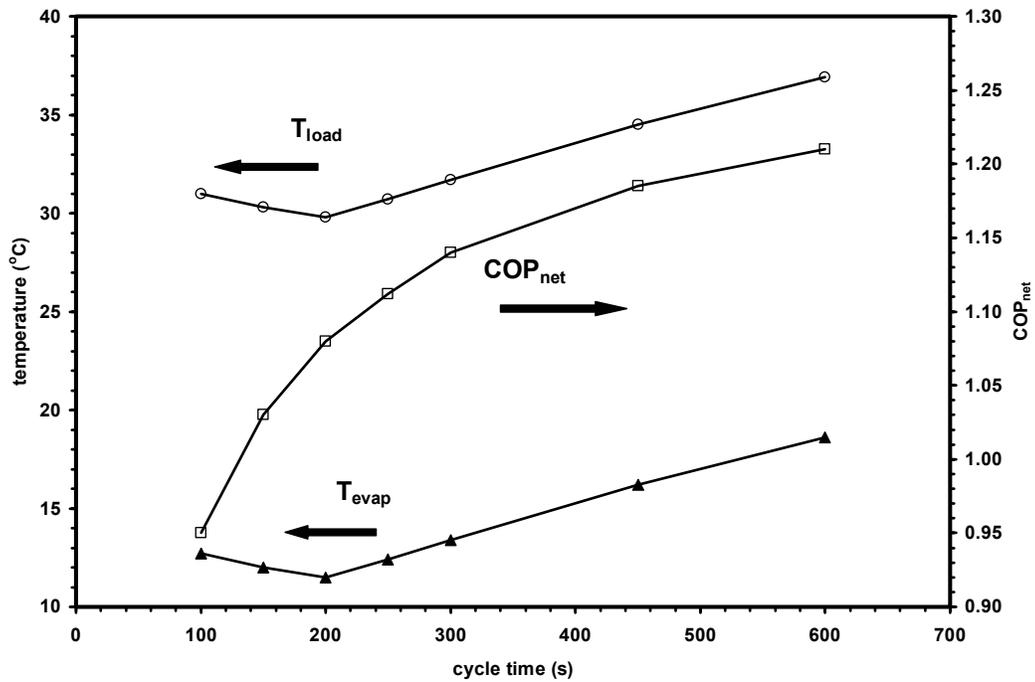


Figure 7:  $COP_{net}$ ,  $T_{load}$  and  $T_{evap}$  as functions of cycle time. ( $COP_{net}$  = net coefficient of performance,  $T_{load}$  = the load temperature and  $T_{evap}$  = the evaporator temperature)

For too short a cycle time, the adsorption beds get insufficient time to respond or saturate. In other words, the bed consumes excessive thermal power due to frequent cycling. On the other hand, the evaporator as well as the load surface temperature goes higher at very long cycle time, because the adsorbent is saturated in less than the allotted time. Figure 7 represents the net Coefficient of Performance ( $COP_{net}$ ), the evaporator temperature and the load surface temperature as functions of cycle time.

## 5 CONCLUSIONS

The thermoelectrically-driven adsorption chiller constitutes a new type of scalable, modular and efficient cooling device that overcomes the low  $COPs$  of the individual thermoelectric and adsorption cycles. This device also eliminates fluid pumps, coolant loops, and mechanical systems. As a result of a more effective thermal regeneration,  $COP_{ads}$  in this system is far larger than that in conventional adsorption chiller. We have already finished the design and are now at the stage of prototyping a bench-top adsorption chiller.

## NOMENCLATURE

$A$	Cross-sectional area	$m^2$	Subscripts	
$c_p$	specific heat	$J/kg\ K$	$ads$	adsorber/adsorption
$COP$	coefficient of performance	(—)	$air$	air cooling condenser
$h$	specific enthalpy	$J/kg$	$bed,i$	sorption bed i
$I$	electrical current	amp	$cond$	condenser
$L$	length of thermoelectric element	m	$connect$	substrate and plate that
$M$	mass	kg	connect the bed and thermoelectric	
$N$	number of thermoelectric element	(—)	$des$	desorber/desorption
$P$	pressure	Pa	$evap$	evaporator
$q$	extent of adsorption/desorption	$kg\ kg^{-1}$	$f$	fluid (liquid phase)
$Q$	heat transfer rate	W	$g$	vapor (gas phase)
$t$	time	s	$hx$	heat exchanger
$T$	temperature	K	$H$	hot junction
$UA$	thermal conductance	$W/K$	$junc$	(hot or cold) junction
$V$	voltage	volt	$load$	cooling load surface
$x$	position (length coordinate) along the thermoelectric	m	$L$	cold junction
$\alpha$	Seebeck coefficient	$V/K$	$net$	net or overall performance
$\delta$	switch of control	(—)	$sg$	silica gel
$\Delta H_{ads}$	heat of adsorption	$J/kg$	$TE$	thermoelectric
$\gamma$	overall control	(—)	$bed,j$	sorption bed j
$\lambda$	thermal conductivity	$W/m\ K$	Superscripts	
$w$	thermoelectric density	$kg/m^3$	$refr$	refrigerant
$\rho_{elec}$	electrical resistivity	ohm-m		
$\sigma$	switch control	(—)		
$J$	current density	$amp/m^2$		
$\Gamma$	Thomson coefficient	$V/K$		
$\theta$	switch of control	(—)		
$\tau$	cycle time	s		

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