

Experimental study on performance improvement of a four-bed adsorption chiller by using heat and mass recovery

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Abstract

The efficacy of a four-bed adsorption chiller has been studied experimentally with respect to a simple but yet effective passive heat and mass recovery schemes. It substantially improves the adsorption chiller COP by as much as 30% over a broad range of cycle time with a wide heat source, coolant and chilled water temperatures. Two schemes have been considered here: Firstly, only the mass recovery is achieved by pressure equalization between the concomitantly cooled adsorber and heated desorber, exploiting the intrinsic vapor-uptake potential by pressure swing that remains in the adsorbent at the end of a half-cycle. Secondly, when both the heat and mass recovery schemes are employed at a rating point of maximum cooling capacity, the chiller COP could increase further to as much as 48%. These improvements are performed without additional hardware changes to the adsorption chiller.

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1. Introduction

For the past decade, adsorption chillers have been successfully commercialized to convert the low-temperature waste heat from industrial sources or the solar energy into useful cooling and silica gel/water has been proven to be the viable and environmental-friendly working pair [1–5]. These heat-driven adsorption chillers, in the standard two-bed design, employ waste heat at temperatures of 75–85 °C. However, by adopting multi-bed and multi-stage designs [6,7], the cycle has been shown to work at temperatures as low as 50 °C but at the expense of a much lower COP. The main advantages of the adsorption chillers are that (i) they have no major moving parts that yields low

maintenance (ii) the adsorbent–adsorbate pair is that of silica gel–water which is environmental-friendly and (iii) the recovery of low-temperature waste heat which otherwise would have been purged into the ambient, minimizing unnecessary global warming.

Owing to the cyclic steady state operation, the adsorption chillers employ adsorbent beds and water-cooled heat exchangers which are concomitantly heated-up and cooled during part of the cycle, and these cyclic processes consume a substantial portion of the input energy. For efficiency improvement, part of these energy potentials (thermal and chemical) can be recovered at the end of a half-cycle, namely, at the start of switching period. Many researchers and engineers have devised both the active and passive schemes for such regenerative purposes [8–14] and the processes demonstrated thus far could have either the long time-scale process of hours, i.e., the solar operated cycle or the short time-scale event that completes in 3–10 min

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such as the chiller cycles. Implementing the heat and mass recovery schemes in adsorption cycle could achieve chiller COPs comparable to those of the single-stage absorption chiller [15–17]. Although these reports have highlighted many of the recovery methodologies, they lack a thorough and systematic analysis in terms of the operation conditions, the cycle time and pressure equalization time, etc., where useful data could emerge and be utilized for chiller plant design and system load control. In this paper, the authors aspire to report on the detailed performance data with the implementation of simple but yet practical methods of heat and mass recovery. The experiments are performed on a prototype and patented four-bed adsorption cycle where the specification of heat exchanger, inlet temperatures, coolant flow rates are adopted from those of a standard chiller. The adsorption cycle and the manner the four-beds are designated are aimed to have the waste heat extraction from the heat source to be maximized, thereby boosting the cooling capacity as well as reducing the temporal fluctuation of the chilled water supply. The heat recovery scheme (incorporated in the prototype four-bed cycle) requires no additional major components as compared to a conventional adsorption chiller. However, the mass recovery scheme demonstrated here would require the incorporation of two solenoid control valves for the vapour flow between the designated beds during activation – a small cost to pay in view of the enormous advantages it brought with mass recovery.

2. Heat and mass recovery schemes

2.1. Heat recovery scheme

Prior to the detailed discussion of the test results, the rationale for energy recovery in adsorption chiller is first laid. Being batch-operated, the adsorption cycle comprises a plurality of beds and built-in heat exchangers that are concomitantly heated-up or cooled. Such a cyclical heating and cooling of these beds consume a significant portion of the input thermal energy. Thus, for efficiency improvement the obvious procedure is to recover part of the intrinsic thermal and chemical potentials within the adsorbent and heat exchangers where these potentials have accrued at the end of a cycle. Having surveyed the many heat recovery methodologies reported in the literature [7–14], the authors are of the opinion that the simplest and yet practical method is the coolant valve-timing delay or VTD in short. In the VTD procedure, the valve timing for opening and closing of cyclic-designated inlet and outlet valves (of the heat source and the coolant circuits) are tuned via software (code) changes, and it ensures the correct diversion of the residual thermal heat that remained within the previously designated lead or master-desorber, and hence, eliminates, for example, any unwarranted mixing of cooler water to water emanating from the previously designated slave-desorber. As the coolant circuits involved are those of the existing heat source and the cooling water, no additional

external pump is needed for the operation of the VTD procedure.

2.2. Mass recovery scheme

A second practical and yet simple energy recovery scheme that has been demonstrated in the prototype four-bed chiller is called the adsorbate or mass recovery by adsorbent using a pressure equalization technique, or PE in short. This occurs between a pair of adsorber and desorber at the end of a half cycle where the adsorbent in desorber has attained a less saturated and its pressure is higher from the heating mode. On the other hand, adsorbent in the adsorber has reached a saturated state but its pressure is lower due to the external cooling. With the implementation of the PE procedure, the vapour-valve linking the mentioned beds are opened for a short period of 10–20 s, allowing a pressure swing between the mentioned beds: The desorber experiences a further desorption instantaneously making the silica gel dryer, whilst the simultaneous pressurization causes the state of silica gel in adsorber to take in more vapour. These PE processes are best shown on a Dühring diagram of P versus T , as shown in the Fig. 1. Points 1 and 3 are states at the end of a cyclic steady state of the adsorber and desorber, respectively, and they correspond to their respective isosteres (q_{\max} and q_{\min}). When a PE procedure is applied across a pair of adsorber and desorber, the pressure inside the desorber (to be switched to adsorber) drops rapidly from point 3 to point 8, leading to more vapor is further desorbed from the adsorbent to point 8. The released vapour flows across to the adsorber (to be switched to desorber) where it experiences an increase in vapour-uptake. The point 1 (q_{\max}) at the end of adsorption moves to point 7 (q'_{\max}) after pressure equalization. The speed of these processes is rapid and the accompanied heat of adsorption is not apparent during the PE process. With higher isosteres (q'_{\max} and q'_{\min}) across the cycle and no external heat input, the potential for improving COP is obviously increased.

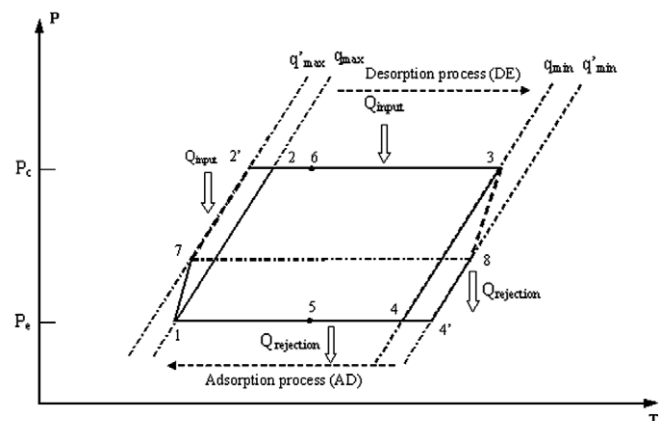


Fig. 1. Dühring diagram of the basic and improved adsorption cycle.

3. Experimental

Figs. 2 and 3 show the pictorial and schematic views of the prototype four-bed adsorption chiller, together with a rating facility placed below the working platform [11]. The chiller is employed as a bench-mark for the implementation of (i) the VTD and (ii) PE procedures. Software modifications are incorporated to the chiller's programmable logic controller (PLC) and Table 1 outlines the details of the valve opening (denoted by "O") and closure (denoted by "X") during the switching and cycle operating time intervals. Being an experimental test facility, the PLC

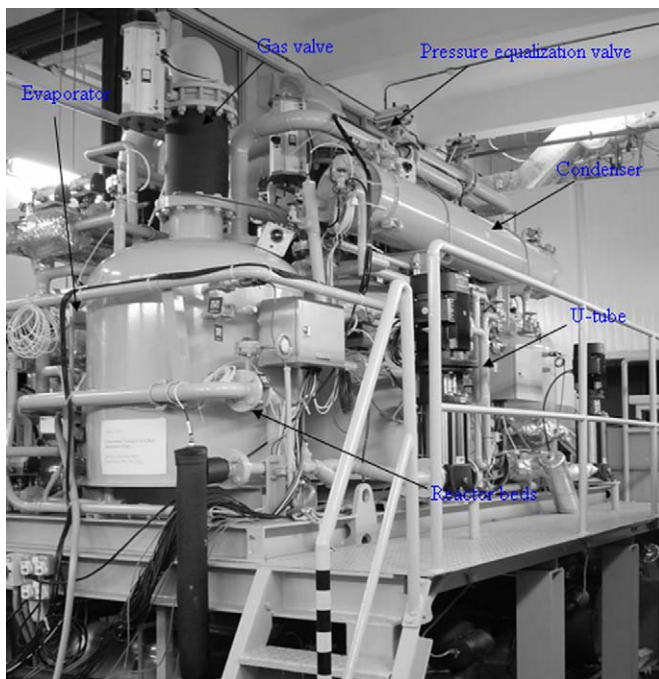


Fig. 2. An aerial view of a four-bed adsorption chiller test facility in our laboratory.

could be configured to operate the prototype chiller as a conventional two-bed, four-bed, with and without the mentioned energy recovery schemes. Also noted in Fig. 3 are the location of the solenoid valves (coolant and the vapour types) and for this investigation, the chiller has been extensively instrumented. All temperatures are measured by 5 k Ω thermistors (± 0.2 °C) with a small time constant, typically about 3 s. A faster response temperature sensor would track accurately the transient swings during both the switching and operation periods and avoiding unnecessary cumulative errors from data sampling. Flow rates of the coolant are measured by the electromagnetic type flow sensors and transmitters ($\pm 0.5\%$ of reading $\pm \pm 0.05$ L/min), and the absolute pressure sensors within the beds have readings to within ± 0.125 kPa.

The flow rates, timing duration and the coolant supplied temperatures to the prototype chiller are listed in the Table 2 where some of the flow rates adopted here are based on commercial standards. At a chilled-water flow rate of 48 L/min, the overall heat transfer coefficient or U-value of the evaporator is estimated to be about at 3000 W/m² K. Similarly, the cooling water flow rate supplied to the condenser is 120 L/min and its corresponding U-value is about 5800 W/m² K. Within the heat exchangers of the beds, the hot water and cooling water have a lower U-value of approximately 1000 W/m² K, due to the effects of the fin-tube arrangement. Assorted operating cycle times have been investigated depending on the operation modes but switching time interval is fixed at 40 s for all tests.

4. Results and discussion

For two sets of supplied hot water temperatures, namely 85 °C and 75 °C, Fig. 4 shows the key performance of a conventional four-bed chiller without energy recovery. The x-axis indicates the half-cycle time duration, ranging from 120 s to 480 s (and fixed switching time of 40 s), whilst the y-axis shows the COP and the cooling capacity in

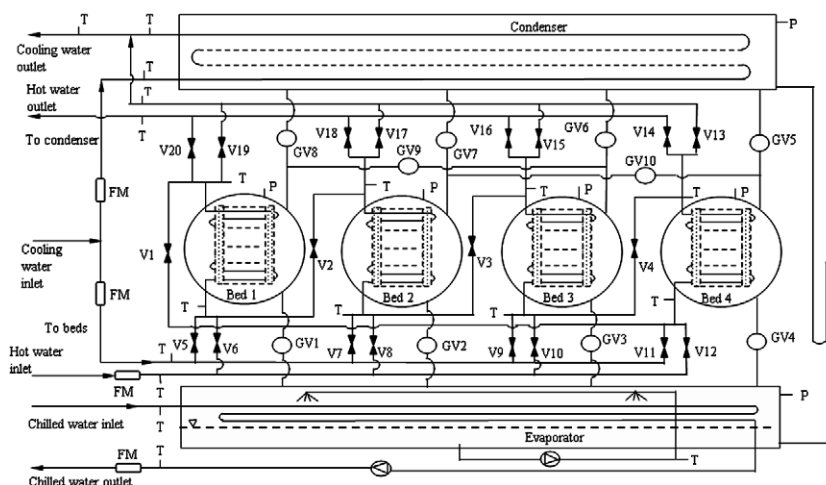


Fig. 3. Schematic of a four-bed adsorption-chiller test facility.

Table 1
Comparison of original four-bed operation scheme and heat and mass recovery schemes

Description	Original scheme			Mass and heat recovery			Heat recovery only			
	C1	S	C2	C1	S		C2	C1	S	C2
					M	H ^a				
Bed 1	MA	MA–SD	SD	MA	MA–SD		SD	MA	MA–SD	SD
Bed 2	SD	SD–MD	MD	SD	SD–MD		MD	SD	SD–MD	MD
Bed 3	MD	MD–SA	SA	MD	MD–SA		SA	MD	MD–SA	SA
Bed 4	SA	SA–MA	MA	SA	SA–MA		MA	SA	SA–MA	MA
V1	O	X	X	O	X	X	X	O	X	X
V2	X	O	O	X	X	O	O	X	O	O
V3	O	X	X	O	X	X	X	O	X	X
V4	X	O	O	X	X	O	O	X	O	O
V5	O	X	X	O	X	X	X	O	X	X
V6	X	X	X	X	X	X	X	X	X	X
V7	X	X	X	X	X	X	X	X	X	X
V8	X	O	O	X	O	O	O	X	O	O
V9	X	X	X	X	X	X	X	X	X	X
V10	O	X	X	O	X	X	X	O	X	X
V11	X	O	O	X	O	O	O	X	O	O
V12	X	X	X	X	X	X	X	X	X	X
V13	O	X	X	O	O	X	X	O	X	X
V14	X	X	X	X	X	X	X	X	X	X
V15	X	O	O	X	X	X	O	X	X	O
V16	X	X	X	X	X	O	X	X	O	X
V17	X	X	X	X	X	X	X	X	X	X
V18	O	X	X	O	O	X	X	O	X	X
V19	X	X	X	X	X	O	X	X	O	X
V20	X	O	O	X	X	X	O	X	X	O
GV1	O	X	X	O	X	X	X	O	X	X
GV2	X	X	X	X	X	X	X	X	X	X
GV3	X	X	O	X	X	O	O	X	O	O
GV4	O	O	O	O	O	O	O	O	O	O
GV5	X	X	X	X	X	X	X	X	X	X
GV6	O	X	X	O	X	X	X	O	X	X
GV7	O	O	O	O	O	O	O	O	O	O
GV8	X	X	O	X	X	O	O	X	O	O
GV9	X	X	X	X	O	X	X	X	X	X
GV10	X	X	X	X	X	X	X	X	X	X

V-water valve, GV-gas valve, S-switching period, C-cycle, M-mass recovery and H-heat recovery; MA-master adsorption, SA-slave adsorption, MD-master desorption and SD-slave desorption.

^a The heat recovery scheme could be extended to the next cycle which depends on the temperature at system outlet.

Table 2
Chiller operation conditions

Description	Conditions
Hot water flow rate to reactor beds	48 L/min
Cooling water flow rate to reactor beds	48 L/min
Cooling water flow rate to condenser	120 L/min
Chiller water flow rate across the evaporator	48 L/min
Hot water temperature	85 °C
Cooling water temperature	29.4 °C
Chilled water temperature	12.2 °C
Cycle time	120 s to 480 s
Switching time	40 s
Gas equalization time	10 s to 40 s

Rtons and the maximum cooling capacities attained are 4.7 Rtons and 3.8 Rtons at 85 °C and 75 °C, respectively. It is observed that the cooling capacity drops while the COP increases with increasing half-cycle duration, and these behaviours could be attributed to the high vapour-

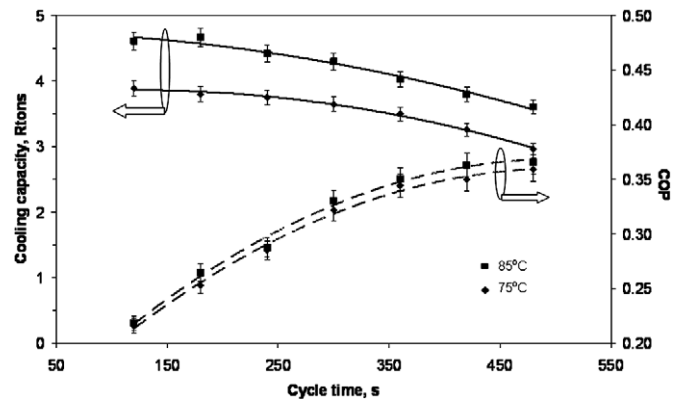


Fig. 4. Performance maps of the four-bed adsorption chiller at different hot water temperature.

uptake potential of the adsorbent at early period of exposure from the unsaturated state. The supplied hot water

temperature has substantial effects on the cooling capacity; however it has lesser effect on the system COP. It is also noted that adsorption chillers, being heat-driven, tend to have obstinately low chiller COP.

Fig. 5 demonstrates the implementation of the simple PE procedure during the start of the switching interval for two sets of hot water temperatures (85 °C and 75 °C) and two half-cycle times, namely 180 s and 300 s. It is observed that the change in PE time has little effect on the capacity. However, the procedure shows a monotonic increase in the chiller COP with increasing PE time, as shown in Fig. 6. A direct correlation of increasing cooling capacity of chiller with increasing the supplied hot water temperature is observed with or without the implementation of PE. The reasons for improving the chiller COP could be attributed to the reduction in the net energy input to the chiller are (i) the hot water supplied to the beds are being by-passed and (ii) the PE raises the switching bed (adsorber to desorber) temperature due to heat of adsorption. Such a phenomenon is captured by the shaded area “A” in the temporal distribution of the out-going heat source of chiller, as shown in Fig. 7. The area covered by inlet and outlet temperature traces of hot water is proportional to energy input. It is noted that the chilled water out-

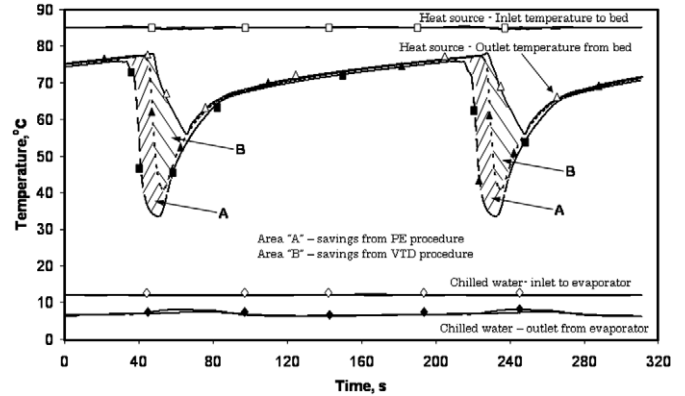


Fig. 7. An explanation of the energy saving by using heat and mass recovery schemes.

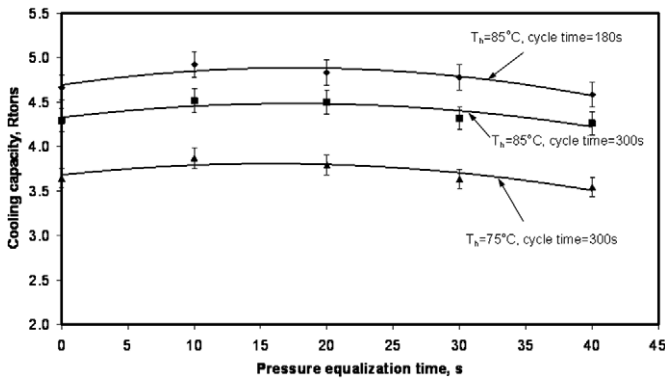


Fig. 5. Pressure equalization time effects on the efficacy of the mass recovery in terms of cooling capacity.

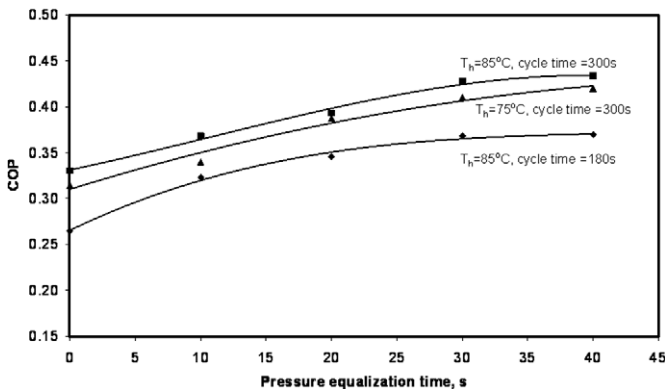


Fig. 6. Pressure equalization time effects on the efficacy of the mass recovery in terms of coefficient of performance (COP).

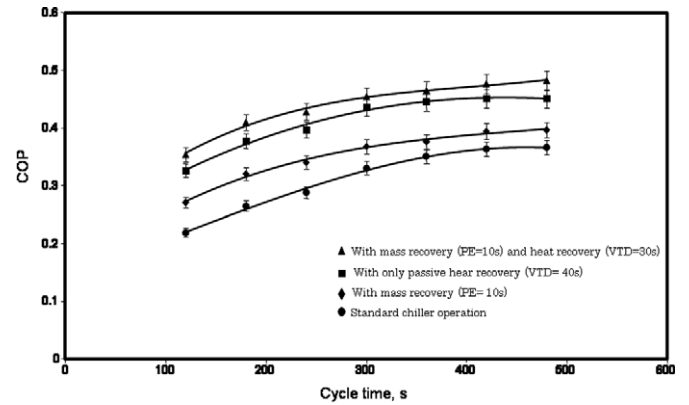


Fig. 8. Heat and mass recovery effects on the system COP of a four-bed adsorption chiller over an assortment of cycle times.

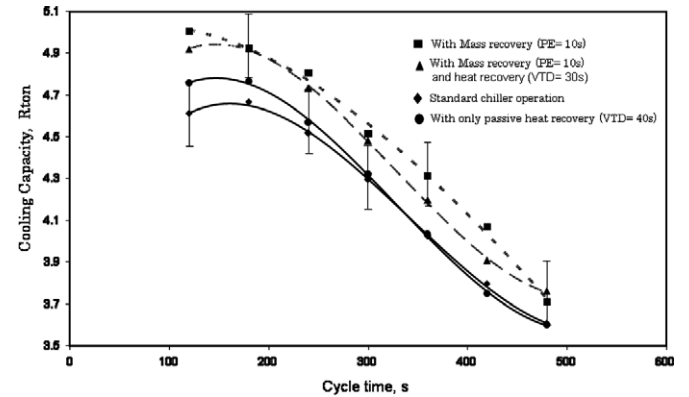


Fig. 9. Heat and mass recovery effects on the system cooling capacity of a four-bed adsorption chiller over an assortment of cycle times.

let temperature is almost constant and thus, no significant effect on the cooling capacity, as mentioned earlier.

The shaded area “B”, as indicated in Fig. 7, represents an additional energy saving by using VTD heat recovery. As stated in the earlier section, VTD procedure re-directs the residual heat in the coolant in the beds to ensure that

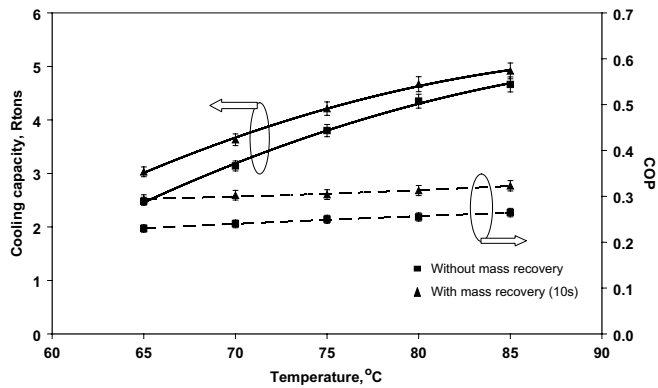


Fig. 10. Heat and mass recovery effects on the system performance of a four-bed adsorption chiller over an assortment of hot water temperature.

the hot water in the desorber is always channeled back to the hot water circuit without unwarranted mixing. This scheme is independent of the adsorption/desorption process in the reactor beds and hence it does not affect the cooling capacity. The VTD time interval in the chiller is 30 s and it is implemented after the PE procedure of 10 s within the switching period.

The combined effect of PE (= 10 s) and VTD (= 30 s) procedures on the adsorption chiller COP is shown in Fig. 8. As compared to the standard chiller, the improvement in chiller COP by using the PE ranges from 8% to 20% at long and short cycle time, respectively. A further improvement of 20%–30% is observed when the VTD procedure is incorporated and these improvements are observed to increase monotonically at longer cycle time. The corresponding changes in the cooling capacities when PE and VTD procedures are applied are shown in the Fig. 9. It is observed that the chiller cooling capacity changes by 3%–7% with PE (= 10 s) procedure at various cycle time. The sensitivity of PE to the hot water temperature is shown in Fig. 10. As expected, only the cooling capacity of chiller increases linearly with increasing hot water temperatures.

5. Conclusions

The performance of a prototype adsorption chiller with and without heat and mass energy recovery has been studied extensively. For the same half-cycle time interval and by incorporating only simple procedures, namely the valvetiming delay (VTD) to the coolant valves and pressure equalization (PE) for gas flowing across desorbers–desorbers, the chiller COPs have been demonstrated to increase signifi-

cantly without any reduction in cooling capacity. Moreover, the tested heat and mass recovery procedures require no major changes to the coolant circuits of the chiller.

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