MODELLING OF COMMERCIAL ABSORPTION HEAT PUMP WITH INTEGRAL STORAGE

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1. INTRODUCTION

The thermo-chemical accumulator (TCA) is a closed absorption batch process that uses a working pair, not only in the liquid, vapor and solution phases but also with solid sorbent, so called triple state operation. It was patented in 2000 (Olsson et al., 2000). Since then the TCA process has been developed in a relatively short space of time by the Swedish company ClimateWell via five generations of prototypes and is now commercially available under the name ClimateWell 10 (CW10). The majority of the 500 machines sold since 2007 are for relatively complex solar heating and cooling systems in the Mediterranean. They provide cooling during summer, space heating during winter and hot water year round. Although in principle both common absorption and adsorption processes can include significant heat storage, this is not used in commercial products. The ClimateWell machine is the first thermally driven heat pump with integral storage on the market. It uses LiCl and water as the working pair. Several prototypes have been developed, with different characteristics and operating principles (Bales et al., 2004). The first simulation model was derived for the 3rd generation of prototypes (Bales and Nordlander, 2005; Bales, 2006).

The 4th generation of machines differs significantly from the previous generations, and was the first to be sold commercially, as from 2007. As a result the simulation model for the 3rd generation had to be rewritten. This paper describes the basic operating principles of the machine, the model as well as the identification of model parameters. Finally the paper describes a series of parametric studies highlighting the influence of a number of parameters on the COP and storage capacity of the machine.

1.1 TCA Principles

Figure 1 (left) shows the schematic of a TCA unit, or barrel, with four different vessels. The reactor (absorber/desorber) and condenser/evaporator are the active parts of the unit with a vapor channel between them, while the two other vessels are stores for salt solution and the refrigerant, in this case water. The unit is operated as a closed system under vacuum conditions and there are heat exchangers in the reactor and condenser/evaporator. Solution and refrigerant are pumped from the storage vessels over these heat exchangers and then flow under gravity back to the storage vessels. The process works in batch mode, with a separate desorption (charge) phase followed by absorption (discharge phase). During desorption the solution comes closer and closer to saturation, and when it reaches saturation point further desorption at the heat exchanger can result in the formation of solid crystals that fall under gravity into the vessel. These then get transferred to the storage vessel. Here they are prevented from following the solution into the pump by a sieve, thus forming a form of slurry in the bottom of the vessel.

For discharging, where the process is reversed, saturated solution is pumped over the heat exchanger where it absorbs the refrigerant evaporated in the evaporator. The heat of evaporation is provided either by the building (cooling mode) or from the environment (heating mode). The solution becomes unsaturated in the reactor, but when it goes to the solution store it has to pass through the slurry of crystals, where some of the crystals are dissolved to make the solution fully saturated again. In this way the solution is kept saturated as long as there are crystals available and the net result is a dissolving of the crystals into saturated solution. The heat of condensation and binding energy release is transferred to the environment (cooling mode) or to the building (heating mode).

The process can, however, be restricted to work in the two phase region during charging to avoid unwanted crystallization in pipes etc, but crystals will form when the solution is cooled down during discharge, thus operation can be two-phase during charge and three-phase during discharge. Discharge is normally extended beyond the point where all crystals have been dissolved, thus the first part will be in three-phase region and the rest in two-phase region. In a complete machine, two units are used so that one is being charged while the other is being discharged (providing useful heating and/or cooling). A switching unit switches the flows between the external circuits and the relevant heat exchangers in the two units (Figure 1, right). This gives quasi-continuous operation, but when the units are swapped at the end of charge/discharge, there is a period without cooling supply of about 10 minutes.

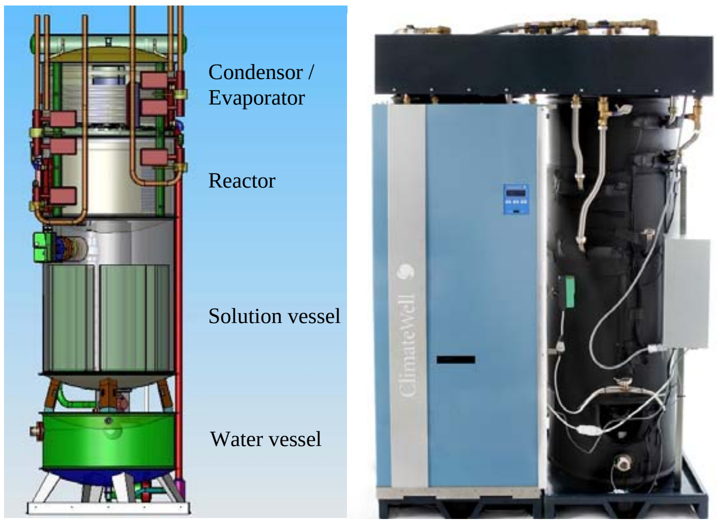


Figure 1: Schematic of a single TCA unit (left) and the complete commercial CW10 machine (right), comprising two barrels (units) and a switching unit above.

2. SIMULATION MODEL

This section gives a brief description of the model for the whole CW10 machine. The model is written for the TRNSYS simulation environment (Klein et al, 2004) and comprises two different component models, one for the TCA unit itself (Type 215) and one for the switching unit and controller (Type 216). A more detailed description of these is given by Nordlander and Bales (2007a, 2007b). Figure 2 (right) shows the simulation model for the complete machine. Figure 2 (left) shows the main masses, temperatures and mass flows for the model of a single TCA unit. There are four single node thermal masses: one each for the reactor and condensor/evaporator and one each for the bulk refrigerant and solution stores. The masses for the reactor and condensor/evaporator are kept constant while the one for the stores vary depending on the state of charge of the machine, due to the vapour transport between the parts. These masses are effective masses as they include the thermal mass of the material of the vessels. There are individual heat loss coefficients associated with each of these masses.

There is a mixing flow between the bulk stores and the reactor and condenser. This models the real mixing flow as well as other heat transfer effects between them. The concentration of the solution is calculated separately for the two solution parts: reactor and the bulk store. The average concentration is also calculated. The temperature difference between the inlet fluid to the reactor and that to the condensor is dependent on the theoretical properties of the working pair (LiCl-water) using equations published by Conde (2004) and the overall heat transfer coefficients of the two heat exchangers. One UA-value is defined for charging and another for discharging, and the individual ones for the reactor / condensor are derived from these. The model takes into account the heat of dilution during absorption of the water, enthalpy of crystallization and the heat of vaporisation for absorption and desorption as well as the sensible energy of the materials themselves. The model can calculate the required vapour flow, and hence heating/cooling rates, to maintain a user given supply temperature during discharge. If the cooling/heating capacity is not sufficient to meet this desired temperature, then the full capacity and resulting temperatures is used.

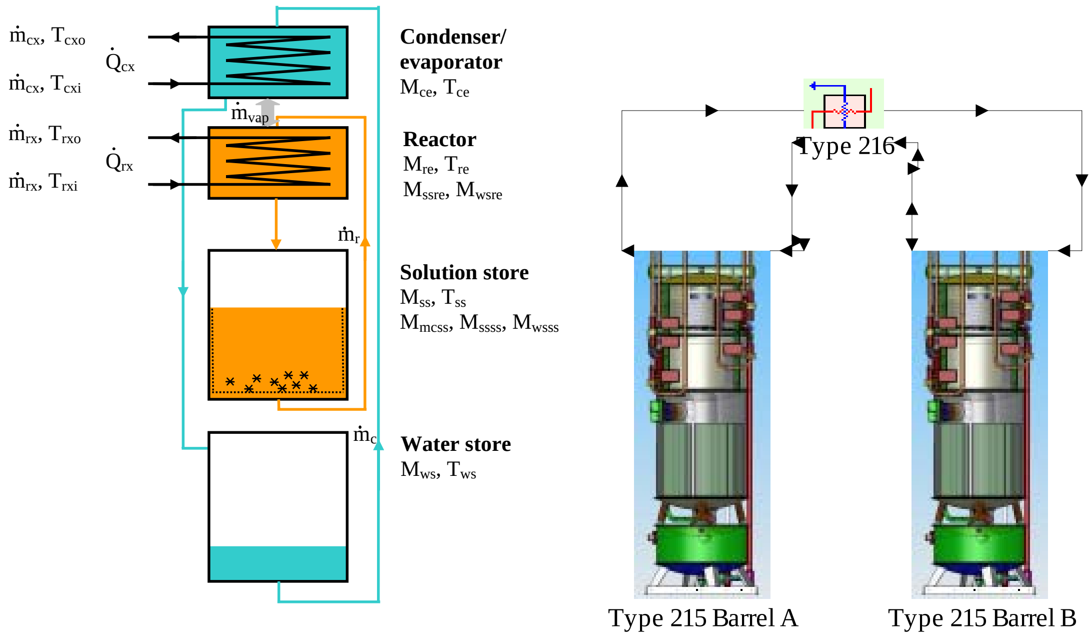


Figure 1: Schematic of Type 215 single TCA unit model (left) and a complete TCA machine in TRNSYS studio (right), comprising two units (Type 215) and a switching/controller unit (Type 216).

The model for the controller and switching unit (Type 216) determines whether a unit is fully charged and also when discharge is complete. The algorithm for this uses the same principles as that used in the commercial machine. There are two modes for determining when a swap between charge and discharge is performed. In the first case, a swap is performed when either one unit is fully discharged or the other has finished discharging. In the second mode, a swap is performed only when both units have finished: fully charged and fully discharged.

3. PARAMETER IDENTIFICATION AND VERIFICATION

Several ClimateWell 10 units were tested over a period of several weeks during April – July 2007 at the ClimateWell testing lab after an initial calibration of the measurement equipment (Ayadi, 2007). The tests were performed after each unit had been loaded with salt and tested for compliance with the internal quality control of the company, and before each unit was delivered for installation. The resulting model parameters are thus for an “average” unit of those tested. The test sequences were made for constant boundary conditions of charging and discharging power and cooling water return temperature, but with different powers and set temperatures for the different test sequences. The controller/switching unit was not connected during these tests. The mass of LiCl and solution are those used in the production process, with a total mass of 171 kg of solution with none in the rest of the machine.

3.1 Parameter Identification

The main parameters concerning the masses and properties of water and Lithium Chloride were fixed to those of the physical quantities. The parameters for heat loss coefficients to ambient were derived using energy balances for a single unit from one machine for one complete cycle, ensuring as well as possible that the internal energy of the unit was the same at start and end of the cycle. Using a simulation model of the whole machine with the same boundary conditions as the tests, the internal heat loss coefficient was identified so that the COP of the simulated machine was the same as the measured value. Thereafter automatic parameter identification was performed using the tools DF

(Spirkl, 1999) and Fittrn (Huber, 1998) together with the model of the unit. Measured flows and temperatures were used as inlets to the model. Table 1 shows the main parameters identified for the model.

The parameter values for the controller model are those defined by ClimateWell for normal operation of the machine. They have not been verified against actual performance of a complete machine.

Table 1: Main parameter values identified for the commercial ClimateWell 10 units tested

Parameter Description	Value	Identification
UA_{re} – heat loss coefficient for reactor	8.6 [W/K]	From energy balance
UA_{ce} – heat loss coefficient for condenser	8.6 [W/K]	From energy balance
UA_{ss} – heat loss coefficient for solution store	9.2 [W/K]	From energy balance
UA_{ws} – heat loss coefficient for water store	9.2 [W/K]	From energy balance
UA_{int} – heat transfer coefficient between reactor and condenser during charge	16.7 [W/K]	From COP test
UA_{ch} – heat transfer coefficient for charging	9992 [W/K]	TRNSYS + DF
UA_{di} – heat transfer coefficient for discharging	4231 [W/K]	TRNSYS + DF
f_{dp} – pressure drop factor for vapour flow	9.62 [-]	TRNSYS + DF
m_r – internal circulation flow of solution	0.278 [kg/s]	TRNSYS + DF
m_c – internal circulation flow of water	0.225 [kg/s]	TRNSYS + DF

3.2 Model Verification

Figure 3a shows the measured and simulated values of heat transfer rate for the reactor and condenser of a single unit over two full cycles. The agreement is in general good except at the start of the charging or discharging phases where the simple model for heat transfer rate is a limiting factor. In reality, during the initial phase of the charge in the reactor, there is only sensible heat transfer, and desorption starts only when the temperature is high enough. The desorption starts earlier in the model. Figure 3b shows the inlet and outlet temperatures to the heat exchangers. This shows that for constant charge and discharge powers, the temperature conditions vary. This is due to the varying concentration of the salt and the resulting vapour pressure above the salt. The temperatures required for charging and those supplied during discharge increase with time.

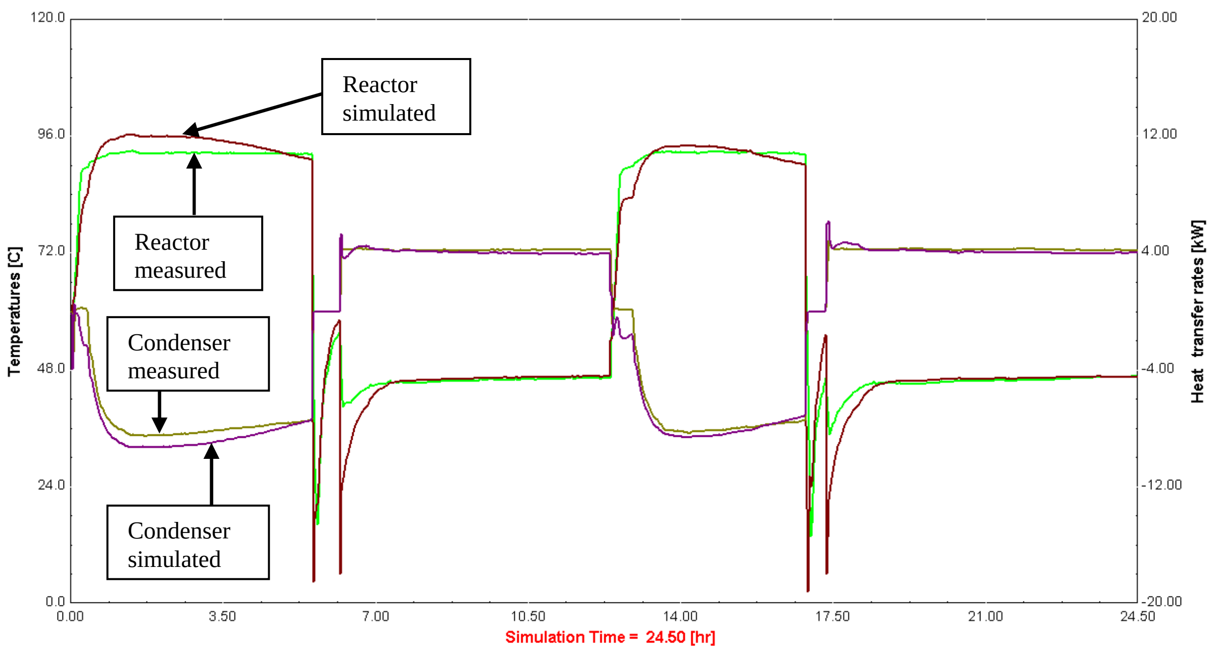


Figure 3a: Measured and simulated heat transfer rates for reactor and condenser for two full cycles of a single unit.

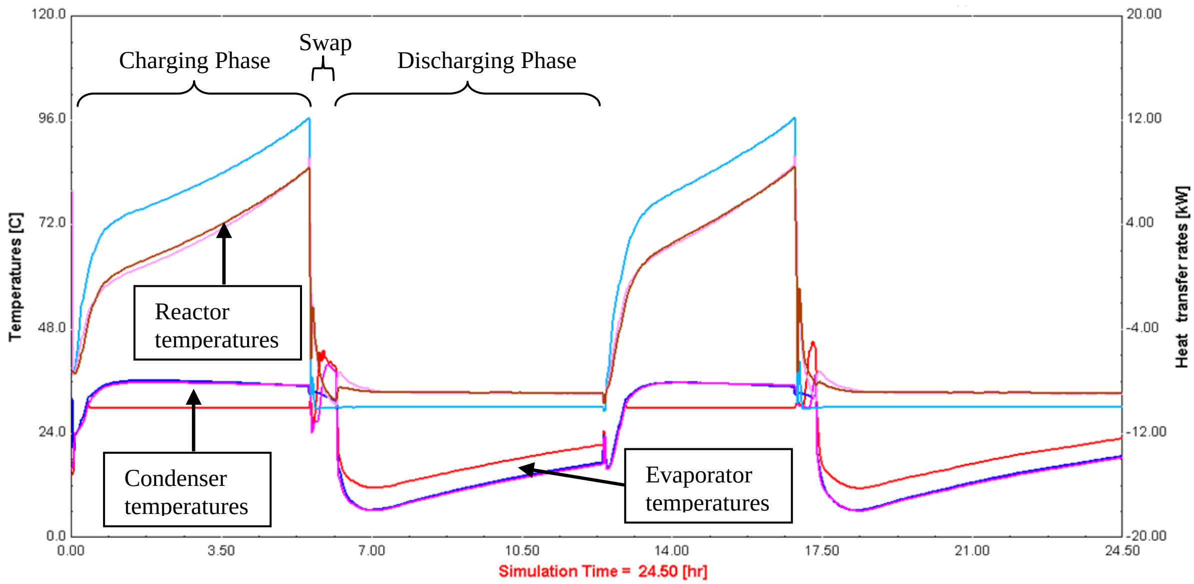


Figure 3b: Measured and simulated inlet/outlet temperatures to reactor and condenser/evaporator heat exchangers.

4. PARAMETRIC STUDIES

This section describes the parametric studies performed using the model described in the previous section.

4.1 Boundary Conditions

Table 2 shows the boundary conditions for the parametric studies that define a reference case that is used for normalizing COP values. Constant heating rates are applied to the reactor during charge and to the evaporator during discharge and the cooling water from the heat sink is kept at a constant temperature to the condenser and reactor respectively. As the model is not connected to a real cooling load, this method can result in unrealistically high supply temperatures from the evaporator at the end of the discharge with high powers and/or cooling water temperatures. In order to make the conditions more realistic, a limit of 20°C is applied to the chilled water return temperature (from cooling load). This in effect reduces the applied cooling load from the nominal value. In this study this reduction is limited to 50% of the nominal cooling load, so that for 8 kW nominal cooling load, a swap will be forced when the actual cooling load has been reduced to 4 kW. Several complete cycles were simulated for each case, and the energies for one complete cycle were used for calculation of COP and storage capacity.

Table 2: Boundary conditions for the reference case to which all results are normalized, as well as operational control values for determining end of discharge.

Description	***Value***	***unit***
Charge (desorption) power	12	kW
Discharge (evaporation) power	6	kW
Inlet temperature to condenser from heat sink during charging	30	°C
Inlet temperature to reactor from heat sink during discharging	30	°C
Flow rate in the reactor during charging	0.25	kg/s
Flow rate in the condenser during discharging	0.25	kg/s
Flow rate in the condenser during charging	0.35	kg/s
Flow rate in the reactor during discharging	0.35	kg/s
Ambient temperature	22	°C
Water content in store when "empty"	8	kg
Mass of LiCl solution in store when unit discharged (empty)	163	kg
Minimum discharge power, below which discharge is stopped	50%	Of nominal
Maximum inlet temperature to evaporator (from cooling load)	20	°C

4.2 Results

Two main values are shown in the diagrams. The first is COP normalized to the value for the reference case (R_{COP}), defined according to Equ. 2. COP is defined by Equ. 1 using the supplied cooling energy from evaporation (Q_{evap}) and the energy required to charge the unit (Q_{desorp}) for a complete charge/discharge cycle with the same internal energy at the start and end of the complete cycles.

$$COP_{cool} = \frac{Q_{evap}}{Q_{desorp}} \qquad \text{Equ. 1}$$

$$R_{COP} = \frac{COP}{COP_{ref}} \qquad \text{Equ. 2}$$

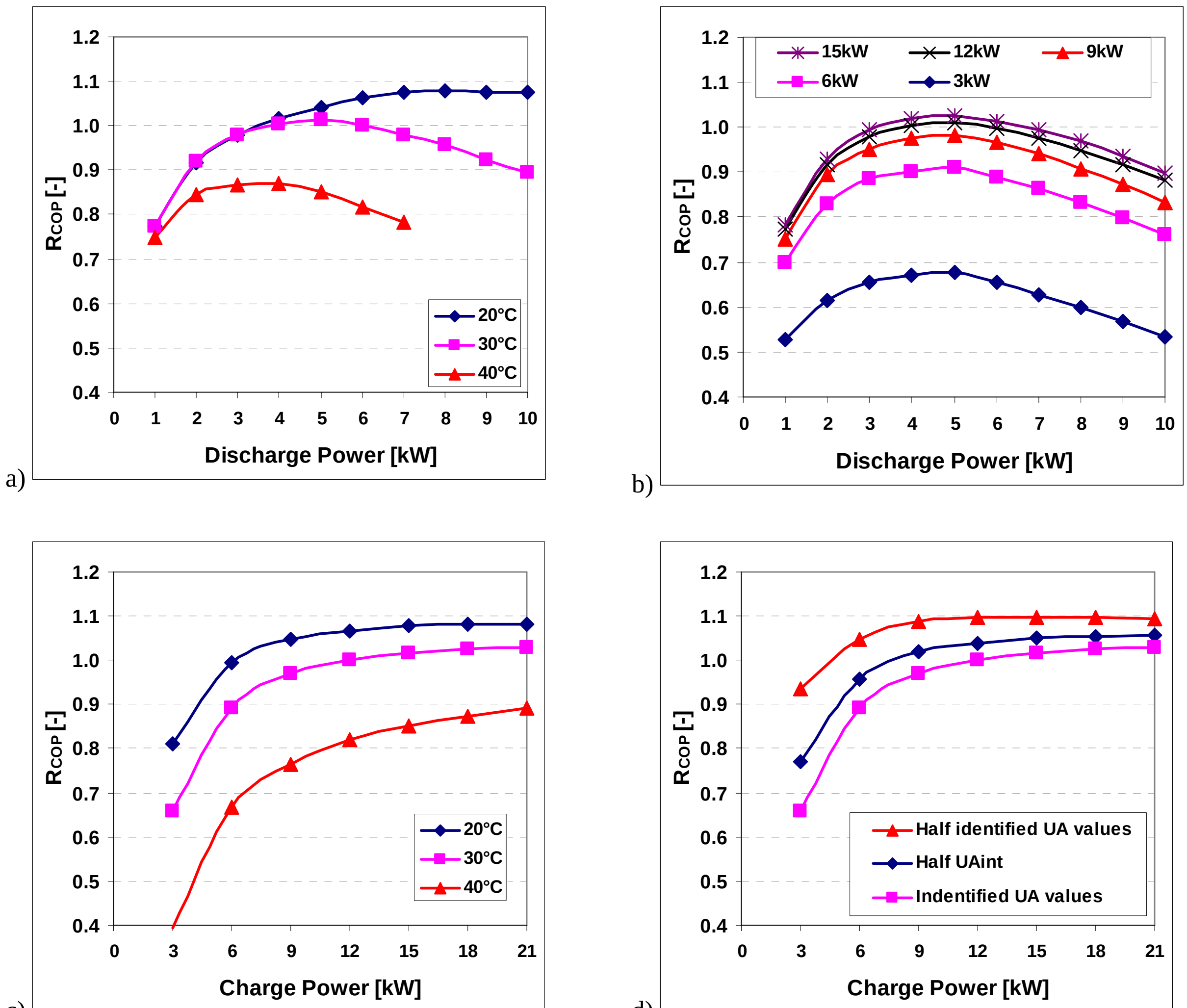


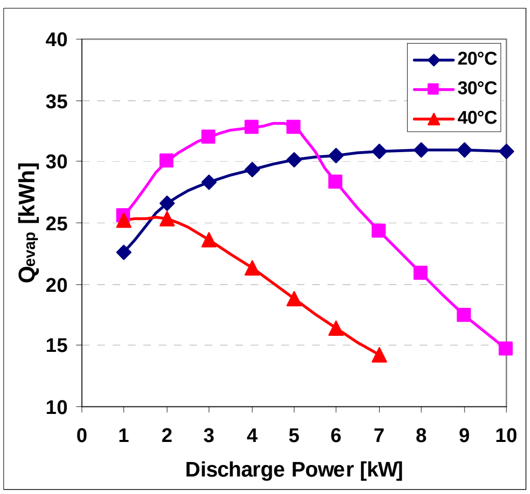
Figure 4: Normalised COP values (R_{COP}) versus discharge powers at different cooling water temperatures (a) and charge powers (b): versus charge power at different cooling water temperatures (c) and heat loss coefficients (d).

Table 3 shows the values for the reference case, using the data defined in tables 1 and 2. Figure 4 shows how the normalized COP (R_{COP}) varies with discharge and charge power as well as cooling water temperature. At low discharge and charge rates the COP is relatively low due to high internal heat losses (between reactor and condenser) as well as losses to ambient over a long period of time. At high cooling water temperatures and high nominal discharge rates the COP is also low. This is mainly due to the fact that the discharge is terminated early when the supplied cooling power (discharge power) is less than 50% of the nominal value. The cooling power is lower than the nominal rate because the chilled water return temperature is limited to 20°C. Figure 4d shows that the COP values can increase significantly by reducing the heat losses. This is especially apparent at low charge rates (as well as discharge rates).

Table 3: Main values for the reference case based on simulations with identified parameters and chosen boundary conditions.

$COP_{cool} = COP_{ref}$	Q_{evap} [kWh]	Q_{desorp} [kWh]
0.60	28.2	46.8

As it is a batch process, the supplied cooling (Q_{evap}) is essentially the stored cooling energy in the barrel. Figure 5 shows how this storage capacity for varies with discharge and charge powers as well as with cooling water temperature. Note that due to the boundary conditions, discharge is terminated early when supplied cooling is less than 50% of the nominal cooling power. This reduces the effective storage capacity (supplied cooling), something that is clearly shown in Figure 5 for high cooling water temperatures and discharge power. The storage capacity is hardly dependent on the charge power which shows clearly that discharge and charge are decoupled.



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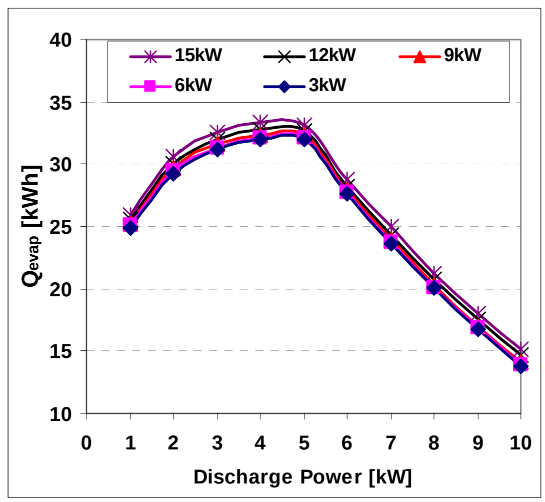

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Figure 5: Variation of the cold storage capacity (Q_{evap}) with the discharge and charge powers as well as cooled water temperatures.

5. DISCUSSION

The results show that the COP of the CW10 is dependent on the boundary conditions. However, the effect is indirect. Charge and discharge are two parts of a complete cycle and are decoupled, but the COP is determined by the ratio of the discharge (cooling energy) and the charging energy over a complete cycle. The difference between these two energy quantities is the losses in the machine. Thus, the greater the losses are, the lower the COP is. Similarly, for given losses, the smaller the effective storage capacity the lower the COP, as shown in figures 4 and 5. The charging process is stopped at given conditions that are designed to achieve a high salt concentration without risking unwanted crystallization in the pipes and pump. The discharging process is stopped in this study when the machine is empty (more or less all water absorbed) or when the machine cannot deliver an acceptable cooling power, defined here as being 50% of the nominal (desired) power. These conditions determine the upper and lower concentrations of the solution over the cycle and thus the effective storage capacity. The heat losses can be split into the heat losses to ambient, heat loss from reactor to condenser and to the fact that the discharge process operates at a lower temperature (and pressure) than the charging process. There is no heat recovery between these two operating temperature as is common in absorption chillers, although in theory it is possible by direct coupling reactors and condensers of the two units in a machine during swap. With the relatively large heat loss coefficients identified, low charge and discharge rates result in long cycle times and thus large losses to ambient with resulting low COP values. Losses due to different operating temperatures are not dependent on cycle time. Reducing the heat loss coefficient to half of the indentified values would result in approximately 10% (relative) increase in COP. The switching unit that was tested was not well insulated, and there was no insulation between the reactor and condenser, so significant reductions in heat losses should be possible in practice.

6. CONCLUSION

A grey box model for the TRNSYS environment of the 4th generation of TCA technology machines has been developed based on previous models. Parameters for it have been derived using data from a number of test sequences applied to several units. The model of a complete machine consists of separate models for TCA unit and for the switching unit/controller. The TCA unit model was verified against the measured data and shows reasonable agreement, although details of the dynamics, especially at the start of the charge and discharge processes show larger deviation. A model for a complete machine, as commercialized by ClimateWell with the brand name CW10, was made and used for parametric studies in order to determine the effect of boundary conditions on the COP and storage capacity. These showed that the COP is dependent on the storage capacity, which in turn depends on the operating conditions. Low charge and discharge rates results in high heat losses and thus low COP. Similarly high nominal discharge rates as well as high cooling water temperature reduced storage capacity and COP.

ACKNOWLEDGMENTS

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