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THE MODELING OF AIR-COOLED ABSORPTION CHILLER INTEGRATION IN CHP SYSTEM

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ABSTRACT

Absorption chillers are well suited for the use of exhaust heat from prime movers, and they improve the heat utilization of Cooling, Heating, and Power (CHP) systems. An air-cooled absorption chiller eliminates the cooling tower and brings considerable advantages as compared to water-cooled chillers. However, the expensive capital cost and crystallization of LiBr (Lithium Bromide) solution in certain operation conditions restrict the commercialization of air-cooled LiBr absorption machines. This paper discusses the feasibility of air-cooled absorption in CHP systems, where the control strategies based on the application can avoid the occurrence of crystallization. By using the fundamental thermodynamic principle, steady-state thermodynamic modeling and simulation have been done in Engineer Equation Solver (EES) to predict the operation of air-cooled absorption chiller integration in CHP systems with special consideration of the crystallization limits. The data of field operation acquired from a CHP system at UMD are used for validation.

INTRODUCTION

Absorption chillers are well suited for the use of exhaust heat from prime movers (such as microturbine) and improve the heat utilization of CHP systems.

The motivation for an air-cooled option is to use air, a free coolant, to lower temperatures for condensers and absorbers. As a result, the cooling tower, water, and the associated maintenance, the winterizing procedure, and Legionella breeding are eliminated. Places in the world where water is a precious commodity can particularly benefit from this.

Since the water-cooled chiller has a cooling tower, it can maintain the entering condenser water temperature (ECWT) lower than the air-cooled condenser air inlet temperature when the weather is hot. Figure 1 shows the comparison of air temperature and cooling water temperature entering the condenser. Therefore water-cooled absorption machines generally can operate year-round with less crystallization issues.

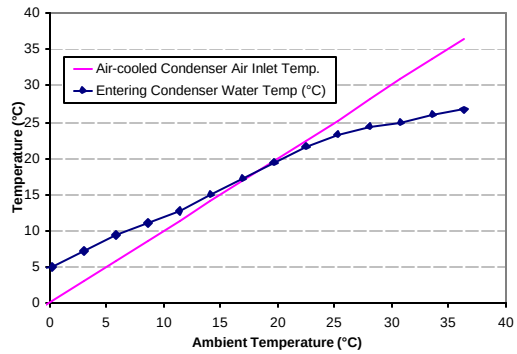

Figure 1. US average ECWT and air inlet temperature of air-cooled condenser (Source: US weather bin data.)

But crystallization is the main obstacle to producing an air-cooled absorption machine based on LiBr, because the air-cooled absorbers tend to run hotter than water-cooled units due to the relative heat transfer characteristics of the coolants. Particularly in hot climates, this presents a difficult design problem [1], [2].

The EES and ABSIM (ABsorption SIMulation) are most commonly used to simulate the operation of absorption chillers [1],[3],[4],[5]. For example, Munther Salim (2001) simulated the automotive LiBr/H_20 absorption A/C machine by ABSIM[6]. There are two major differences between EES and other equation-solving programs or software. First, EES allows equations to be entered in any order with unknown variables placed anywhere in the equations; EES automatically reorders the equations for efficient solution. Second, EES provides many built-in mathematical and thermo-physical property

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functions of working fluids useful for engineering calculations. The program also enables researchers to build an interface and make plots. The authors use EES and the fundamental thermodynamic principle to create models that predict the operation of air-cooled absorption chiller in CHP systems with special consideration of the crystallization limits.

Little research has been reported on the experimental work about Air-cooled Absorption Chillers, and they are all restricted on small tonnage machines, such as a 3kW air-cooled absorption prototype tested by J. Castro (2002) [8].

NOMENCLATURE

Abbreviations:

ABSIM	ABsorption SIMulation
AC	Absorption Chiller
CHP	Combined Cooling, Heating. and Power
COP	Coefficient of Performance
EES	Engineer Equation Solver
LiBr	Lithium Bromide
LMTD	Log Mean Temperature Difference
UMD	University of Maryland

Parameters/Variables:

h	Enthalpy
m	Mass flow rate
P	Pressure
Q	Heat exchange capacity
T	Temperature
UA	Overall heat transfer coefficient
x	Concentration of LiBr

Subscripts

a	Absorber
c	Condenser
e	Evaporator
g	Generator / desorber
hx	Solution heat exchanger

MODELLING

Figure 2 shows the schematic diagram of a single-effect air-cooled absorption chiller. There are 18 points total in the modeling, and each has its temperature, pressure, enthalpy, flow rate, etc. Besides the fundamental thermodynamic principle of mass and energy conservation, UA-LMTD method is used, i.e. after an absorption chiller is built, the overall heat transfer coefficient (UA) is relatively constant throughout each heat exchanger.

Assumptions

The following assumptions are used in the modeling of single-effect absorption chillers.

- Steady state;
- There are 2 pressures [P_{high} and P_{low}] in the system: pressure in the generator and condenser is at $P_{high,}$ while the pressure in the evaporator and absorber is at P_{low}, and there is no pressure drop or heat transfer in the piping network;
- After the chiller is built, the overall heat transfer coefficient (UA) of each heat exchanger is known and constant. The UA-LMTD method is adopted;
- The throttling device is isoenthalpic;
- The solution pump is adiabatic, and it is used to maintain the constant solution level in the desorber.

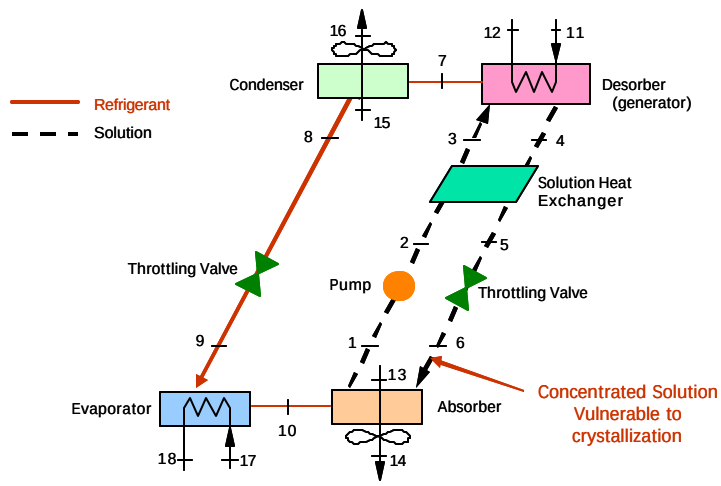

Figure 2: Diagram of single-effect air-cooled absorption chiller

Table 1 summarizes the thermodynamic status of each state point:

Table 1. Thermodynamic state point summary

Point	State	Notes
1	Saturated liquid solution	Vapor quality = 0
2	Sub-cooled liquid solution	State calculated from pump model, enthalpy $h_2 \sim h_1$
3	Sub-cooled liquid solution	State calculated from solution heat exchanger model
4	Saturated liquid solution	Vapor quality = 0
5	Sub-cooled liquid solution	State calculated from solution heat exchanger model
6	Vapor-liquid solution state	Vapor flashes as liquid passes through expansion valve, $h_6 \sim h_5$
7	Superheated water vapor	No salt content
8	Saturated liquid water	At pressure P_{high}
9	Vapor-liquid water state	Vapor flashes as liquid passes through expansion valve, enthalpy $h_9 \sim h_8$
10	Saturated water vapor	At pressure P_{low}

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Generator / Desorber

The energy balances on the solution side and heat source are:

$$Q_g = m_4 \cdot h_4 + m_7 \cdot h_7 - m_3 \cdot h_3 \quad (1)$$

$$Q_g = m_{11}(h_{11} - h_{12}) \quad (2)$$

The heat transfer rate is calculated by

$$Q_g = UA_g \cdot LMTD_g \quad (3)$$

where

$$LMTD_g = \frac{(T_{11} - T_4) - (T_{12} - T_7)}{\ln(\frac{T_{11} - T_4}{T_{12} - T_7})} \quad (4)$$

The mass and salt balances are:

$$m_3 = m_4 + m_7 \quad (5)$$

$$m_3 \cdot x_3 = m_4 \cdot x_4 \quad (6)$$

Condenser

The energy balances on the solution side and cooling air are:

$$Q_c = m_7(h_7 - h_8) \quad (7)$$

$$Q_c = m_{15}(h_{16} - h_{15}) \quad (8)$$

The heat transfer rate is calculated by

$$Q_c = UA_c \cdot LMTD_c \quad (9)$$

where

$$LMTD_c = \frac{T_{16} - T_{15}}{\ln(\frac{T_8 - T_{15}}{T_8 - T_{16}})} \quad (10)$$

Evaporator

The energy balances on the solution side and chilled water are:

$$Q_e = m_9(h_{10} - h_9) \quad (11)$$

$$Q_e = m_{17}(h_{17} - h_{18}) \quad (12)$$

The heat transfer rate is calculated by

$$Q_e = UA_e \cdot LMTD_e \quad (13)$$

where

$$LMTD_e = \frac{T_{17} - T_{18}}{\ln(\frac{T_{17} - T_{10}}{T_{18} - T_{10}})} \quad (14)$$

Absorber

The energy balances on the solution side and cooling air are:

$$Q_a = m_{10} \cdot h_{10} + m_6 \cdot h_6 - m_1 \cdot h_1 \quad (15)$$

$$Q_a = m_{13}(h_{14} - h_{13}) \quad (16)$$

The heat transfer rate is calculated by

$$Q_a = UA_a \cdot LMTD_a \quad (17)$$

where

$$LMTD_a = \frac{(T_6 - T_{14}) - (T_1 - T_{13})}{\ln(\frac{T_6 - T_{14}}{T_1 - T_{13}})} \quad (18)$$

Solution Heat Exchanger

The energy balances on the cold and hot solution side are:

$$Q_{hx} = m_1(h_3 - h_2) \quad (19)$$

$$Q_{hx} = m_4(h_4 - h_5) \quad (20)$$

The heat transfer rate is calculated by

$$Q_{hx} = UA_{hx} \cdot LMTD_{hx} \quad (21)$$

where

$$LMTD_{hx} = \frac{(T_4 - T_3) - (T_5 - T_2)}{\ln(\frac{T_4 - T_3}{T_5 - T_2})} \quad (22)$$

System Thermal COP

$$COP = \frac{Q_e}{Q_g} \quad (23)$$

SIMULATION RESULT

In the real operation, the system performance is manipulated by all these parameters and variables. To simulate the performance of absorption chillers with respect to the exhaust heat temperature into the desorber, all parameters (all UA, m_{11}, m_{13}, m_{15}, m_{17}, T_{17} and ambient temperature) are fixed except the exhaust temperature T_{11}. The performances of the absorption chiller vs. T_{11} are plotted as follows in Figure 3 through Figure 6.

When the exhaust temperature T_{11} increases, the condenser pressure increases slightly, while the evaporator pressure decreases at an insignificant level. Both strong and weak solution become more concentrated, which may cause crystallization. VFD Solution pump has to increase its flow rate to maintain the solution level in the desorber. As a result, the capacity of each heat exchanger increases, but the COP decreases slightly.

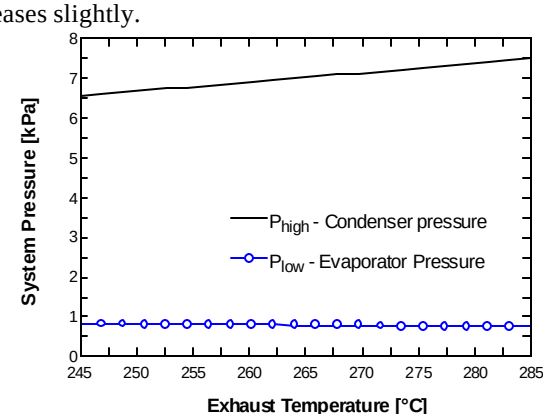

Figure 3: System pressure vs. exhaust T into desorber

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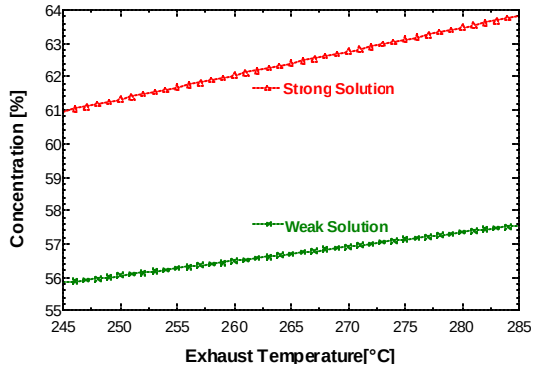

Figure 4: LiBr concentration vs. exhaust T into desorber

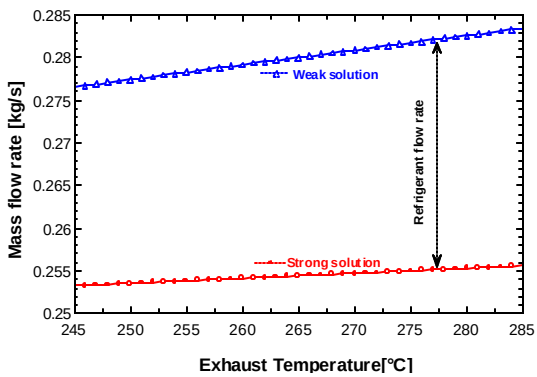

Figure 5: Mass flow rate vs. exhaust T into desorber (the difference is the flow rate of refrigerant water)

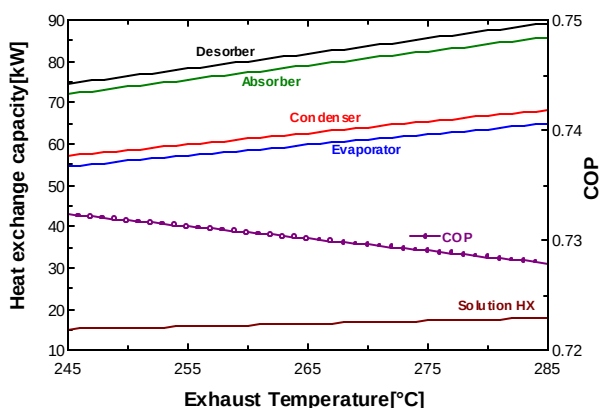

Figure 6: Heat exchange capacity and COP vs. exhaust T11

CRYSTALLIZATION AND CRYSTALLIZATION CONTROL GUIDELINES

Besides the capital cost that hinders the commercialization of air-cooled absorption chillers, crystallization is the main obstacle in designing and producing an air-cooled absorption machine based on LiBr.

In absorption chillers, if the solution concentration is too high or the solution temperature is reduced too low, crystallization may occur and interrupt machine operation. The location is also decided by the mechanical structure of pipes and fittings; this is most likely to occur in strong solution entering the absorber, i.e. the point 6 in Figure 2. In such a case, the concentrated solution temperature needs to be raised above its saturation point so that the salt crystals will return to the solution, freeing the machine.

The big difference between water-cooled and air-cooled LiBr-water absorption chillers is the temperature of the absorber. With air-cooled, one cannot achieve a temperature of the solution in the absorber sufficiently low enough to maintain the evaporator pressure. The only way to compensate for the high absorber temperature is to increase the concentration of LiBr in the solution, but that brings it closer to crystallization.

The following situations or the combination of these situations may cause crystallization of air-cooled absorption chiller:

- High ambient temperature: The air-cooled absorbers tend to run hotter than water-cooled units due to the relative heat transfer characteristics of the coolants [1]. Figure 7 gives the overall impression of how each point changes when the ambient T increases in the Dühring P-T chart. The system runs with the same exhaust temperature and chilled water temperature setting, when the ambient temperature increases from 25°C (dash lines) to 35°C (solid lines), crystallization happens !
- Air leak into the machine or non-absorbable gases produced during corrosion: Both deteriorate the UA and cause higher system pressure, decreased capacity and COP, and higher crystallization probability. A direct method for keeping the required pressure is to evacuate the vapor space periodically with a vacuum pump [1]. This situation can be simulated by assuming a decreased UA, which will cause x_6, the concentration of point 6 closer to the crystallization line limit. As a precaution to this issue, the system should be evacuated routinely.

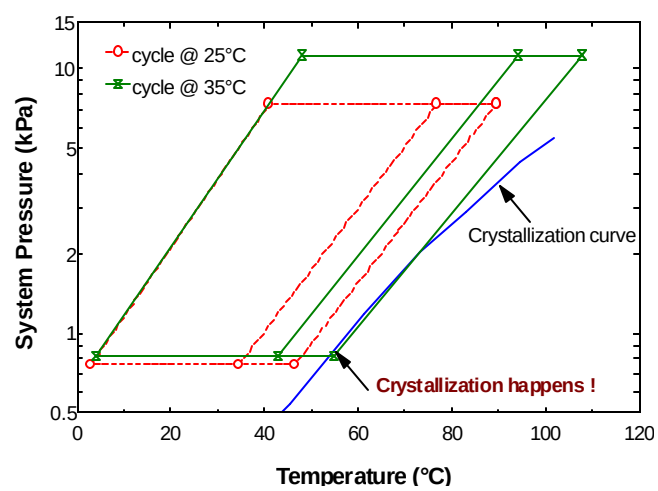

Figure 7: The Dühring P-T chart of cycle (dash line) @ ambient 25°C and cycle (solid line) @ ambient 35°C

- Too much heat input to the desorber: i.e. either the exhaust temperature T_{11} or the flow rate m_{11} is too high. As

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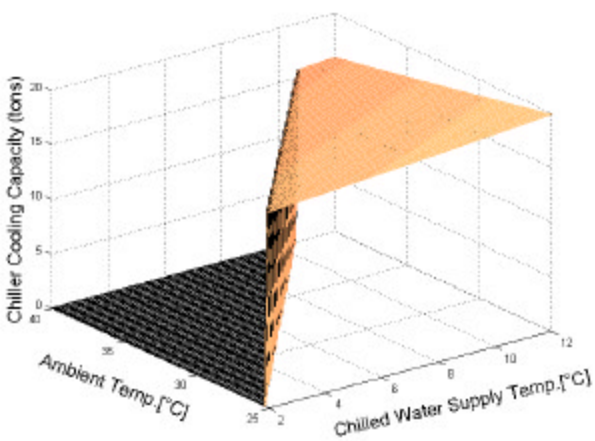
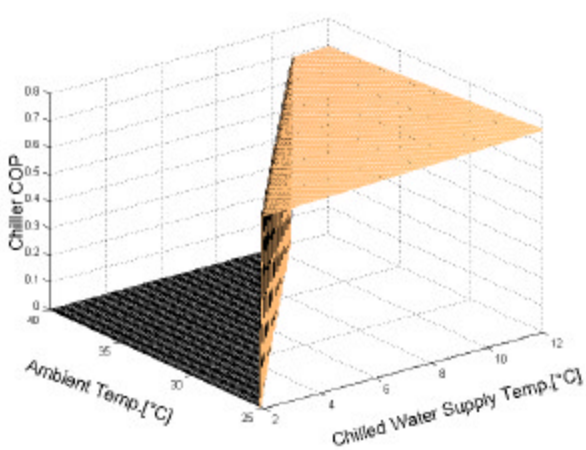
a precaution to this issue, the exhaust temperature or flow rate into the desorber should be maintained within a specific range.

- Failed dilution after shutdown: During normal shutdown, the machine undergoes an automatic dilution cycle, which lowers the concentration of the solution throughout the machine. In such a case, the machine may cool to ambient temperature without crystallization occurring in the solutions. Crystallization is most likely to occur when the machine is stopped due to power outage while operating at full load, when highly concentrated solutions are present in the solution heat exchanger [1].
- Chilled water supply temperature is set too low when the weather is hot: Usually the chilled water supply temperature can be set by the control system. The darker zone in Figure 8 represents the unfeasible temperature combination. The air-cooled chiller should not run in this zone to avoid crystallization; while the lighter zone is safe for the chiller operation.



(a) Chiller cooling capacity



(b) Chiller COP

Figure 8: Chiller performance over the temperature combination

In the past, two principal technical approaches to air-cooled LiBr absorption design have been used. They involve: (1) Mechanical design changes, such as very highly efficient heat exchangers, to bring the air-cooled operation within the existing LiBr/H2O crystallization limits. (2) The use of chemical additives, such as 2-Ethyl Hexanol to shift the crystallization line to higher temperatures to allow air-cooled operation with commercially practical margins of safety from crystallization using conventional heat exchangers.

The third approach proposed by the authors is the control strategy. Like the simulation results shown in Figure 8, though hot weather may cause crystallization, increasing the chilled water temperature settings can prevent crystallization, the byproducts include: improved cooling capacity and COP.

In some applications, where the chilled water supply temperature is allowed to increase appropriately with the ambient temperature, the air-cooled concept is feasible. In the case of the CHP application, the chiller is used to cool down the process air leaving a desiccant wheel, and the process air is usually at more than 40°C, so the chilled water supply temperature can be hotter than the normal setting, because the temperature difference is still large enough.

EXPERIMENTAL SETUP AND VALIDATION

Since no air-cooled absorption is available, the tests were done on an 18-ton water-cooled absorption chiller at the CHP test center on the University of Maryland campus, which was driven by the exhaust from a 60kW microturbine. The simulated tests are used to validate the modeling, in which the ambient temperature in air-cooled simulation equals the cooling water temperature in water-cooled test. The data acquisition system records all data points once per minute. Since the machines are installed outdoors and the chiller has large thermal inertia, the operation conditions, such as the weather, cannot be maneuvered. Figure 9 shows the chiller performance in a typical day, there is about 1 hour transient period when the chiller is started, however the experimental validation is based on the performance at the steady state.

The temperature of exhaust into desorber can be adjusted by mixing the exhaust from microturbine and outdoor make-up air. The correlation between the cooling capacity and exhaust temperature is shown in Figure 10. The calculated model shows a good match with the experimental data.

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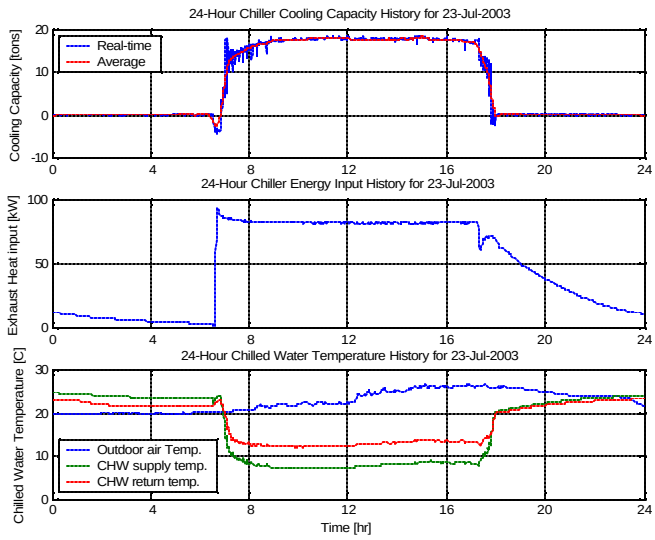

Figure 9: The chiller performance in a typical day

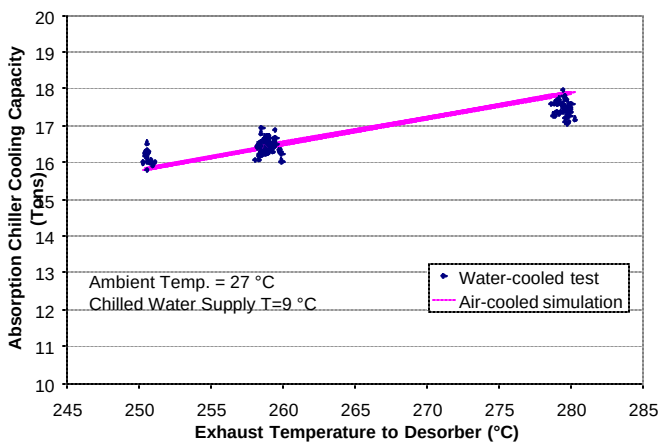

Figure 10: The experimental validation with varied exhaust temperature

To prove the proposed crystallization control strategy, the chiller was tested under two different conditions, both having the same exhaust inlet temperature (276°C) but different chilled water supply temperature and cooling water temperature. In Test A, the chilled water supply temperature was set at 8°C, and when the cooling water temperature increased the cooling capacity dropped. In Test B, as the cooling water temperature continued to increase (>=32.2°C), the chilled water supply temperature was set to 9.5°C, and the chiller could still run decently without the crystallization issue. Figure 11 (a) and (b) show the experimental validation of chiller cooling capacity and COP under the two conditions respectively. Solid lines are experimental data, solid plus dot lines are simulation results, the comparison is within ±3.0% for cooling capacity and ±3.6% for COP.

CONCLUSIONS

In some applications, where the chilled water supply temperature is not necessary to be too cold, the concept of air-cooled absorption chiller is feasible. Based on the steady-state thermodynamic modeling and simulation of a single-effect air-cooled absorption chiller, together with the experience of running water-cooled absorption chillers, the authors propose the crystallization control guideline, which is applicable for either air-cooled or water-cooled absorption chillers. The experiments at UMD based on steady-state operation conditions prove both the modeling and the crystallization control strategy.

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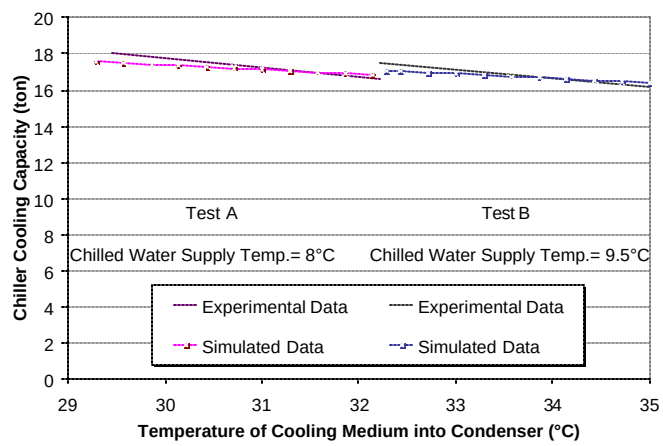
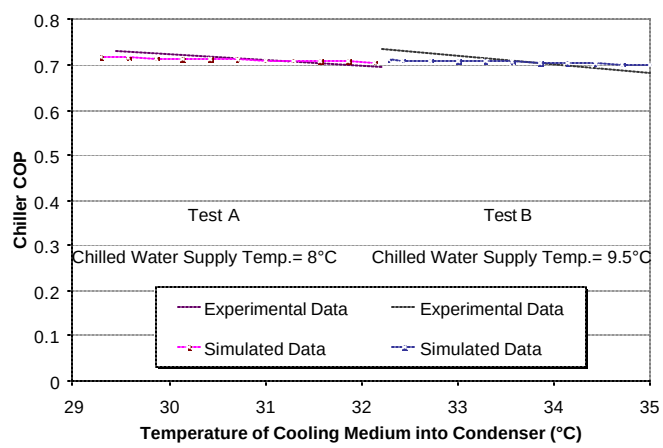


(a) Chiller cooling capacity



(b) Chiller COP

Figure 11: The experimental validation under 2 different conditions for the crystallization control strategy

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