AN ABSORPTION CHILLER MODEL FOR HVACSIM$^+$

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ABSTRACT

An absorption chiller model is developed for HVACSIM+(J). The model simulates dynamic characteristics of the chiller, such as dynamic trends of chiller temperatures and COP. The total system simulation including the chiller and the other HVAC system enables to evaluate energy consumption for the HVAC systems and how much the system save energy. Furthermore, the simulations show the effect of the control strategies. In the paper, the chiller model is described, and the simulation results which contain independent chiller system and a total HVAC system. The results show the interference of chiller controller and room control system.

INTRODUCTION

Concerns about green house effect caused by chloroflurocarbons(CFCs) and electric capacity shortage during mid-day in hot summer days, have brought growing interest in absorption chillers. Then, intensive research and development efforts were done for absorption chiller to improve its efficiency and expand its energy sources, in last decades. A HVAC simulation is very important to examine how much energy is saved by the improved chiller or by a improved system. HVACSIM+ is developed to simulate the HVAC systems in USA and Japan. HVACSIM+ is based on the dynamic simulation program by NIST, and has been improved for HVAC systems in Japan. The simulator has static general purpose chiller model. In order to examine precise dynamic characteristic, the dynamic chiller model is necessary. Then the absorption chiller model which is presented in the paper is developed and added to the simulator as the type function. The model simulates dynamic characteristics of absorption chillers. The model consists of the equations that describe heat balances and water and LiBr mass balances. Then, the integrated HVAC system which consists of buildings and chillers can be simulated. The interference between room temperature, humidity control and chiller control can be examined. The paper contains model descriptions and simulation results for a big conference room HVAC system. The results show the interference of room controller and chiller controller.

CHILLER MODEL

Absorption chiller was developed since 19th century, and is reliable heat source because it is almost static system. The working fluid is usually LiBr solution in water. Its dynamic characteristics are comparably stable because the dynamics are mainly governed by heat transfer. The chiller is composed of 4 vessels, that is, an evaporator, an absorber, a generator, and a condenser(Fig.1). In many cases, the chiller has two generator, one is high pressure generator and the other is low pressure generator to improve the performance coefficient.

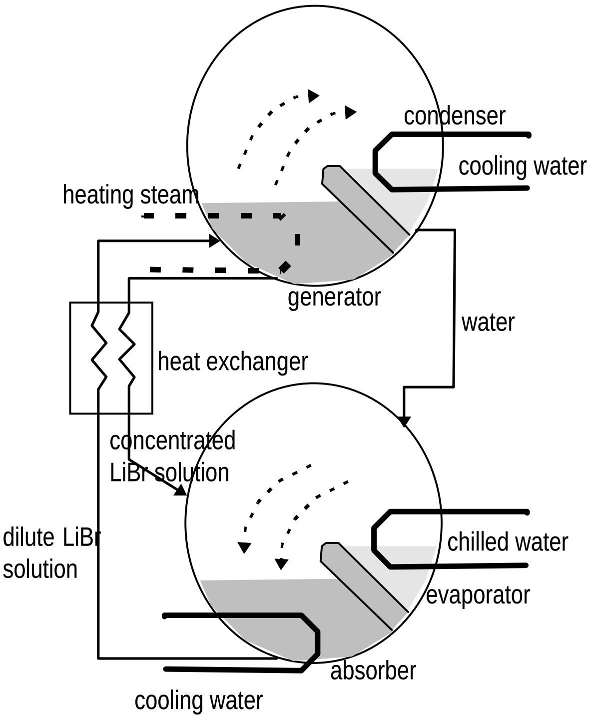


Fig.1 an absorption chiller

The water and LiBr solution cycle in the chiller is as follows.

(1)in the evaporator, water evaporates in low pressure environment and take heat from chilled water in heat exchange pipe.

(2)in the absorber, LiBr solution absorbs steam coming from the evaporator. The absorption yields the condensation heat and dilute the solution. So, the absorber is cooled by cooling water, and its solution is pumped up to the generator to condense the solution.

(3)in the generator, the solution is heated by heating steam or hot water so that the solution boils to remove some of its water. Then the solution become concentrated and return to the absorber.

(4)in the condenser, the steam from the generator is condensed to water. So, the latent heat is released. The condenser is cooled by cooling water.

Fig.2 shows the refrigerant cycle on the Duhring diagram.

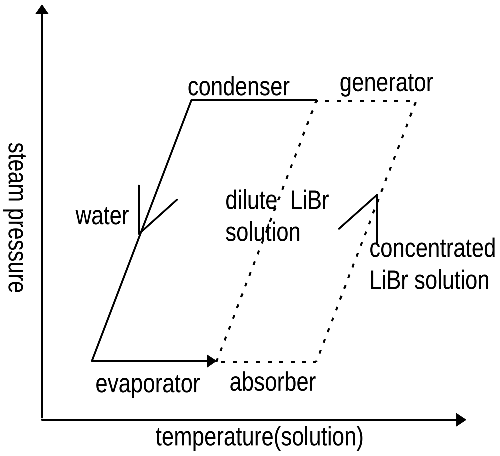


Fig.2 the refrigerant cycle

The model consists of the equations which express the above mentioned phenomena. The equations contain the mass balances, energy balances, and equations for equilibrium states of LiBr/H_2O solution as follows.

In the absorber:
(heat balance equation)

$$(C_a^{LB}W_a + C_{Va})\frac{dT_a}{dt} + C_a^{LB}T_a\frac{dW_a}{dt} = (r_a + C_W T_V)G_a - \alpha_a(T_a - T_{cool}) + C_r^{LB}G_{dw}T_{ch} - C_a^{LB}G_{up}T_a \quad (1)$$

(water mass balance equations)

$$\frac{dW_{wa}}{dt} = G_a - (1 - Conc_a)G_{up} + (1 - Conc_r)G_{dw} \quad (2)$$

$$G_a = f(Conc_a, T_v, T_a) \quad (3)$$

The function $f(Conc, T1, T2)$ means the amount of the vapor flow and is defined the end of the section.
(solution mass balance equations)

$$\frac{dW_{LBa}}{dt} = Conc_r G_{dw} - Conc_a G_{up} \quad (4)$$

$$Conc_a = \frac{W_{LBa}}{W_a} = \frac{W_{LBa}}{W_{LBa} + W_{wa}} \quad (5)$$

(condensation heat)

$$r_a = \frac{q_w}{\mu_w}\frac{T_a^2}{T_v^2}\Delta T_a \quad (6)$$

In the above equation, μ_w implies molecular weight and ΔT_a means the pure water temperature change such that the change yield the same vapor pressure change as one degree change of the LiBr solution temperature yields in the absorber, and is read from the Duhring diagram.

In a generator:
(heat balance equation)

$$(C_r^{LB}W_r + C_{Vr})\frac{dT_r}{dt} + C_r^{LB}T_r\frac{dW_r}{dt} = -(r_r + C_W T_r)G_r + \alpha_r(T_{vpr} - T_r) + C_a^{LB}G_{up}T_{th} - C_r^{LB}G_{dw}T_r \quad (7)$$

(water mass balance equations)

$$\frac{dW_{wr}}{dt} = -G_r + (1 - Conc_a)G_{up} - (1 - Conc_r)G_{dw} \quad (8)$$

$$G_r = f(Conc_r, T_c, T_r) \quad (9)$$

(solution mass balance equations)

$$\frac{dW_{LBr}}{dt} = Conc_a G_{up} - Conc_r G_{dw} \quad (10)$$

$$Conc_r = \frac{W_{LBr}}{W_r} = \frac{W_{LBr}}{W_{LBr} + W_{wr}} \quad (11)$$

(evaporation heat)

$$r_r = \frac{q_w}{\mu_w}\frac{T_r^2}{T_c^2}\Delta T_r \quad (12)$$

In the above equation, ΔT_r means the pure water temperature change such that the change yield the same vapor pressure change as one degree change of the LiBr solution temperature yields in the generator, and is read from the Duhring diagram.

In the condenser:
(heat balance equation)

$$(C_w W_c + C_{Vc})\frac{dT_c}{dt} + C_w T_c\frac{dW_c}{dt} = (\frac{q_w}{\mu_w} + C_w T_r)G_r - \alpha_c(T_c - T_{cool}) - C_w G_w T_c \quad (13)$$

(water mass balance equation)

$$\frac{dW_c}{dt} = G_r - G_w \quad (14)$$

In the evaporator:
(heat balance equation)

$$(C_w W_v + C_{Vv})\frac{dT_v}{dt} + C_w T_v\frac{dW_v}{dt} = -(\frac{q_w}{\mu_w} + C_w T_v)G_a + \alpha_v(T_{clt} - T_v) + C_w G_w T_c \quad (15)$$

(water mass balance equation)

$$\frac{dW_v}{dt} = G_w - G_a \quad (16)$$

The above heat balance equations use heat transfer coefficients α, the developed simulator adopts the heat transfer efficiency η defined as follows in order to avoid simulation instabilities due to large heat transfer coefficients.

$$\eta = \frac{T_{out} - T_{in}}{T_{vessel} - T_{in}} \qquad (17)$$

In the above equation, T_{in}, T_{out} means the output and input temperature of cooling water or heating vapor and T_{vessel} implies the mean temperature of solution and vessel such as an absorber.

The model equipped with chilled water temperature controller, by adjusting vapor supply. The control algorithm is described as follows.

$$G_{vap} = Kp(T_{clt} - T_{set}) + \frac{Kp}{Ti}\int (T_{clt} - T_{set})dt \qquad (18)$$

Finally, the vapor flow between the solution and water is modeled as diffusion process. The main motive force is the vapor pressure differences that are in equilibrium states to the solution or the water in the vessels. In case of the absorber,

$$G_a = -S_a D_a \frac{w_{sa} - w_{sv}}{d_a} \qquad (19)$$

S_a means the absorber cross section, D_a implies diffusion coefficient, w_{sa}, w_{sv} are vapor equilibrium densities to the absorber solution and the evaporator water. d_a is the absorber diameter.

The above mentioned equations are programmed in FORTRAN language as the type function of HVACSIM+(J).

SIMULATION

Two simulation results are shown in the paper. One is for an independent single-effect absorption chiller. In the simulation, the typical characteristics of an absorption chiller is observed. The other one is for the HVAC system simulation with absorption chiller. In the simulation, the interference of the absorption chiller and HVAC system can be observed.

(1)Independent chiller

A 675USRT single-effect absorption chiller is simulated. Supplied cooling water, returned chilled water , and heating vapor conditions are fixed here. The condition parameters are given in Table 1 and chiller parameters in Table2.

Table 1 Simulation conditions

parameters	values
Cooling water flow rate	174kg/sec
Cooling water temperature	32°C
Chilled water flow rate(return)	94kg/sec
Chilled water temperature(return)	14°C
vapor temperature	150°C
vapor pressure	200kPa

Chilled water return temperature is changed 14°C to 10°C 2 hour after the starting point, and 10°C to 14°C at 6 hour. Furthermore, chilled water flow rate is changed 94kg/sec to 70kg/sec at 10 hour after the starting point.

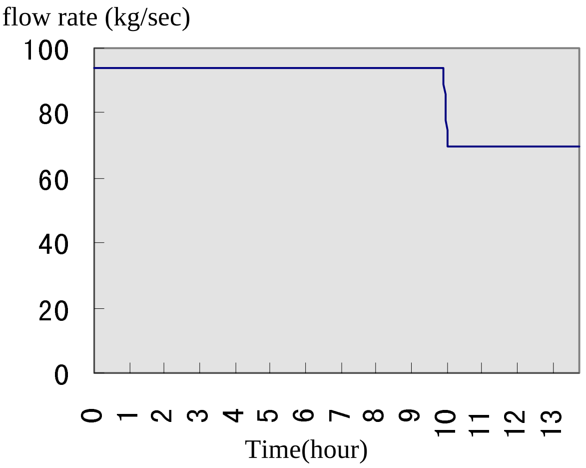
Table 2 Chiller parameters

parameters	*value*
Heat exchange coefficient for absorber	0.9
... for evaporator	0.95
... for condenser	0.9
... for generator	0.85
... for heat exch.	0.9
Heat capacity for absorber	1474kJ/°C
... for evaporator	1474kJ/°C
... for generator	737kJ/°C
... for condenser	737kJ/°C
Cross section for absorber	12m^2
Absorber radius	1m
Cross section for generator	3.3 m^2
Generator radius	0.55m
Time lag for solution heat exchanger	10min
Solution circulation flow rate	10kg/sec
Proportional gain for temp. controller	0.15
Integral gain for temp. controller	1 hour
Chilled water temp. set value	8°C
Low temp. protection	6°C

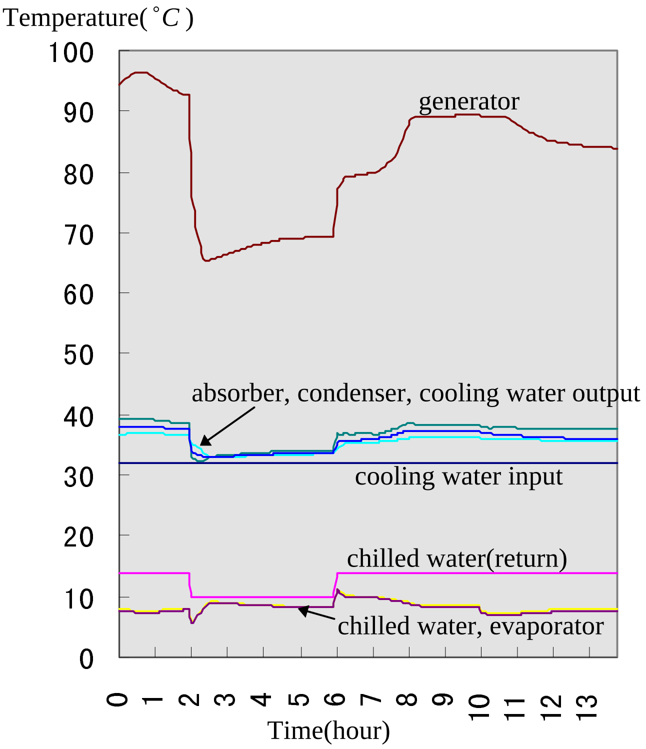
The simulation results are shown in Fig. 3. At 2 hour, the chiller temperatures drops, according to chilled water return temperature dropping. Consequently, chilled water temperature drops to lower than 6°C and protection control works so that heating vapor flow rate goes to 0. Then chilled water temperature quickly go back to the set value 8°C. While the vapor flow rate is small, COP is very high temporally, then go back to normal value. The concentration difference between dilute solution in the absorber and enriched solution in the generator becomes small because of supplied vapor decreasing. The vapor flow rate is controlled by the temperature regulator, then chiller capacity is also decreasing as the return chilled water temperature drops. When the return water temperature go back to initial value, the reverse process goes on. The temperatures go up, the concentration difference becomes large, and capacity increase to initial value. At 10 hour, chilled water flow rate decreases from 94kg/sec to 70kg/sec. The phenomena is similar to that of the chilled water return temperature dropping. In this case, step change is smaller than that of the mentioned above. Then, protection algorithm doesn’t work.

By the simulation, the expected trends are obtained. Although the trends differ depending on the chiller parameters, this shows the validity of the simulator.

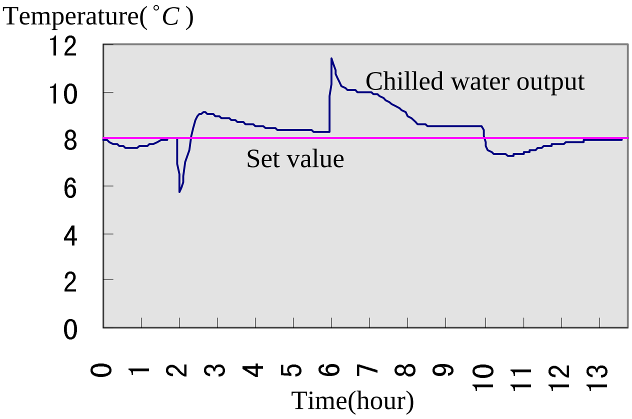
By the simulator, adjusting the parameter, many states in the chiller which are difficult to measure directly, can be estimated.



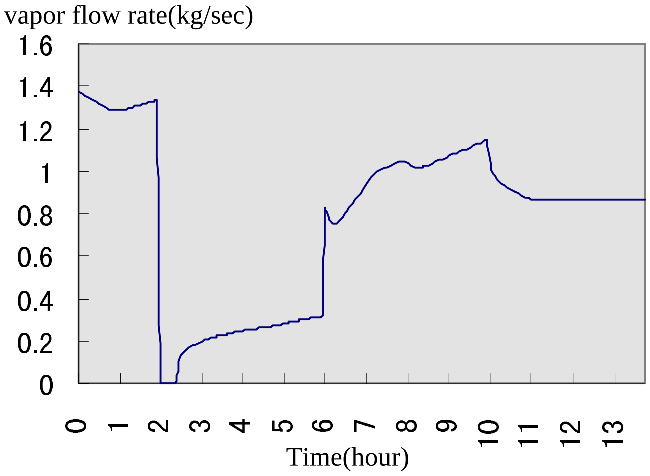
(a) chilled water flow rate



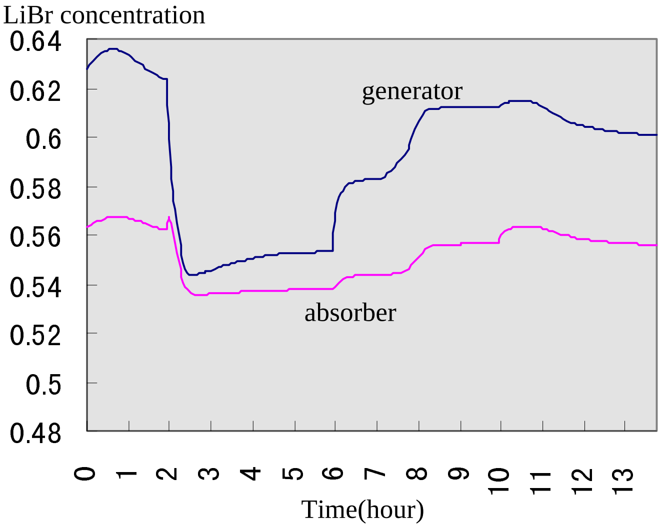
(b)Chiller temperatures



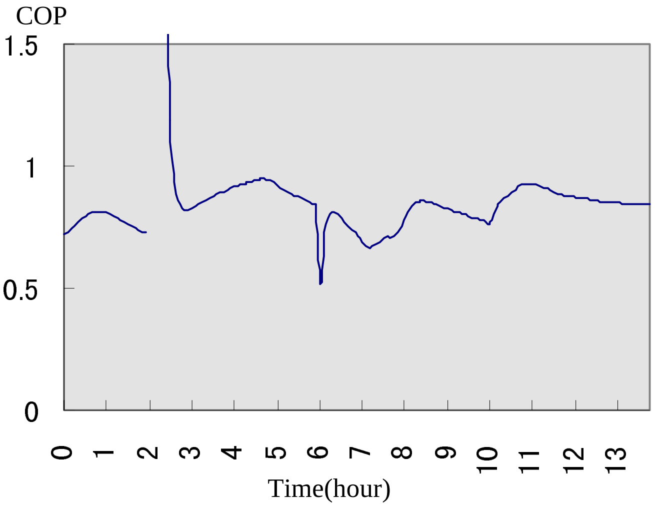
(c)Chilled water temperature control



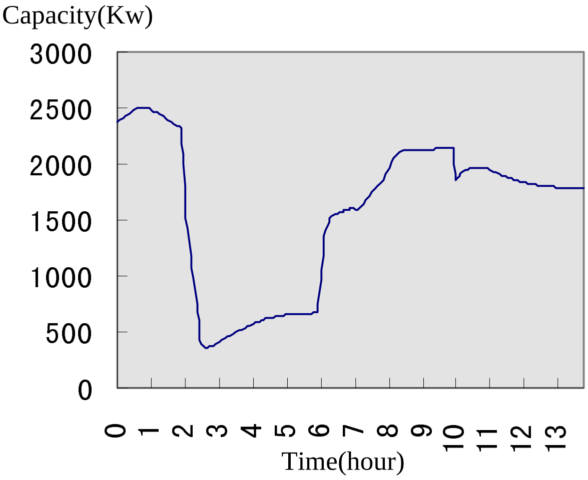
(d)heating vapour flow rate



(e)weight concentration of LiBr solution



(f) COP trend



(g) Capacity trend
Fig.3 Trend graph for independent absorption chiller

(2)system simulation results

The system simulation including a room, air ducts, fan, and absorption chiller is described in the section. The system model is shown in Fig.4.

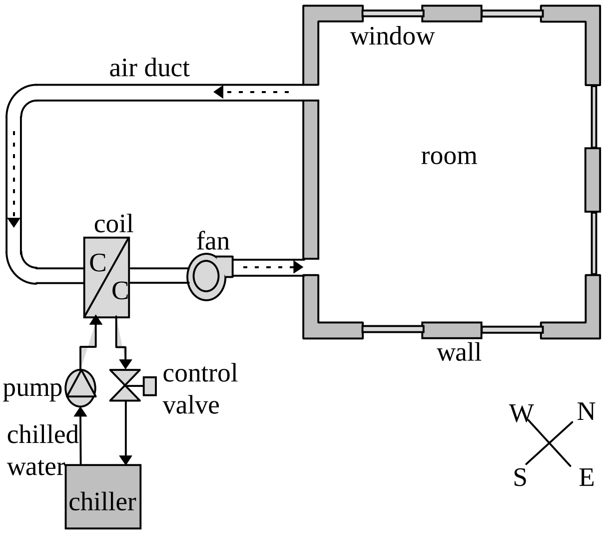


Fig.4 The system model

The condition for the system is also shown in Table 3 and Fig.5.

Table 3 The system condition

parameters	*value*
weather	fine, partly cloudy
simulation period	7:00 - 17:30
HVAC system operation time	8:00 - 17:30
room temperature set value	$26^{\circ}C$
valve controller (P-Gain)	$4^{\circ}C$
... (I-Gain)	4min
power for lighting	2.88kW
number of persons in the room	7

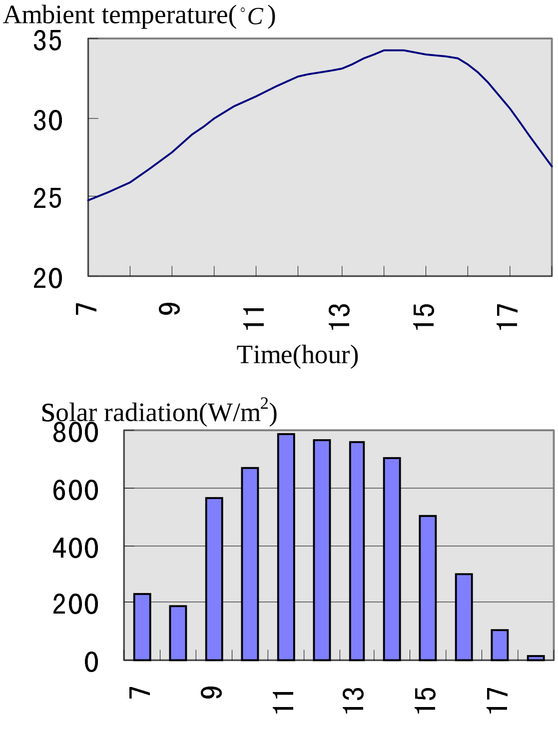


Fig.5 Weather conditions

Chilled water flow rate is controlled by the valve in order to maintain the room temperature. The air fan sends constant amount of the air to the room. The chiller temperature controller regulates its chilled water to be $8^{\circ}C$. In the room, 7 persons working, and 2.88kW heat source exists. The ambient temperature is high in midday, then heat comes from outside through the window and the wall. The weather is so fine that the solar radiation has to be considered.

Fig.6 and Fig.7 are simulation results with the chiller and without the chiller. In the case without the chiller, chilled water is supposed to be supplied constant temperature.

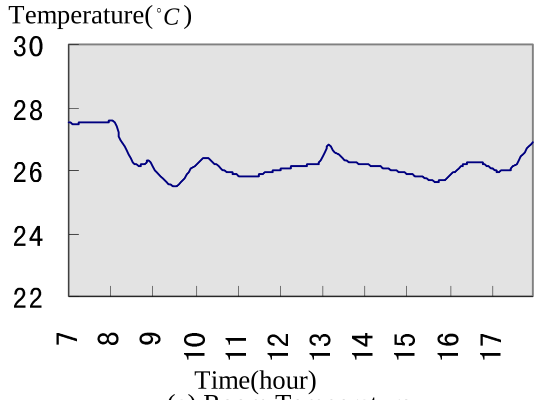
Comparing Fig.6 with Fig.7, the followings are observed.

(1)both trends are similar to each other, because the heat load trends are the same for the both cases.

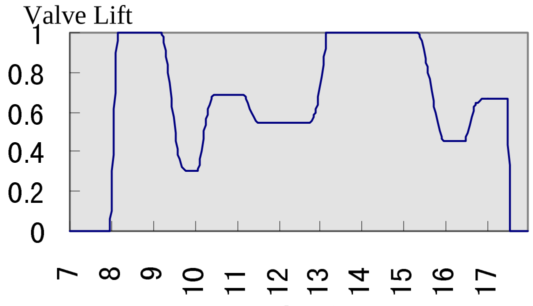
(2)the control valve lift trend differ from each other a little bit, because of the chiller dynamics.

(3)the system dynamics are very stable, because the chiller controller's response is almost proportional and its integration gain is much slower than that of the control valve.

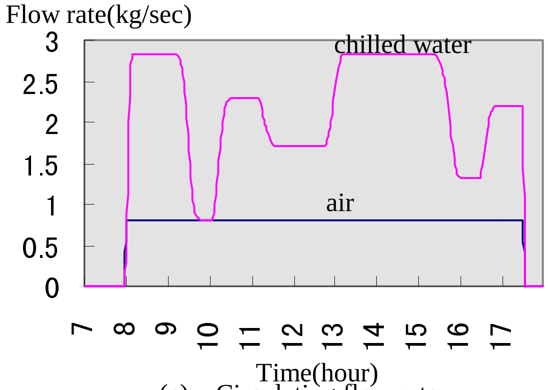
Next, Fig.8 shows COP and vapor consumption rate of the chiller for the simulation. It depends totally on the initial state that COP is abnormally high in the morning. COP and steam consumption rate is strongly related to the control valve operation. It implies that the cooperation of a chiller controller and room temperature controller is very important for saving energy.



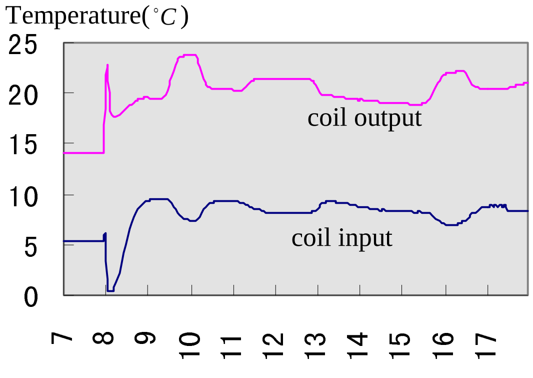
(a) Room Temperature



(b) Chilled water control valve lift

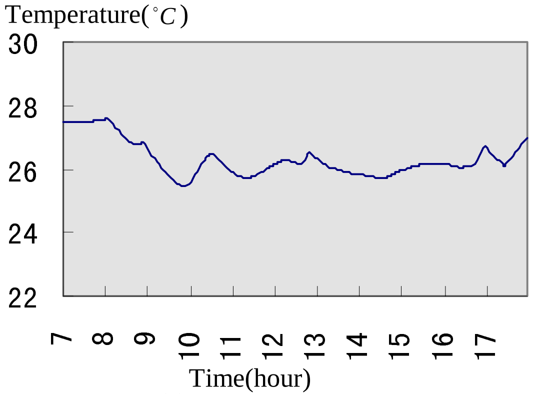


(c) Circulating flow rate

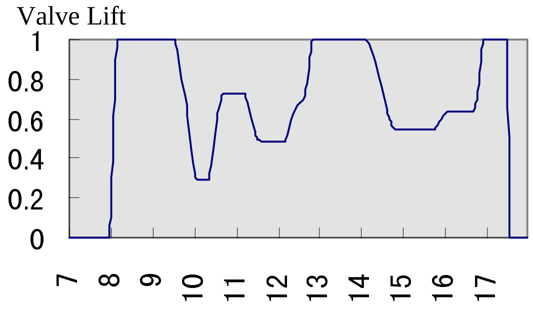


(d) chilled water temperature in cooling coil

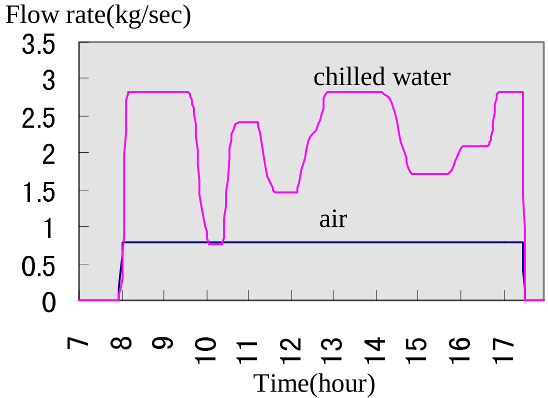
Fig.6 System simulation results(with the chiller)



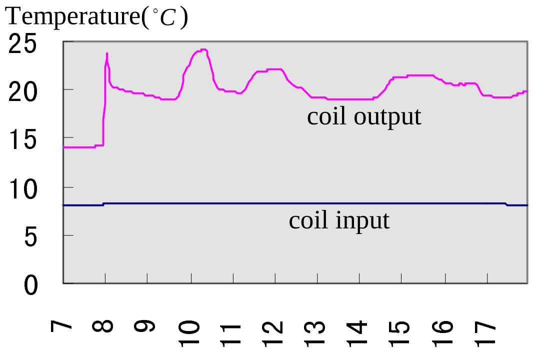
(a) Room Temperature



(b) Chilled water control valve lift

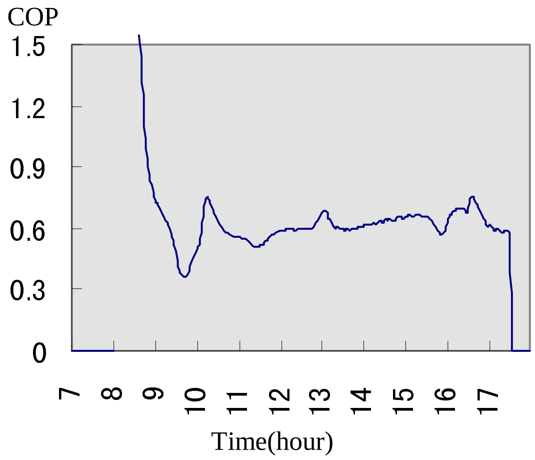


(c) Circulating flow rate

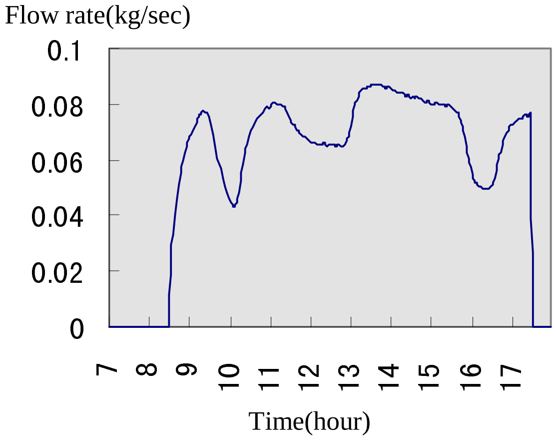


(d) chilled water temperature in cooling coil

Fig.7 System simulation results
(with a constant heat source)



(a) COP for the absorption chiller



(b) Heating vapor flow rate

Fig.8 The chiller operation for the system

CONCLUSIONS

The absorption chiller dynamic model is developed for the HVACSIM+(J). The conventional chiller model for the HVACSIM+ is static all purpose model. It can conveniently model many kinds of chillers, but it simulates only static characteristics, and it cannot fully consider the difference by the refrigeration cycles. In particular, the absorption chiller has slow dynamics and complicate characteristics. So, the model is developed to consider the chiller characteristics fully in HVAC system design and control strategy. The model is tested by an independent chiller model simulation and HVAC system simulations mentioned above.

Observing the simulations, cooperation of chiller and room controller is very important to save energy. Furthermore, chiller control action and valve or fan control action would affect each other, if the fast responses are required.

Hereafter, more verification should be done and using the simulator, energy saving system is expected to be designed.

ACKNOWLEDGEMENTS

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REFERENCES

(1)J.Kim, Y.Park and H.Lee, "Performance of evaluation of absorption chiller", Applied Thermal Eng., 19(1999) pp217-225.
(2)G.P.Xu, Y.Q.Dai, K.W.Tou and C.P.Tso, "Theoretical analysis and optimization of a double-effect series-flow-type absorption chiller", Applied Thermal Eng., 16(1996) pp975-987.
(3)R.Tozer et al. "Thermoeconomics applied to an air conditioning system with cogeneration", Building Serv. Eng. Res. Tech., 17(1996) pp37-42.
(4)M.Salman and S.Kotob, "Optimal control of solar cooling systems", Optimal control Applications and Methods, 9(1988) pp187-199.

NOMENCLATURE

variables:

T :temperature ($^\circ C$)
C :heat capacity (kJ/kg $^\circ C$)
$Conc$:weight concentration (-)
W :weight (kg)
r :evaporation heat (kJ/kg)
q_w :molecular evaporation heat (kJ/kmol)
G :flow rate (kg/sec)
α :heat transfer rate (kJ/h $^\circ C$)
h :enthalpy (kJ)

suffixes:

'a' : absorber
'r' : generator
'c' : condenser
'v' : evaporator
'LB' : LiBr
'w' : water
'vpr' : vapor

other variables:

T_{clt} : chilled water average temperature ($^\circ C$)
G_r : vapor flow rate from a generator to a condenser (kg/sec)
G_a : vapor flow rate from an evaporator to an absorber (kg/sec)

APPENDIX : THE EXTRACT LISTING

The extract listing is shown below. The full listing of the type is so long that the essential parts are shown in the paper.

```
C*****************************************
      subroutine type654(xin,out,par,saved,iostat)
C******************************************
C
      real xin(27), out(22), par(21), saved(30)
      INTEGER IOSTAT(27)
```

```
      common /chrono/ time,tstep,ttime,tmin,itime
      common /tmparm/ timel,tint,delt,fintim
      timel = time
     tint = 0.
      delt = tstep
      fintim =1.0e8
c      time=time, tint=simulation initial time,
c      delt=integration time step width.
        ...
c   ---- dynamic part ----
      call contrl(tset,tlimit,modabs,gcola,gcolc,gclt,
     &          tclti,tclto,gp,ti,
     &         gvapi,gvap,gup,svgup,paux,x1,x2,x3,
     &         aidle,vstart,qc)
      call hex(thx,ta,tr,tchi,tthi,tch,tth,etahx)
      call absvap(gdw,gup,tch,tcoli,tclti,conr,cvv,
     &            cva,gcola,gclt,gco,tc,sa,da,
     &            wlbai,wwai,wvi,tai,tvi,etaab,etaev,
     &            wlba,wwa,wv,cona,ta,tv,tcola,tclto,ga)
      call gene(gdw,gup,tth,tvpr,gvap,pvap,tcoli
     &              ,cona,cvc,
     &            cvr,gcolc,sr,dr,wlbri,wwri,tri,tci,wci,
     &            wlbr,wwr,wc,conr,tr,tc,tcolc,gr,gco,
     &            etagn,etacd,qvap)
c
        ...
        return
        end
c
c   ************************
c   *  absorber subroutine *
c   ************************
      subroutine absvap(gdw,gup,tch,tcoli,tclti,
     &                 conr,cvv,
     &                 cva,gcola,gclt,gco,tc,sa,da,
     &                 wlbai,wwai,wvi,tai,tvi,eta1,eta2,
     &                 wlba,wwa,wv,cona,ta,tv,tcolo,
     &                 tclto,ga)
c
c   --- absorber dynamics ---
        cw=4200.
        dwlba=conr*gdw-cona*gup
        call intgrl(1.0,wlbai,dwlba,wlba)
     if(wlba.lt.0.) wlba=1.0e-8
c
        wa=wlba+wwa
        cona=wlba/wa
     if(cona.lt.0.) cona=1.0e-8
     if(cona.gt.1.0) cona=0.99999
c
        ga=vpflow(cona,tv,ta,sa,da)
     if(ga.lt.0.) ga=0.
     if(ga.gt.0.002*wv) ga=0.002*wv
        during=grad(cona,ta)
        pv=pat(tv)
        ra=(hgpt(pv,tv)-hlpt(pv,tv))*((tv+273.)
    &       /(ta+273.))**2*during
     &     *4200.
c  --- ra : jouki no kyushu ni yoru hatuneturyou (J/kg)
c
        tcolo=tcoli+eta1*(ta-tcoli)
        tclto=tclti-eta2*(tclti-tv)
c
        dwa=dwwa+dwlba
        call entplb(cona,ta,entpa)
        call entplb(conr,tch,entpr)
        calb=spcap(cona,ta)
        dta=((ra+cw*(tv-ta))*ga-cw*gcola*(tcolo-
     &        tcoli)+(entpr-entpa)*gdw
     &       )/(calb*wa+cva)
        call intgrl(1.0,tai,dta,ta)
c
c  ---- entp : enthalpy,
c       calb : libr liquid specific heat in absorber (J/kg)
c       cw   : water specific heat (J/kg)
c
c   --- evaporator dynamics ---
        dwv=gco-ga
        pv=pat(tv)
        qw=(hgpt(pv,tv)-hlpt(pv,tv))*4200.
        dtv=(-qw*ga+cw*gclt*(tclti-tclto)+cw*gco*(tc-
     &        tv))/(cw*wv+cvv)
        call intgrl(1.0,tvi,dtv,tv)
c
c
        dwwa=ga-(1-cona)*gup+(1-conr)*gdw
  call intgrl(1.0,wwai,dwwa,wwa)
     if(wwa.lt.0.) wwa=1.0e-8
        call intgrl(1.0,wvi,dwv,wv)
     if(wv.lt.0.) wv=1.0e-8
      return
      end
c
c    **************
c    *  generator *
c    **************
      ...
      return
      end
      ...
```