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A Dynamic Model of an Absorption Chiller for Air Conditioning

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Abstract. In this paper we study the absorption chiller with a water/lithium bromide solution. Its dynamic behaviour is described by means of constitutive correlationships and conservation equations. We will work out a detailed model linking the plant dynamic behaviour to the various phenomena and their interactions.
The model is implemented using Simulink libraries that interact with several S-functions written in the C programming language.

Key words

Absorption chiller, Lithium bromide, Air Conditioning, Modelling, Dynamic.

1. Introduction

Over the last several years there has been increasing attention to the effective technologies in order to achieve both energy saving and CO_2 emission reduction.
The absorption chiller is a technology enabling the production of cooling power.
Generally, cooling power production needs electrical or mechanical power, whereas absorption chillers can produce chilled water from low temperature heat.
Such heat can be provided by solar thermal collectors, see e.g. [3] or thermal power plant fed by biomasses.
Of course another possibility is to resort to the heat produced by the recovery generator of a microgas turbine (MGT).
This may lead to a so-called trigenerative plant for the simultaneous production of electricity, heating and cooling powers. In this way, a remarkable efficiency is obtained if compared with the separated supply of the three forms of energy see e.g. [2].
In the literature one can find several studies on absorption chiller systems. Most of them deal with the plant functioning in in steady-state operation [5], [14], [4], [11], [12], [10], [13]. However only the dynamic simulation of absorption chiller cycle can provide a complete description of the plant behaviour. Furthermore, the corresponding dynamic simulator is most useful to assess the applicability and limitation of alternative control strategies.
Therefore, research on the dynamic simulation of absorption chiller is gathering increased attention [7]-[8], [9].
In this paper we study the absorption chiller with a water/lithium bromide solution. Its dynamic behaviour is described by means of constitutive correlationships and conservation equations. We will work out a detailed model linking the plant dynamic behaviour to the various phenomena and their interactions.
The model is implemented using Simulink libraries that interact with several S-functions written in the C programming language.

2. Plant description

The working fluid used in the absorption chiller is lithium bromide (LiBr) solution in water. The chiller is constituted by four main components: generator, condenser, absorber and evaporator. Figure 1 shows the single-effect LiBr/water absorption cycle.
In the generator the weak solution (containing a low concentration of LiBr salt) is sprayed on the heat exchanger tubes crossed by hot water; so that the weak

solution is heated and part of the water in it evaporates. Therefore the concentration of the LiBr salt increases (strong solution). This solution is sent to the absorber. The water vapour derived from the evaporation process flows to the condenser. Here it is put into contact with a heat exchanger fed by cooling water so that it is condensed and the heat is rejected to the ambient, using cooling tower water (it's not shown in the figure 1).
The condensed water flows to the evaporator through an expansion device, where water evaporates in low pressure and low temperature surrounding environment . It takes heat from water in heat exchange tube (EHE), providing the desired cooling effect.

NOMENCLATURE	
c	Specific heat (J kg^{-1} K^{-1})
e	Internal energy (J kg^{-1})
f	LiBr concentration
g	Gravity (m s^{-2})
H	Difference of height between absorber outlet and generator inlet (m)
h	Entalphy of the pure vapour (J kg^{-1})
M	Mass (kg)
p	Pressure (Pa)
$\dot{Q}$	Heat transfer rate (W)
S	Active surface area of heat transfer (m^2)
t	Time (s)
T	Temperature (K)
w	Mass flow rate (kg s^{-1})
α_{fr}	Loss factor of the pipes (m^2 kg^{-1})
α_r	Loss factor of the pump (m^2 kg^{-1})
γ	Heat transfer coefficient (W m^2 K^{-1})
Δp_0	Head of the pump (Pa)

SUBSCRIPTS	
ab	Absorber
cd	Condenser
dw	Down
ev	Evaporator
gn	Generator
in	Inlet
lat1	Lateral (from the generator to the condenser)
lat2	Lateral (from the evaporator to the absorber)
met	Metal of the heat exchanger
out	Oulet
sat	Saturation conditions
ves	Vessel
vsr	Superheated vapour
vs	Vapour in saturated condition
water	Pure liquid water

In the absorber, the strong solution absorbs the water vapour coming from the evaporator, diluting the solution. The absorption yields the condensation, so the absorber is cooled by cooling water. The weak solution is then pumped from the absorber to the generator, where the solution cycle restarts. A solution heat exchanger preheats the weak solution before entering the generator while it cools the strong solution before entering the absorber.
The entire cycle operates below atmospheric pressure.

3. Model of the Absorption Machine

The absorption machine is constituted by various part which, for modelling purpose, are grouped as follow: generator-condenser, absorber-evaporator, heat-exchangers, vessels, pump. Herein we will focus on the two first systems due to space limitations.
Each model is based on conservation equations and constitutive relationships.

A. Generator-Condenser

First, we consider the liquid phase constituted by: the weak solution sprayed on the tubes of the generator heat exchanger (GHE) together with the liquid percolating from the tubes.
We write the mass and the energy conservation equations for such liquid phase:

$$\frac{dM_{gn}}{dt} = w_{gn\_in} - w_{lat1} - w_{gn\_dw} \tag{1}$$

$$M_{gen}\frac{d\,e_{gn}}{dt} + e_{gn}\frac{dM_{gn}}{dt} = w_{gn\_in}\,c_{gn\_in}(f_{gn\_in})T_{gn\_in} - w_{gn\_dw}\,c_{gn}(f_{gn})T_{gn} + \dot{Q}_{gn} - w_{lat1}h_{vsr} \tag{2}$$

The hentalphy of superheated vapour is computed as:

$$h_{vsr} = h_{vs}(T_{cd}) + c_{vsr}(T_{gn} - T_{cd}) \tag{3}$$

The heat power $\dot{Q}_{gn}$ defined as:

$$\dot{Q}_{gn} = S_{gn}\gamma_{gn}(T_{met\_gn} - T_{gn}) \tag{4}$$

is transferred by the heat exchanger to the liquid phase witch evaporates.
The mass flow rate of the liquid percolating from the heat exchanger tubes is a function of the liquid mass:

$$w_{dw} = k_{gn}M_{gn} \tag{5}$$

where k_{gn} is a suitable parameter. The LiBr concentration of the liquid phase can be evaluated writing the mass conservation equation of the salt, under the assumption of well-stirred reactor. The same assumption is implicitely adpted in the sequel as well.

$$M_{gn}\frac{df_{gn}}{dt} + f_{gn}\frac{dM_{gn}}{dt} = w_{gn\_in}f_{gn\_in} - k_{gn}M_{gn}f_{gn} \tag{6}$$

Of course, the solution falling to the bottom of the vessel contains a higher concentration of LiBr (strong solution). A key variable is the mass flow rate of pure water vapour outgoing from the generator (w_{lat1}). Assuming that there is no storage in the gas phase, the mass flow rate entering the condenser coincideswith the one fromthe generator (w_{lat1}).
The condenser is crossed by the tubes of the heat exchanger (CHE) containing cooling water. Therefore, the pure water vapour coming from the generator is condensed on the tubes and there is a liquid

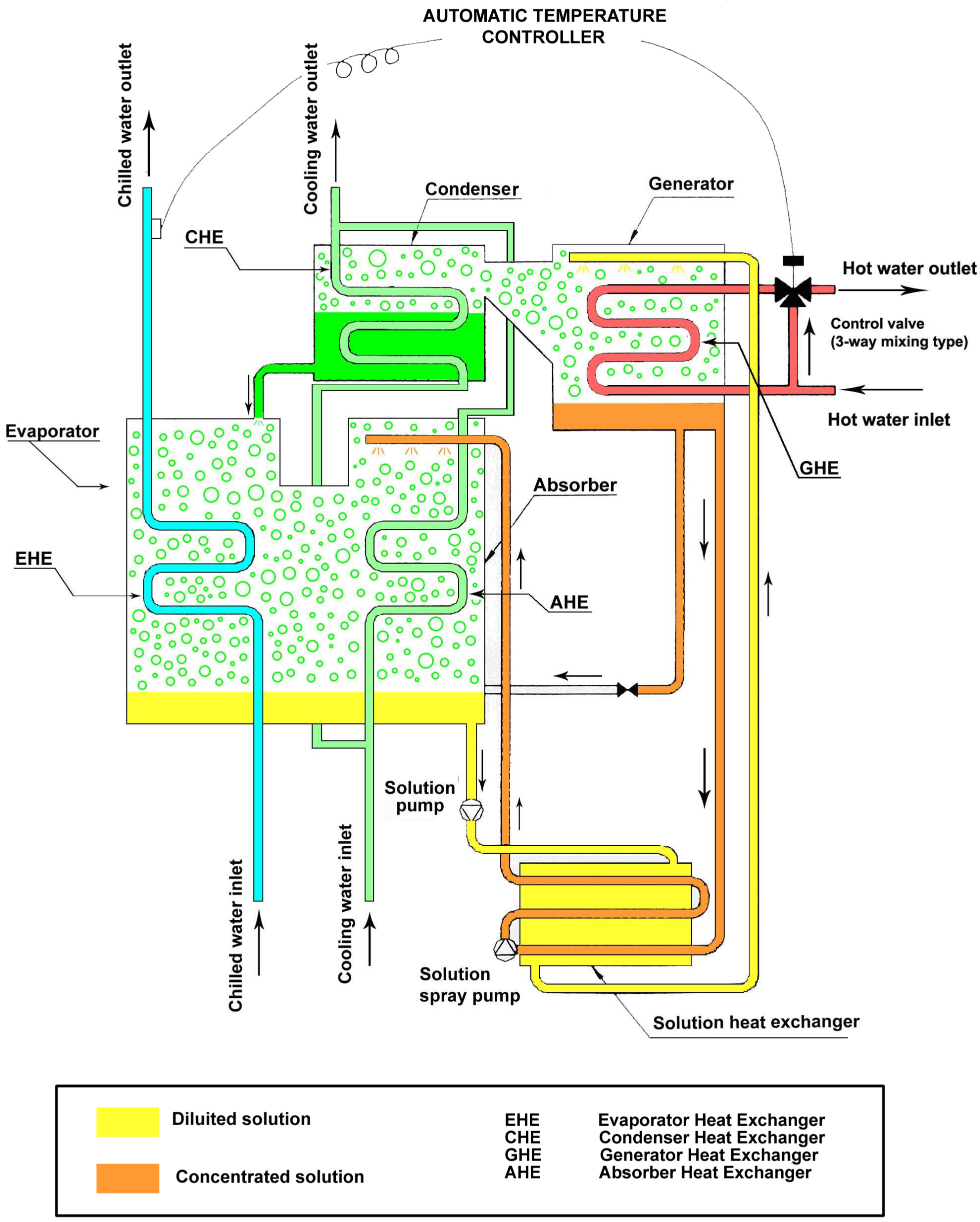

Fig 1. Layout of the absorption chiller

phase of the water on the surface of the tubes, with a certain mass M_{cd}.

The corresponding mass conservation equation is:

$$\frac{dM_{cd}}{dt} = w_{lat1} - w_{cd\_dw} \tag{7}$$

while the energy conservation equation is:

$$M_{cd} c_{cd} \frac{d\,T_{cd}}{dt} = w_{lat1}(h_{vsr} - c_{cd} T_{cd}) - \dot{Q}_{cd} \tag{8}$$

The heat power $\dot{Q}_{cd}$ defined as:

$$\dot{Q}_{cd} = S_{cd} \gamma_{cd} (T_{cd} - T_{met\_cd}) \tag{9}$$

is transferred by the heat exchanger to the water vapour witch condenses. Having assumed that there is no storage in the gas phase between the generator and the condenser, the variable w_{lat1} in eq.(7) and eq.(8) is the same and can be eliminated. Assuming also that the pressure drop between the generator and the condenser is neglectable, the saturation pressure of the fluid in the condenser is equal to the saturation pressure of the fluid in the generator:

$$p_{sat}(T_{cd}, 0) = p_{sat}(T_{gn}, f_{gn}) \tag{10}$$

The left hand-side can be expressed by the Antoine formula [6]:

$$p_{sat}(T, 0) = e^{a_0 - \frac{b_0}{T + c_0}} \tag{11}$$

Here the three parameters a_0, b_0, c_0 appear. As for the right hand-side, we have adopted the same Antoine formula with the three parameters being expressed as functions of LiBr fraction (f).

$$p_{sat}(T, f) = e^{a(f) - \frac{b(f)}{T + c(f)}} \tag{12}$$

The functions $a(f)$, $b(f)$, $c(f)$ have been worked out by interpolating the diagrams of saturation equilibrium properties supplied by the manufactured. This interpolation have been carried on under the constraint that the function $p_{sat}(T, f)$ be continuous together with first derivative.

In conclusion, the temperature T_{cd} can be algebraically computed from the remaining variables. This leads to an analytical expression linking Tcd to $Tgen$ and $fgen$ by means of witch eqs. (2) and (8) above can be merged into the single differential equation:

$$\begin{aligned} & M_{gn}c_{gn}(f_{gn})\frac{d\,T_{gn}}{dt}+(c_{gn}(f_{gn})T_{gn}-c_{cd}T_{cd})\frac{dM_{gn}}{dt} \\ & +M_{gn}T_{gn}\frac{d\,c_{gn}}{df_{gn}}\frac{d\,f_{gn}}{dt}+M_{cd}c_{cd}\frac{d\,T_{cd}}{dt}= \\ & w_{gn\_in}(c_{gn\_in}(f_{gn\_in})T_{gn\_in}-c_{cd}T_{cd}) \\ & -w_{gn\_dw}(c_{gn}(f_{gn})T_{gn}-c_{cd}T_{cd})+\dot{Q}_{gn}-\dot{Q}_{cd} \end{aligned} \tag{13}$$

Hence, the global model of generator-condenser is captured by the four differential eqs. (1), (6), (7), (13). As for eqs.(1) and (7) they can be elaborated by substituting the expression w lateral. In this way, we come to a state space non linear model with four state variables:

$$X_1=\left[T_{gn}\ f_{gn}\ M_{gn}\ M_{cd}\right]$$

B. Absorber-Evaporator

Between the condenser and the evaporator there are nozzles crossed by the condensed water which flows thanks to the pressure gap between condenser and evaporator. The corresponding mass flow rate is dispersed into small drops falling in the tubes of the evaporator heat exchanger (EHE).

A fraction of this mass flow rate immediately flashes, while the remaining part of liquid falls on the tubes of EHE where it evaporates.

The mass and energy conservation equations of the liquid phase are:

$$\frac{dM_{ev}}{dt}=w_{ev\_in}(1-x_v)-w_{ev\_dw}-w_{lat2} \tag{14}$$

$$M_{ev}c_{ev}\frac{dT_{ev}}{dt}=\dot{Q}_{ev}-w_l(h_{vs}-e_{ev}) \tag{15}$$

where x_v is the mass fraction of flashed vapour and the heat power $\dot{Q}_{ev}$ defined as:

$$\dot{Q}_{ev}=S_{ev}\gamma_{ev}(T_{met\_ev}-T_{ev}) \tag{16}$$

In the absorber the strong solution, coming from the generator, is sprayed on the heat exchanger (AHE) tubes. In this way it absorbs the evaporated and flashed vapour. The equations that describe the absorber behaviour are:

$$\frac{dM_{as}}{dt}=w_{as\_in}+w_{ev\_in}x_v-w_{as\_dw}+w_{lat2} \tag{17}$$

$$\begin{aligned} & M_{as}\frac{de_{as}}{dt}+e_{as}\frac{dM_{as}}{dt}=w_{as\_in}c_{as\_in}(f_{as\_in})T_{as\_in} \\ & -w_{as\_dw}c_{as}(f_{as})T_{as}-\dot{Q}_{as}+w_{lat2}h_{vs}+w_{ev\_in}x_vh_{vs} \end{aligned} \tag{18}$$

$$f_{as}\frac{dM_{as}}{dt}+M_{as}\frac{df_{as}}{dt}=w_{as\_in}f_{as\_in}-k_{as}M_{as}f_{as} \tag{19}$$

The heat power $\dot{Q}_{as}$ is defined as:

$$\dot{Q}_{as}=S_{as}\gamma_{as}(T_{as}-T_{met\_as}) \tag{20}$$

Here one can elaborate the various equation in a fully analogous way as previously seen for generator-condenser system. In particular, eqs.(15) and (18) can be merged into the single equation:

$$\begin{aligned} & M_{as}c_{as}(f_{as})\frac{d\,T_{as}}{dt}+(c_{as}(f_{as})T_{as}-c_{ev}T_{ev})\frac{dM_{as}}{dt} \\ & +M_{as}T_{as}\frac{d\,c_{as}}{df_{as}}\frac{d\,f_{as}}{dt}+M_{ev}c_{ev}\frac{d\,T_{ev}}{dt}= \\ & w_{as\_in}(c_{as\_in}(f_{as\_in})T_{as\_in}-c_{ev}T_{ev})-\dot{Q}_{as}-\dot{Q}_{ev} \\ & -w_{as\_dw}(c_{as}(f_{as})T_{as}-c_{ev}T_{ev})-w_{ev\_in}x_v(h_{vs}-c_{ev}T_{ev}) \end{aligned} \tag{21}$$

In conclusion, the evaporator-absorber system is described by eqs. (14), (17), (19) and (21) and associated state variable are:

$$X_2=\left[T_{as}\ f_{as}\ M_{as}\ M_{ev}\right]$$

C. Vessels

In each vessel there is a mass storage of liquid phase of each component.

$$\frac{dM_{ves}}{dt}=\sum_i w_{in\_i}-\sum_k w_{out\_k} \tag{22}$$

$$\begin{aligned} & M_{ves}\frac{df_{ves}}{dt}+f_{ves}\frac{dM_{ves}}{dt}= \\ & \sum_i(w_{in\_i}f_{in\_i})-\sum_k(w_{out\_k}f_{out\_k}) \end{aligned} \tag{23}$$

$$\frac{d(M_{ves}e_{ves})}{dt}=\sum_i(w_{in\_i}e_{in\_i})-\sum_k(w_{out\_k}e_{out\_k}) \tag{24}$$

Obviously, the mass in the vessel determines the level of liquid. With the increasing of the level a part of the CHE tubes is submerged in the liquid. Therefore the condensation surface diminishes and the associated mass flow rate (w_{lat2}) diminishes too. This gives rise to a feedback producing a stable equilibrium condition.

D. Heat Exchangers

As seen above, the plant is characterized by five heat exchangers.

Their modellization is achieved by means of a classical approach, subdividing each exchanger into a number of control volumes. For each of them, assuming that there is no mass storage, the energy conservation equations are considered to work out the overall model.

Then, the $T_{met\_\bullet}$ rapresents the average metal temperature of each heat exchanger.

E. Pumps

The absorption chiller is equipped with two pumps: the solution spray pump and the solution pump. The mass flow rate from the absorber to the generator has been obtained by considering the linear momentum equation of the fluid in the tubes between the absorber and the generator together with the pump characteristic:

$$w_{as\_gn} = \frac{1}{\sqrt{\alpha_r \alpha_{fr}}}\sqrt{\Delta p_0 + \rho g H - (p_{gn} - p_{as})} \qquad (25)$$

The same structure of model has been considered for the solution pump.

Remark.
In the heat exchangers CHE and EHE the heat transfer coefficients are evaluated using the classical theory of Nusselt.
The same approach has been used for the heat transfer coefficients of GHE and AHE. However the boundary layers of these exchangers contains salt too, besides water. In order to encompass the diffusion of salt in the boundary layer, the model of the heat transfer coefficients should be suitably modified [1]. For simplicity, in this paper we have neglected such dependence.

4. Simulations

The model of the absorption chiller has been implemented in Simulink. The differential equations constituting the model has been numerically by means of the implicit Euler method with the Jacobian matrix analytically computed.
This overall model has been implemented with S-functions written in C language. To assess the chiller dynamics in a realistic situation we have connected it to a load constituted by an equivalent fan-cooler describing the overall air conditioning system of a building. Such load represents the final user of the conditioning system. The temperature of the chilled water outlet is controlled by a three-way control valve of the hot water inlet. The valve operates in an on-off way with hysteresis as depicted in figure 2.

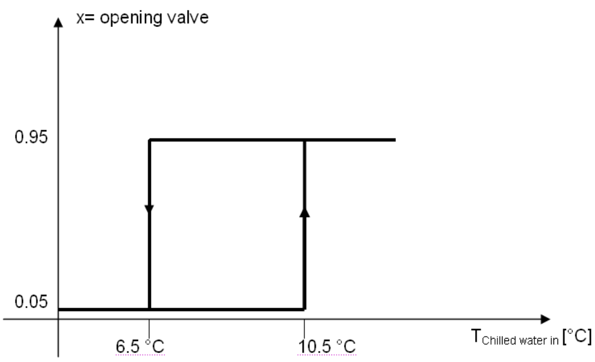

Fig. 2. Three-way control valve

The conditioning performance of the chiller with such final user has been tested starting from the equilibrium condition referring to an ambient temperature of 25°C. The corresponding temperature of chilled water outlet is 7.8°C. Note that in such an equilibrium condition the chiller is continuously operating. The transient taking place when the ambient temperature is reduced to 20°C is depicted in figure 3 and figure 4.

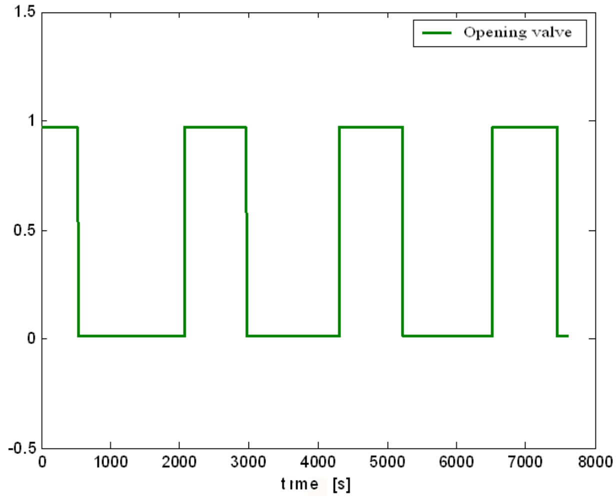

Fig. 3. Three-way valve opening during the simulation

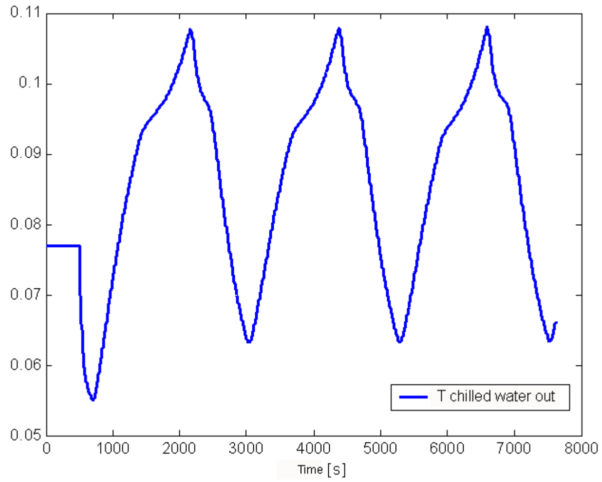

Fig. 4. Normalized Temperature (T/100) in °C of chilled water outlet during the simulation

5. Conclusion

The absorption chiller is a promising tool to refrigerate buildings by means of low temperature heat, such that furnished by a solar panel.
In this paper we have developed an accurate model, thanks to which we have worked out a plant simulator. Such simulator is most useful to study the dynamics of the plant , so as to asses the applicability and limitations of the refrigeration chiller in air conditioning systems.

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