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Optimal control of single stage LiBr/water absorption chiller

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A B S T R A C T

Low-capacity refrigeration and space conditioning systems have increased significantly in the last years, increasing primary energy demand. For this reason, it is important to start implementing refrigeration and space conditioning system that can be driven by unconventional energy sources, such as a single stage lithium bromide absorption refrigeration chiller since it can be powered by a low grade heat source. Therefore, we establish an optimal control strategy to operate these systems. For the implementation of the optimum control a dynamic model to evaluate the system is developed and discretized and solved using the interior point optimization (IPOPT) solver. The cases studied where a step and a sinusoidal perturbation on the hot water inlet temperature. The results obtained are promising because, through the implementation of the optimal control strategy, the coefficient of performance (COP) of the refrigeration system was significantly improved, reducing operational cost and all this without affecting the cold water outlet temperature.

Régulation optimale d'un refroidisseur à absorption de LiBr/ H_2O mono-étagé

Mots-clés: Régulation optimale; Optimisation; Refroidisseur à absorption; LiBr/H_2O; Modèle dynamique

1. Introduction

Since the beginning of the last century, the average global temperature has increased by 0.6 °C according to the Intergovernmental Panel on Climate Change (IPCC) and it could increase between 1.4 °C and 4.5 °C for the year 2100 (Kim and Infante Ferreira, 2008). Despite the initiatives to mitigate this process, higher life and work environment quality standards, adverse environmental conditions and the decreasing prices of air conditioning units, have caused a significant increase on the demand of these machines. Which causes, energy consumption of commercial and residential buildings represents 40% of the energy budget and therefore increasing carbon dioxide emissions (Constantinos et al., 2007).

With this scenario, it is necessary to take advantage of the cooling technologies that operate with sustainable energy sources that may help to alleviate the problem. The fact that the maximum cooling demand is associated with high solar radiation provides an excellent opportunity for heat-driven refrigeration technologies such as absorption refrigeration, which seems to be the best option for this purpose (Kim and Infante Ferreira, 2008).

However, absorption refrigeration presents two major obstacles for large scale application: in first place the high investment cost (Castro et al., 2008), and in second place the lack of practical experience and acquaintance among architects, builders and planners with the design, control and operation of these systems (Constantinos et al., 2007). For this reason, very interesting work have been presented recently developing models and in some cases validating them experimentally.

One of them is the one presented by Kohlenbach and Ziegler (2008a,2008b) which paid attention to the dynamic behavior, considering the heat and mass storage and the solution transport delay between the absorber and generator. The model can describe with great precision the shape of the dynamic response.

Evola et al. (2013) developed a mathematical model for the dynamic simulation of a single stage commercial absorption chiller based on mass and energy balances in the main components. The model was verified with an error less than 1% in the overall test campaign. Jeong et al. (1998) proposed a dynamic model to simulate a steam-driven LiBr–H_2O heat pump taking advantage of waste heat. Other works developing dynamic mathematical models have

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Nomenclature

Symbol

A	area [m^2]
C_1	cost parameter [\$;/kW]
C_2	cost parameter [\$;/kW]
C_d	discharge coefficient [−dimensionless]
C_p	heat Capacity [kJ/kg°C]
D	diameter [m]
F	fouling factor [m^2/kW]
g	gravity acceleration [m^2/s]
H	height [m]
J	objective function
M	mass [kg]
$\dot{m}$	mass flow [kg/s]
NC	net cost [\$;]
P	pressure [kPa]
p	time independent parameters
$\dot{Q}$	thermal power [kW]
R	gas constant for water vapor $R = 0.455$kJ/kg °C
S	pipe section [m^2]
T	temperature [°C]
t	time [s]
th	thickness [m]
U	heat transfer coefficient [kW/m^2 °C]
u	control variables
V	volume [m^3]
$\dot{V}$	volumetric flow rate [m^3/s]
$\dot{W}$	work [kW]
w	mass fraction [−dimensionless]
y	algebraic variable
Z	liquid level [m]
z	differential variables

Greek letters

α	convective heat transfer coefficient [kW/m^2 °C]
β_i	weight parameter
ρ	density [kg/m^3]
ζ	pressure lost coefficient [−dimensionless]
θ	temperature difference [°C]

Subscripts

A	absorber
C	condenser
d	dissipated
E	evaporator
env	environment
ext	external
G	generator
hx	heat exchanger
hx_sol	solution heat exchanger
i	finite element
int	internal
j	collocation point
L	liquid
LiBr	lithium bromide
P	solution Pump
S	solution
sat	saturation
V	vapor
$wall$	wall of the vessel
wG	hot water

Superscripts

sp	set point

been recently presented by Shin et al. (2009) and Ochoa et al. (2016).

Considering that the purpose of this work is to study the optimal control of the absorption refrigeration chiller, it is important to review the works on the optimization area.

Fewer studies have addressed the dynamic optimization and optimal control of the absorption systems. Koeppel et al. (1995) used for first time an optimization algorithm (simulated annealing) to develop guidelines for monitoring and optimal control for a direct flame double-effect water–LiBr absorption chiller. A simulated annealing optimization algorithm was incorporate with a transient simulation program TRNSYS, were the components model of the absorption chiller were written based on curve fits from a steady state mechanistic model.

Chow et al. (2002) proposed an optimal control strategy for a direct flame double-effect lithium bromide–water absorption chiller, using as objective function the system operating cost associated with fuel and electricity consumption. To model the system, it introduces the concept of artificial neural networks (ANNs) based on commercial absorption units and the optimization is achieved by implementing GA.

Both works obtained promising results since both achieve to significantly reduce the energy consumption during the machine operation and consequently the operating cost. However, in both cases the system under study was a double effect refrigeration chiller and the two works considered a direct flame heat source. Furthermore, Koeppel et al. (1995) used an over simplified model and the artificial neural networks (ANNs) used by Chow et al. (2002) are not appropriate to understands the behavior of the machine.

For this reason, this work aims to obtain the optimal control profile of a single stage absorption refrigeration system using a dynamic mechanistic model, when occur changes in the hot water inlet temperature (driving energy), considering in the objective function a cost structure.

To achieve this objective, a dynamic model used to evaluate the absorption refrigeration system is presented in Section 2. The equations used to calculate the model parameters are mention in Section 3. In Section 4 the optimal control problem is formulated by establishing the objective function, the control variables and the problem discretization.

The cases study and the perturbations used are presented in Section 5, the results in Section 6 and the conclusion in Section 7.

2. Absorption chiller dynamic model

A single stage LiBr/H_2O absorption refrigeration system, as shown in Fig. 1, is made up of a generator, an absorber, a condenser and an evaporator. A solution pump, between the generator and the absorber, ensures the lithium bromide solution circulation and a solution heat exchanger is used to recover thermal energy.

The model used to represent the refrigeration system is based on the first law of thermodynamics. The dynamic behavior is considered through the mass, lithium bromide mass fraction and energy balances in the main components.

The following assumptions were made to simplify the formulation and implementation of the model:

- Thermodynamic variables (T, P, w) are homogeneous inside each component.
- The fluid transport delay between two components is neglected.
- Global heat transfer coefficients of each heat exchanger are constant.
- The lithium bromide solution leaving the generator and the absorber are saturated.