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Simulation of an ammonia–water absorption chiller

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ABSTRACT

An increased interest in absorption chillers has been observed [1] because these systems can utilize solar, geothermal and biomass energy sources, but also because they are quiet, vibration-free, require little maintenance and are ecological [2]. Instead of a compressor system, which uses electricity, an absorption cooling system, using renewable energy and kinds of waste heat energy, may be used for cooling. This paper presents the simulation of a single stage solar absorption chiller operating with an ammonia–water mixture under steady state conditions. This simulation is based on heat and mass balances for each component. The heat and mass transfers in the absorber, the condensation of binary vapor of ammonia–water in the condenser and a thermosyphon desorber placed under the purification column were modeled. The numerical model was compared and validated with experimental data obtained with a solar absorption chiller. The calculated results agree well with experimental data. Simulations based on experimental data were used to predict the temperature and concentration profiles in each heat exchanger. A parametric study was conducted to investigate the effect of evaporator and desorber temperature on the absorption chiller's performance. The COP decreases by 25% with a decrease of 10 °C in evaporator temperature and the COP increases by 4% with an increase of 10 °C in desorber temperature.

1. Introduction

In the first years of the 20th century, absorption chillers were frequently used. However, compressors, motors and the advent of CFCs were such that the technology became far less prevalent. Nevertheless, over recent years, an increased interest in absorption chillers has been observed [1] because these systems can utilize solar, geothermal and biomass energy sources, but also because they are quiet, vibration-free, require little maintenance and are ecological [2]. Instead of a vapor compressor system, which uses electricity, an absorption cooling system, using renewable energy and waste heat energy, may be used for cooling.

Numerical models found in literature to evaluate the performance of absorption chillers are generally relatively simple. Whether it is under steady or dynamic state, most of the models account for the heat transfer coefficient U in the heat exchangers and the refrigerant is consider to be pure. These numerical models do not take into consideration the mass transfer coefficients in the absorber [3,4]. Modeling absorbers was of interest to researchers over the last years. A review of a publication on the methods used for the modeling of absorbers (NH_3–H_2O as well as H_2O–LiBr) by Killion and Garimella [5] illustrates the progress made in this respect. Bohra [6] enumerates different studies on the analysis of absorbers. However these models are rarely incorporated in complete absorption cycles. It should be noted that the thermal transformer proposed by Sunye [7] does take into account the mass transfer in the liquid phase of the absorber. In order to improve the understanding and the performance of solar absorption chiller, detailed numerical model has to be developed to take into account these phenomena.

The modeling described in this document takes into account the mass transfer in the liquid and vapor phases of the absorber and the condensation of a binary solution in the condenser while also respecting the specific features of the solar absorption chiller (cooling ceiling) [8,9] used to validate the numerical model. These features are essentially a thermosyphon desorber and vapor purification effected with the rich solution.

The correlations used to evaluate the heat transfer coefficients have been chosen based on the type of heat exchanger and how it is put to use. When several correlations are available, the correlation that is the most representative of the experimental data is used. An analysis of the uncertainties of the chosen correlations demonstrate that a 10% variation in the heat transfer coefficients results in

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Nomenclature

A	area (m^2)
ΔA	area element (m^2)
D	diameter (m)
g	gravitational constant ($m\ s^{-2}$)
h	enthalpy ($J\ kg^{-1}$)
hc	convection heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
H	height (m)
k	thermal conductivity ($W\ m^{-2}\ K^{-1}$)
K^*	mass transfer coefficient ($kg\ m^{-2}\ s^{-1}$)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
$\dot{Q}$	heat transfer rate (W)
P	pressure (Pa)
ΔP	pressure drops (Pa)
qv_p	volumetric flow rate – pump ($L\ s^{-1}$)
T	temperature (K)
ΔT_{LM}	logarithmic mean temperature difference (K)
U	overall heat transfer coefficient ($W\ m^{-2}\ K^{-1}$) or ($kW\ m^{-2}\ K^{-1}$)
W	electric power (W)
x	mass concentration of ammonia
Δy	length element (m)
z	phase mass concentration of ammonia

Greek letters

ε_f	efficiency
ρ	density ($kg\ m^{-3}$)
η	isentropic efficiency

Indices

A	ammonia
bu	boiling
Cc	condenser's condensation zone
Cs	condenser's sub-cooling zone
e	exterior
Ec	evaporator's heating zone
Ee	evaporator's evaporating zone
Es	evaporator's superheating zone
E	water
ECH	heat exchanger
I	interface
in	inlet
L	liquid phase
n	inner
out	outlet
p	pump
P	wall
Pa	poor
R	rich
s	isentropic
sat	saturation
V	vapor phase

little variation on the profiles of the components and on the general performance of the cycle [8].

The numerical models of absorption chillers in past literature do not account for mass transfer coefficients in the absorber and condensation of binary vapor in the condenser. This paper, however, takes these aspects into account while also respecting certain technical specificities of a real absorption chiller. This numerical model was also validated and compared with experimental data.

2. Description of the absorption chiller

Absorption chillers are cooling systems much like compression cooling cycles. The major difference is the fact that they use thermal energy (absorber and desorber) as opposed to electricity in their cycles. The fluids used in an absorption cycle consist of a refrigerant and an absorbent. In this study, ammonia is used as the refrigerant and water is used as the absorbent. This therefore involves a purification column to purify the vapor leaving the desorber. The cycle under study corresponds to the system show in Fig. 1.

The high pressure refrigerant (3) from the condenser is expanded (4) and then evaporated (5) in the evaporator. In order to compress this vapor before re-injecting it in the condenser, thermochemical compression is used. As a result, the vapor (6) is absorbed in a poor ammonia (15) solution in the absorber and its pressure is increased with a pump (8). The desorber partially separates the ammonia and the water to complete the cycle. The solution heat exchanger (SHX) recovers heat internally, which results in a decrease in the heat to evacuate from the absorber and in the heat supplied to the desorber.

3. Modeling

A numerical model was developed to evaluate the performance of an absorption chiller using ammonia and water. This detailed model, coded in FORTRAN, is based on mass, species and energy conservation equations. The numerical model of the absorption chiller consists in different sub-models, including:

- a condenser
- an evaporator, an expansion valve and a refrigerant heat exchanger (RHX)
- a purification column
- a desorber
- an absorber
- a solution heat exchanger (SHX), a pump and an expansion valve

The computational algorithms of the model of the absorption chiller and sub-models are described in detail by Le Lostec [8].

The known data of the model are the pump's flow rate, the geometric configurations of the heat exchangers and the inlet temperatures of the secondary solutions (points 20, 22, 26 and 28 on Fig. 1). The values of points 1 to 15, 21, 23, 27, 29 must therefore be calculated.

The simulation hypotheses are as follows:

- Steady state
- Pure ammonia in the evaporator (the assessment of the amount of non-evaporated mass, where there is a significant amount of water, at the evaporator's outlet is difficult. To surmount this problem, the refrigerant is presumed to be pure in this component
- Negligible pressure drops
- Negligible heat losses to the environment
- Negligible leaks to the environment
- Saturated vapor at the purification column's outlet (1)

The thermodynamic and thermophysical properties of the ammonia/water and water/ethylene glycol mixtures are evaluated based on the correlations of the references mentioned in