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Heat and mass transfer in a bubble plate absorber with $NH_3/LiNO_3$ and $NH_3/(LiNO_3 + H_2O)$ mixtures

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ABSTRACT

An experimental study of bubble absorption in a plate heat exchanger using ammonia/lithium nitrate and ammonia/(lithium nitrate + water) mixtures has been carried at operating conditions of air-cooled absorption systems driven by low temperature heat sources. An experimental test has been layout and set-up for the absorber characterization at different operation conditions. Experiments have been performed at a nominal system pressure of 510 kPa absolute using a corrugated plate heat exchanger formed by three channels in which absorption takes place in the central one.

A sensitive study of the main operating conditions such the weak solution inlet concentration and flow rate, and cooling-water inlet temperature and flow rate on the absorber efficiency parameters has been performed.

For both binary and ternary mixtures, the mass absorption flux, heat transfer coefficient, subcooling and mass transfer coefficient increase as the solution flow rate increases.

The mass absorption flux achieved with the binary mixture is enhanced as the cooling-water inlet temperature decreases. This trend is reversed for the solution-side heat transfer coefficient. This is attributed to a limiting heat transfer process in the absorber at lower cooling-water inlet temperatures. Increasing the concentration of ammonia in the binary mixture by 3% by weight significantly reduces the mixture's capacity to absorb ammonia.

The mass absorption flux and the solution heat transfer coefficient achieved with the ternary mixture are around 1.3–1.6 and 1.4 times higher, respectively, than those of the binary mixture under similar operating conditions. This is due mainly to the lower viscosity of the ternary mixture and the high affinity of ammonia for water.

Empirical correlations for the solution Nusselt and Sherwood numbers are proposed on the basis of the experimental data presented here for the absorption of ammonia vapor by ammonia/lithium nitrate mixture in a plate heat exchanger.

1. Introduction

The demand for summer air conditioning continues to grow not only in the tertiary sector but also in residential applications. The corresponding demand for electric power may cause failures in the electricity supply network, which must cover increasingly higher peak loads. Furthermore, the environmental impact of these systems in terms of climate change may be very important in the future. In this context, small capacity absorption systems are becoming increasingly attractive in applications where the input energy can be obtained from solar energy. Presently, two types of heat driven technology are widely used in residential solar air-conditioning systems: the water/lithium bromide system and the ammonia/water system. These technologies have some drawbacks caused by the working fluids used.

The water–lithium bromide working pair has problems such as corrosion and vacuum operation, but the main problem is the crystallization that occurs at high cooling-water temperatures. Consequently, these types of chiller usually need wet cooling towers for re-cooling in order to dissipate the heat generated internally in the absorber and condenser, thus limiting their use in the residential sector because of the cost involved and because of the risk of legionella. Furthermore, a wet cooling tower consumes large quantities of water to replenish the water that is evaporated and released from the cooling tower. These drawbacks severely impede the use of these chillers in the domestic sector [1].

The performance of an absorption cycle using the ammonia/water working pair is lower and additionally requires higher driven

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Nomenclature

A	heat transfer area
Cp	heat capacity
e	plate thickness
F	NH_3 mass absorption flux per heat transfer area
h	heat transfer coefficient
Km	mass transfer coefficient
k	thermal conductivity
$LMTD$	logarithmic mean temperature difference
$\dot{m}$	mass flow rate
Nu	Nusselt number
P	pressure
Pr	Prandtl number
Q	thermal load
Re	Reynolds number
Sh	Sherwood number
U	overall heat transfer coefficient
V	volumetric flow rate
x	NH_3 mass fraction in solution

Subscripts

AB	absorber
Cw	cooling water
Eq	equilibrium
In	absorber inlet
NH_3	ammonia
Out	absorber outlet
S	solution
Sat	saturation state
Sub	subcooling
W	wall

Greek letters

ΔT	temperature difference
μ	dynamic viscosity
ρ	density

temperatures. Moreover, the ammonia/water working pair has to be rectified because the absorbent (water) is relatively volatile, which means that ammonia vapor leaving the generator usually contains a significant amount of water vapor. For this reason the ammonia/water system has to include a distillation column attached to the top of the generator. Distillation of vapor increases the complexity of the plant and the fixed costs. However, because ammonia and water are mutually soluble throughout the concentration range, this working pair does not cause crystallization and thus allows the use of dry towers. Nevertheless, on hot days, the driven temperature resulting from using a dry cooling tower becomes too high for solar driven systems.

In order to overcome the limitations of the traditional working pairs, alternative working fluids such as ammonia/lithium nitrate have been proposed in the literature [2]. The advantages of this working pair over conventional water/lithium bromide are: a) it does not cause crystallization in solar air-conditioning systems and so allows the cycle to be air-cooled; b) the absorption cycle does not operate under vacuum conditions. Compared with the ammonia/water working pair, ammonia/lithium nitrate a) does not require a rectifier at the generator outlet because the absorbent is a salt, and b) can be used at a lower temperature in the generator, according to the results of the thermodynamic simulation [3–6].

However, poor results have been obtained with prototypes of absorption refrigeration machines designed initially to operate with the ammonia/water working pair [5,7,8] but loaded with the ammonia/lithium nitrate working pair. The authors of these experimental studies agree that the main reason for the poor performance is due to the high viscosity of this mixture compared with that of ammonia/water. This high viscosity reduces the performance predicted by the thermodynamic models. This reduction is higher at low cooling-water temperatures because the viscosity increases drastically in the absorber.

To overcome this drawback Ehmke and Renz [9] and Bokelmann [10] proposed adding water to the binary mixture of ammonia/lithium nitrate to be used in absorption heat pumps. Later, Reiner and Zaltash [11] proposed using the ternary mixture for GAX systems as an alternative to the ammonia/water systems.

Ehmke [12] studied the effect of water on the solubility and viscosity of the ternary mixtures and suggested an optimal water mass fraction of between 0.20 and 0.25 in the absorbent mixture (lithium nitrate + water). The author also determined and correlated the density and vapor pressure of the solutions with a 0.25 water mass fraction of the absorbent mixture. Bokelmann [10] reported experimental research concerning the performances of an absorption heat pump. Similar data were also reported by Manago [13] in a study on new mixtures for absorption heat pumps that formed part of the Heat Pump Program of the International Energy Agency. Reiner and Zaltash [14] measured the densities and viscosities of ternary mixtures with an ammonia mass fraction of 0.04 and a water mass fraction of 0.605, this being a typical composition for GAX systems. They also measured the boiling point of this mixture at atmospheric pressure. Bothe [15] presented a comparative study of the ammonia/water system and the ammonia/(lithium nitrate + water) ternary mixture. The author reported that the ternary mixture had higher operation temperatures and important COP improvements in heat pump applications than did the binary. He also highlighted the need to make a minor rectification to increase the capacity. Moreno-Quintanar et al. [16] compared the effect of both the binary mixture ammonia/lithium nitrate and the ternary mixture ammonia/(lithium nitrate + water) on the performance of a solar powered intermittent absorption refrigeration system. The authors concluded that the ternary mixture produced a higher amount of ammonia during the generation when there were absorbent water concentrations of 20% and 25%. It was also found that with the ternary mixture the solar coefficients of performance were up to 24% higher than those obtained with the binary mixture (varying from 0.066 to 0.093) and that the initial generation temperatures were up to 5.5 °C lower than those required for the ammonia/lithium nitrate mixture. No traces of water in the ammonia vapor were observed at any point during the experimental test.

Regarding the thermophysical properties of the binary and ternary mixtures, Libotean et al. [17,18] presented experimental measurements and equations for calculating the vapor–liquid equilibrium and the transport properties of the binary mixture ammonia/lithium nitrate and the ternary mixture ammonia/(lithium nitrate + water) with absorbent water concentrations of 20, 25 and 30%. Cuenca et al. [19] published experimental data of thermal conductivity for the binary mixture ammonia/lithium nitrate at temperatures ranging from 35 to 50 °C and ammonia mass fraction in the range 0.30–0.50.

The recent solubility data compiled by Eysseltová and Orlova [20] also confirm that adding water improves the solubility of the solution, making the ternary mixture more suitable for high generation temperatures or low cooling temperatures.