

Thermodynamic and Heat Transfer Characteristics in Single Stage NH₃-H₂O Absorption Heat Pump

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ABSTRACT: In this paper, the thermodynamic behavior of the ammonia-water mixture at different pressures and range of ammonia concentration, ξ , after rectifier of 0.9000 to 0.9999 has been theoretically studied. At $\xi = 0.9000$ and saturation pressures of 75 and 0.5 bar, the temperature glides are 64.4 and 81.21°C respectively, while this glides are 0 and 16.1°C at $\xi = 0.9999$ and the same pressures. This mixture properties affects considerably the absorption system performance and the design of the rectifier as well as other absorption components. The effects of ξ , mass fraction spread, $\Delta\xi$, specific solution circulation ratio, f , and pressure ratio, R_p , on the heat transfer coefficients during the condensation and the evaporation are investigated. ξ has insignificant effect on the evaporation heat transfer coefficient, but has a little effect on the condensation and the absorber heat transfer coefficients. $\Delta\xi$ and f have considerable effects on the heat transfer coefficient for different absorption heat pump components. R_p has pronounced effect on the evaporation heat transfer coefficient; while has a slight effect on the condensation and the absorber heat transfer coefficients. For $\Delta\xi > 0.18$, the effect of R_p may be eliminated on the heat transfer coefficient in the absorber.

Keywords: thermodynamic, heat transfer, absorption, ammonia-water

Nomenclature

$\dot{m}$ mass flow rate [kg/s]
 f specific solution circulation ratio [-]
 K overall heat transfer coefficient [kW/m²K]
 Nu Nusselt number, $(a L/\lambda)$ [-]
 P pressure [bar]
 Pr Prandtl number, $(C_p \mu/\lambda)$ [-]
 Re Reynolds number, $(\rho v L/\mu)$ [-]
 T temperature [°C]
 v velocity [m/s]

Greek symbols

$\Delta\xi$ mass fraction spread [-]
 α heat transfer coefficient [kW/m²K]
 λ thermal conductivity [kW/m K]

μ dynamic viscosity [kg/m s]
 ρ density [kg/m³]
 ξ ammonia concentration [-]

Subscripts

ABS absorber
 CON condenser
 EVP evaporator
 l liquid
 R refrigerant, ratio
 rs rich solution
 sat saturated
 v vapor
 ws weak solution

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1. INTRODUCTION

The technologies of the absorption system based on large scale development are, in the beginning, in the refrigeration industry. Recently, the gas-powered and solar absorption refrigerators as well as heat pump under modified cycles using compact heat exchangers were developed, [1, 2].

The binary mixture of the ammonia-water is the most common working pair used in absorption system since its early development and at the present time due to the specific properties which presents the possibility of using different types of cycles, [3]. Ammonia-water is a zeotropic mixture and its condensation as well as evaporation behaves quite different from the condensation and evaporation of a pure substance or an azeotropic mixture due to the existence of simultaneous mass and heat transfer process, [4]. Additionally, the use of natural substances of ammonia and water cause no environmental harmful, such as ozone layer depletion and global warming potential. Moreover, the absorption machine uses low quality of thermal energy that can be obtained from waste heat in many applications. Therefore, it is classified as

environmentally friendly, [5, 6].

Researches are conducted theoretically and experimentally on the absorption system focusing on the improvement of the system performance and investigating new working fluid pairs. The rate of heat transfer for different components and some performance parameters like specific solution circulation ratio and the heat transfer during condensation has been studied by different authors, [2, 6]. The heat and mass transfer coefficients in the vapor phase have no significant effect on the absorption process. However, the others heat and mass transfer coefficients should be always taken into account in the analysis of the absorption system, since their effects on the absorption are important, [4].

The present paper represents a thermodynamic analysis and heat transfer characteristics of ammonia-water absorption heat pump. The analysis has been carried out investigating simulated model for a prototype absorption heat pump. The effect of performance parameters for the absorption such as specific solution circulation ratio, mass fraction spread, and pressure ratio has been developed

2. THERMODYNAMIC BEHAVIOR

The behavior of the properties of the ammonia-water mixture is completely different from the properties of the water and the ammonia, especially when the vapor takes place in the mixture (vapor quality more than 0.75). This behavior depends on the concentration of the ammonia in the mixture. Table 1 represents the saturation temperature for water, ammonia, and $\text{NH}_3\text{-H}_2\text{O}$ at different concentrations corresponding to the saturation pressures. The

concentration is varied from 0.9000 to 0.9999, to analyze the effect of the very small changes in the concentration (0.0999) on the saturation temperature which is considerably affected by the other parameters. The concentration range covers the concentration limits of the refrigerant in the absorption system. The concentration of the refrigerant mixture should be near to the pure refrigerant as possible, since the evaporator heat addition, heat rejection and

air conditioning capacity all increase with the higher refrigerant side mixture concentration, [7].

The difference between the saturated vapor and liquid temperatures is called temperature glide. Glides occur only if the refrigerant containing two or more compounds that do not have unique boiling points. The glides can be clearly indicated from Table 1 when the ammonia concentration in the mixture falls from 0.9999 to 0.9000. At the high pressure (75 bar) and concentration (0.9999), the temperature glide is zero, whereas at the same concentration and low saturation pressure (0.5 bar) is 16.1 °C. At the same saturation pressures (75 and 0.5 bar) but with the concentration 0.9900, the glides are 1.7 and 53.2 °C respectively. Another

important remarks can be noticed at $\xi = 0.9000$ and the same saturation pressures, the glides in this case are 64.4 and 81.21 °C respectively. The reason behind the large bandwidth of the temperature glides when the concentration falls down is mainly attributed to the high boiling point temperature of the water compared to the boiling point temperature of the ammonia. This interpretation is very useful to understand the actual tendency of the two compounds mixture ($\text{NH}_3\text{-H}_2\text{O}$). Additionally, care should be taken during the modeling of the system and for designing the rectifier in order to produce high $\text{NH}_3\text{-H}_2\text{O}$ vapor concentration whenever possible. It should be noted that the properties of the ammonia-water mixture is obtained using the program EES, [8].

Table 1: Comparison between the saturation liquid and vapor temperatures for water, ammonia, and ammonia-water at various saturation pressures

Pressure [bar]	Water (H_2O) $T_{\text{Sat.}} [^\circ\text{C}]$	Ammonia (NH_3) $T_{\text{Sat.}}$	$\text{NH}_3\text{-H}_2\text{O}$							
			$\xi = 0.9000$		$\xi = 0.9900$		$\xi = 0.9990$		$\xi = 0.9999$	
			$T_{\text{Sat.l.}}$	$T_{\text{Sat.v.}}$	$T_{\text{Sat.l.}}$	$T_{\text{Sat.v.}}$	$T_{\text{Sat.l.}}$	$T_{\text{Sat.v.}}$	$T_{\text{Sat.l.}}$	$T_{\text{Sat.v.}}$
75	290.5	109.6	116.5	180.9	109.1	126.1	108.3	110.0	109.1	109.1
60	275.6	98.04	104.1	170.9	97.9	117.3	97.2	99.2	97.9	97.9
45	257.5	83.98	89.21	159.5	84.1	107.6	83.5	86.3	84.1	84.2
30	233.9	65.75	70.25	145.6	66.1	95.0	65.6	70.2	66.1	66.1
15	198.3	38.62	42.25	122.1	39.1	75.8	38.7	49.8	39.1	39.8
1.0	99.65	-33.55	-31.8	47.8	-33.4	18.3	-33.6	-9.7	-33.4	-22.1
0.5	81.37	-46.48	-44.9	36.31	-46.4	6.8	-46.5	-18.5	-46.4	-30.3

3. ABSORPTION SYSTEM DESCRIPTION

Fig. 1 shows a schematic diagram for the absorption heat pump. The vapor is coming out from the rectifier with a certain concentration entering the condenser at higher pressure and temperature (18 bar and 65 °C). The inlet condition to the condenser is assumed to be at saturated vapor. The subcooling may take place at the exit of the condenser. For the favorable condition, the subcooling can occur at the exit of the

condenser and in the pre-cooler heat exchanger (high-pressure side). The liquid refrigerant exiting from the pre-cooler passes through the condenser-valve to the evaporator with constant enthalpy considering adiabatic expansion. The heat is transferred to the refrigerant from the chiller side and its temperature is rising up. The refrigerant coming out from the evaporator may be superheated. For most experimental

measurements under various operating conditions, the refrigerant coming out from the evaporator has vapor quality in the range of 0.98-0.99, [9]. The superheating takes place in the pre-cooler heat exchanger (the low-pressure side). The vapor is drawn from the pre-cooler to the absorber at low

pressure. The weak solution coming out from the generator and cooled through the solution heat exchanger is mixed with the refrigerant in the absorber. The heat releases during the mixing process is transferred to the coolant side. The rich solution is pumped again to the generator.

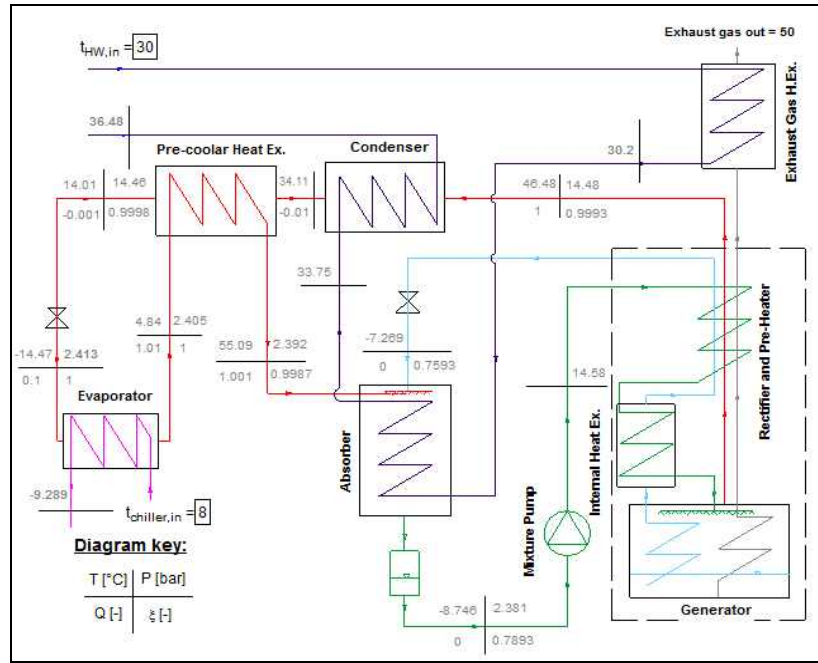


Figure 1: Schematic diagram for absorption heat pump

4. HEAT TRANSFER EVALUATION

A steady state simulation program was carried out considering the mass balance and the energy balance for the absorption system components, [10]. The two performance parameters of the ammonia-water absorption system are; the specific solution circulation ratio (f) and the mass fraction of the internal streams (the mass fraction spread; $\Delta\xi$). The specific circulation solution ratio was determined as the ratio between the mass flow rates of the rich solution and the refrigerant. Eq. 1 describes the relation between the two parameters.

$$f = \frac{\dot{m}_{rs}}{\dot{m}_R} = \frac{\xi_R - \xi_{ws}}{\xi_{rs} - \xi_{ws}} = \frac{\xi_R - \xi_{ws}}{\Delta\xi} \quad (1)$$

The convection heat transfer coefficients are

obtained in the coolant and chiller side for both condenser and evaporator respectively. The coolant water in the condenser and chilled water in the evaporator are only single liquid phase. In order to determine the single phase heat transfer coefficient for both condenser and evaporator, Nusselt correlation is developed. Whenever, the heat exchangers geometry, the coolant as well as the chiller side heat transfer coefficients and the rate of heat transfer, the heat transfer coefficient in the refrigerant side will be obtained.

To obtain the heat transfer coefficient to the refrigerant side for the different components, the heat transfer coefficient in the liquid side should be firstly acquired.

Some authors in the literature assumed that Nusselt number for the fully developed laminar flow in a rectangular channel is constant and its value dependant on the aspect ratio (ratio of the width to the height) of the channel, [11]. Others considered a correlation of Nusselt number as a function of Reynolds and Prandtl numbers, [12, 13, 14]. An attempt was carried out to characterize the correlation that will be used for the plate type heat exchangers under investigation. Eq. 2 represents the developed correlation for water side in the present heat

exchangers and has been applied in the wide range of validity of; $100 < Re < 3000$ and $1 < Pr < 10$

$$Nu = 0.28 Re^{0.69} Pr^{0.41} \quad (2)$$

Referring to the equation of the overall heat transfer of each component and the heat transfer coefficient in the coolant as well as the chiller side, the refrigerant heat transfer coefficient can be obtained, Eq. 3.

$$\frac{1}{K \cdot A} = \frac{1}{\alpha_c \cdot A_c} + \frac{1}{\alpha_h \cdot A_h} + \frac{\delta_p}{\lambda_p \cdot A_p} \quad (3)$$

5. RESULTS AND DISCUSSION

5.1 Refrigerant Vapor Concentration

Fig. 2 shows the convection heat transfer coefficient (α) versus the pressure ratio in different absorption system components at different values of the refrigerant vapor concentration. The vapor concentration has a slight effect on the evaporative heat transfer coefficient (α_{EVP}) in the evaporator. At low pressure ratio ($R_p = 4 - 5$), increasing vapor concentration, a little increasing in α_{EVP} is observed. However, at higher values of pressure ratios ($R_p > 5$), there is no change in α_{EVP} with changing the vapor concentration. Increasing vapor concentration, the mixture tends to be pure ammonia and behaves like ammonia. However, decreasing the vapor concentration signifies that the water content in the mixture increases. The behavior of the properties of the ammonia-water mixture deviates than that of the ammonia. Due to the increasing of the water content in the mixture, a reduction of the evaporative heat transfer coefficient occurred. This reduction is attributed to the thermophysical properties and diffusional resistance, [15].

The changes in thermophysical properties are relatively small especially at the low pressure and lower range of the vapor concentration (0.9990 – 0.9999). Increasing the pressure ratio decreases the evaporator pressure. Therefore, this qualified the

phenomena at R_p more than 5; thereby there is no effect of the vapor concentration on α_{EVP} . Thus, the thermophysical properties can not be alone distinguished decreasing in the evaporative heat transfer coefficient. The diffusion phenomenon is supposed to have a more significant effect. As ammonia evaporates, the water left behind builds up at the interface. Owing to the locally high concentration of water, the saturation temperature at the interface is higher than that of the average water content of the film. Consequently, the thermal driving force for the heat transfer is less than it would be if there is no water concentration gradient.

The refrigerant vapor concentration has a pronounced effect on both the condensation and the absorber heat transfer coefficient. Decreasing the vapor concentration increases the condensation as well as the absorber heat transfer coefficients. In addition, the absorber heat transfer coefficient increases as the pressure ratio increases. However the condensation heat transfer coefficient exhibits no change with the pressure ratio at different values of vapor concentrations. The effect of the thermophysical properties becomes more prominent on the condensation heat transfer coefficient in compared to the evaporative heat transfer coefficient. The condensation

occurred at high pressure and temperature which the thermophysical properties affected considerably by these conditions.

The enhancement in the condensation heat transfer coefficient due to decrease the

vapor concentration from 0.9999 to 0.9990 is 40 %. However this improvement in the absorber heat transfer coefficient is 16 % at the same pressure ratio ($R_p = 5$).

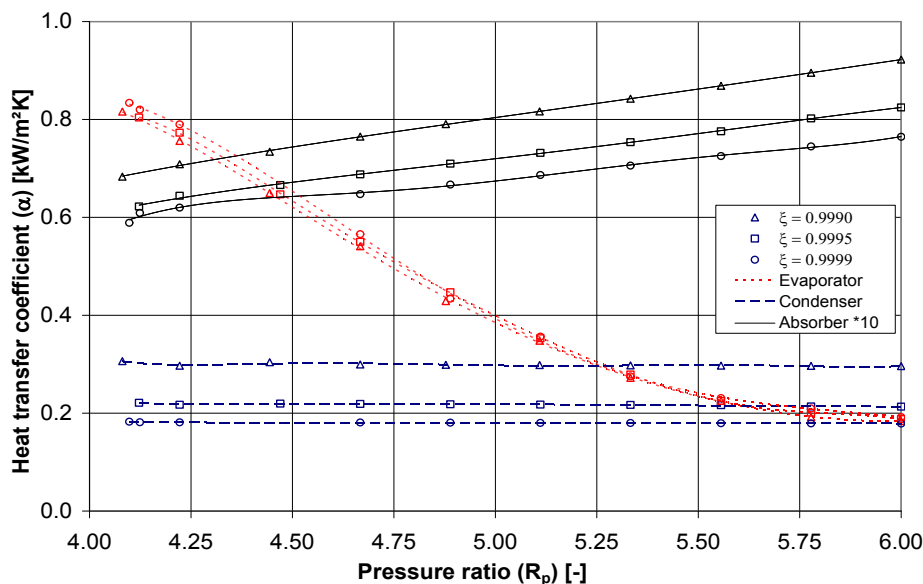


Figure 2: Heat transfer coefficient versus pressure ratio at various ξ

5.2 Pressure Ratio

Convective heat transfer coefficients in the different components versus the mass fraction spread is presented in Fig. 3 for different values of pressure ratios. A reduction in the pressure ratio has a significant effect on the evaporative heat transfer coefficient. The decreasing of the pressure ratio at constant condenser pressure boosts the evaporator pressure. Increasing the evaporator pressure changes the thermophysical properties of the mixture in the evaporator. The bandwidth between the increasing in α_{EVP} due to reduce the pressure ratio from 5 to 4 is greater than the pressure ratio decreases from 6 to 5. On the other words, the low pressure ratio, the high evaporative heat transfer coefficient. At constant mass fraction spread ($\Delta\xi = 0.12$), the evaporative heat transfer coefficient is

augmented by $225 \text{ W/m}^2\text{K}$ as the pressure ratio decreases from 6 to 5. However, when the pressure ratio reduces from 5 to 4, the evaporative heat transfer coefficient is enhanced by $390 \text{ W/m}^2\text{K}$.

The pressure ratio has insignificant effect on the condensation heat transfer coefficient. The reason behind this trend is mainly attributed to the constant condenser pressure and the inlet condition to the condenser. However, the heat and mass transfer performance of a binary mixture depends on the flow characteristics of not only the liquid but also the vapor flow. The vapor flow rate may be maximized to increase heat and mass transfer performance in ammonia-water absorption process [16]. However, the condensation pressure was found experimentally to be a very weak effect, [15].

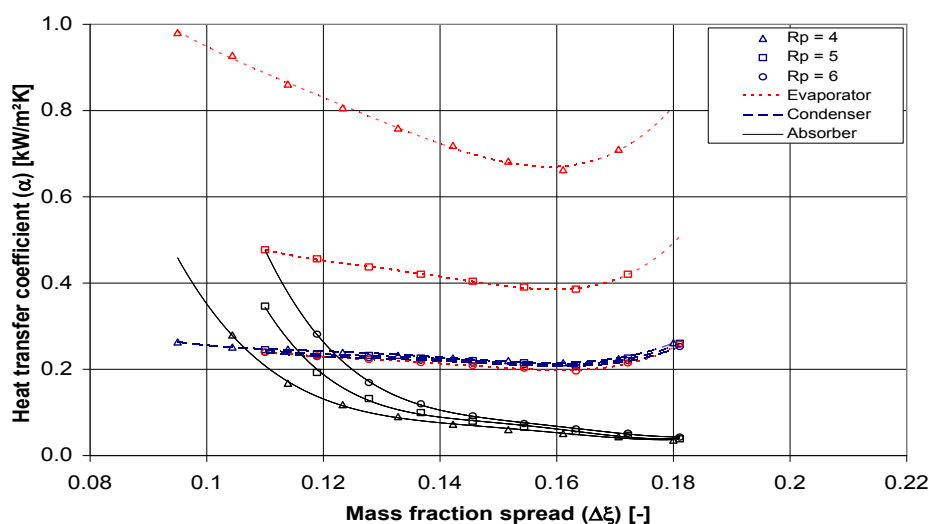


Figure 3: Heat transfer coefficient versus mass spread fraction at various R_p .

In addition, increasing the pressure ratio increases the absorption heat transfer coefficient. This increasing will be diminished with increasing the mass fraction spread. It can be seen at $\Delta\xi = 0.18$, all absorption heat transfer coefficients tend to

merge together producing one curve eliminating the effect of the pressure ratio. At $\Delta\xi = 0.12$, the reduction in the absorption heat transfer coefficient is 57 % due to reducing the pressure ratio from 6 to 4.

5.3 Specific Solution Circulation Ratio

Fig. 4 illustrates the effect of the specific solution circulation ratio and the mass fraction spread on the heat transfer coefficient in the different absorption system components. $\Delta\xi$ and f have insignificant effect on the evaporation and the condensation heat transfer coefficients because both of them are playing their rules only on the performance of the absorber.

The effect of the two parameters under consideration is more pronounced on the absorber heat transfer coefficient (α_{ABS}). At certain $\Delta\xi = 0.1$; increasing f , decreases the absorber heat transfer coefficient. However, at $f = 7$, increasing $\Delta\xi$, decreases the absorber heat transfer coefficient. On the other hand, increasing both $\Delta\xi$ and f , declines the absorber heat transfer coefficient. It is observed that, a minimum value of the absorber heat transfer coefficient ($\alpha_{ABS} = 40 \text{ W/m}^2\text{K}$) for all $\Delta\xi$ and f may be reached.

The trends of the absorption heat transfer

coefficient may be explained from the viewpoints of the weak and rich solution properties. f denotes the rich solution mass flow rate as a relation of the refrigerant mass flow rate. However, $(f-1)$ signifies the weak solution as a function of the refrigerant mass flow rate. With increasing f at constant $\Delta\xi$ increases the weak solution mass flow rate as well as decreases the weak solution concentration. Reducing weak solution concentration means that the water content in the mixture increases. As the weak solution concentration decreases, the thermophysical properties of the mixture consequently decrease. It should be noted that the specific heat of the mixture as well as the ammonia is higher than the water at the same temperature. Also, the dynamic viscosity increases as ξ increases until $\xi = 30 \%$ then decreases with continuous increasing of ξ , [17]. The same explanation can be established as $\Delta\xi$ increases.

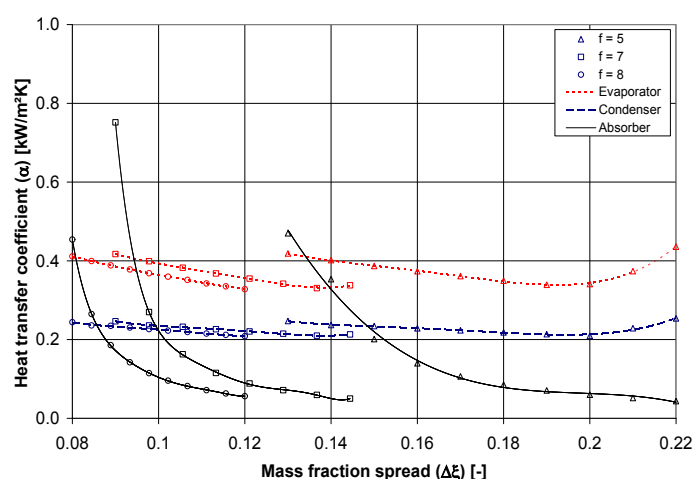


Figure 4: Heat transfer coefficient versus mass spread fraction at various f .

6. CONCLUSION

The thermodynamic behaviors and heat transfer characteristics in single stage ammonia-water absorption heat pump has been theoretically investigated. The performance parameters of the absorption system (ξ , R_p , $\Delta\xi$ and f) and their effects on the evaporation, condensation and absorption heat transfer coefficients have been studied. The following conclusion can be drawn from the analysis of the results.

1. From thermodynamic analysis, attention should be paid during the modeling of the system and for designing the rectifier to produce high $\text{NH}_3\text{-H}_2\text{O}$ concentration.
2. A correlation of Nu is developed for the plate heat exchanger.
3. ξ has insignificant effect on the evaporation heat transfer coefficient but has a slight effect on the condensation as well as the absorber heat transfer coefficient.
4. R_p has great effect on the evaporation heat transfer coefficient and has a little effect on the condensation as well as the absorber heat transfer coefficient.
5. $\Delta\xi$ and f have a pronounced effect on the heat transfer coefficient for the different absorption system components.

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