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Upgrading of Performance of Diffusion Absorption Refrigeration System

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Abstract: This paper deals with the effects of absorbent used on the thermal performance of commercial diffusion absorption refrigeration systems (DARSs). For this purpose, an ammonia solution with added lithium bromide was used in the DARS system instead of a commercial ammonia solution of NH_3-H_2O (NH_4OH) (25% ammonia and 75% water), and all comparison experiments used a fixed amount of refrigerant to experimentally investigate the effects on performance. The system cooling performance was calculated by means of experimental data. The performance of all the solutions prepared was compared to each other. The added lithium bromide increased the amount of water absorbed by the coolant, increasing the amount of refrigerant carried to the generator and condenser. Consequently, the thermal efficiency of the system was increased. By using a 5% solution of lithium bromide with the ammonia solution, the thermal performance increased by up to 12%. It was concluded that lithium bromide has a higher refrigerant absorption capability than water in diffusion absorption refrigeration systems.

Keywords: Diffusion, absorbent, refrigeration, ammonia, Lithium Bromide (LiBr).

1. INTRODUCTION

The diffusion absorption refrigeration system, DARS, was invented in the 1920s [1]. The DARS is based on the use of limited heat capacity, and this system has been commonly used in domestic refrigerators, caravans, recreational vehicles, camping, and especially hotel rooms and offices owing to its silent operation [2]. Since the efficiency and capacity of DARS has been low, it is restricted to small capacities [3]. Literature shows that a few studies have been done looking at improving the performance of DARS, which are traditionally low-performance systems. Three methods have been demonstrated to improve the performance of heat and mass transfer in DARS: Zohar *et al*. [2] studied and compared the performance of two fundamental configurations of a DARS cycle, with and without condensate sub-cooling prior to entering the evaporator. It was found that the DARS cycle, without condensate sub-cooling, shows a higher coefficient of performance (COP) of between 14 to 20% in comparison to the DARS cycle with condensate sub-cooling.

Sözen *et al*. [3] experimentally investigated the variations in the system by installing an ejector in front of the absorber in a DARS system. The weak solution coming from the generator is separated into two parts with equal flows, and then, one is connected to the mixing tube of the ejector and the other is connected to the absorber. Experimental results show that the DARS cycle with the ejector demonstrated a higher performance compared to the DARS cycle without the ejector. Zohar *et al*. [4] investigated the effect on performance of the bubble pump of a major factor in DARS. The results indicated that the maximum performance was obtained using a partially attached configuration. Ersöz [5] experimentally examined the effect of three different heat inputs to the generator of a DARS unit. The results illustrated that, as the heat input increases, the COP and the circulation ratio decreases. Different cooling and absorbing fluids have previously been used in combination with pressure-regulating gases such as hydrogen and helium in order to enhance performance. Diffusion absorption refrigerator systems are operated with different binary refrigerants, various fluid pairs and absorbents.

It has recently been observed that nano fluids, which are metal oxide particles of certain sizes added in a certain ratio to a working fluid, improve the performance in terms of heat absorption and transfer. Previous work has shown that fluids used in heat pipes, absorption refrigeration systems and heat exchangers contain metal oxides in nano size, a situation that enhances system heat-transfer performance. This study has been based on the results of Yang *et al*. [6] in which they carried out performance analyses using nano refrigerators. Other studies by Mahbubal *et al*. [7] and Kim *et al*. [8] indicated the nano refrigerator's thermo-physical properties and absorption properties. Sözen *et al*. assessed the effect on system performance of cooling/absorbent fluid mixtures with Al_2O_3 nanoparticles [9]. Jelinek *et al*. [10] investigated

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the effect of the purity of the coolant at the evaporator inlet on the performance of a diffusion absorption refrigeration cycle under three different configurations of pre-cooling. The study illustrated that the temperature at the evaporator inlet did not affect the performance of the DARS.

While there are several studies in the literature related to absorption refrigeration systems, the number of studies related to diffusion absorption refrigeration systems is limited. The novel purpose of this study was to investigate upgrading a diffusion absorption refrigeration system by using a $LiBr–NH_4OH$ absorption solution. In this study, a 54% LiBr solution (w/w) was added to a commercial 25% ammonia solution (w/w) – which is used in conventional DAR cycles – in defined amounts in order to specify the effects of these chemical improvements on the system performance of the DARS.

2. DIFFUSION ABSORPTION REFRIGERATION SYSTEMS (DARS)

A mechanical pump placed between the absorber and the boiler is used to circulate the solution in high-capacity absorption refrigerator systems that do not use diffusion. A mechanical pump does not exist in a DARS, such as a mini-bar. In DARS, the pressure difference between absorber and boiler is regulated by using the partial pressure of hydrogen and helium gases circulating between the evaporator and absorber [11]. This experimental study indicates the effects of absorbent on the system performance.

The DARS includes four main components: the boiler, condenser, evaporator and absorber (Figure **1**). Dalton's law is employed in DARS and the system is free of moving parts [12]. Heat is supplied from the boiler system by a burner or a resistance heater. The working fluid is obtained by mixing certain proportions of ammonia, water and helium, and a sufficient amount of pressure is sustained to keep the ammonia condensed at room temperature. The heat supplied from the boiler system results in ammonia bubbles rising through the siphon pump (1c). Ammonia bubbles also carry some amount of the weak ammonia solution within themselves. The weak ammonia solution goes into the tube (1e). The ammonia vapor continues through the vapor pipe and the water separator (1d). In the water separator, water is condensed and pure ammonia vapor is fed to the condenser (2). The system operating pressure range is between the initial system pressure of 15 bar and the maximum operating pressure of 19 bar. Later on, the ammonia vapor is condensed in the condenser by the air circulation in the condenser (3). When the ammonia vapor condenses, the air circulation in the condenser transfers heat. The ammonia vapor turns into liquid ammonia due to the heat exchange in the condenser, and the liquid ammonia arrives at the evaporator. In the evaporator, liquid ammonia comes into contact with helium (4a). Helium decreases the vapor pressure of liquid ammonia to a sufficient level that enables evaporation of the liquid ammonia (4b). Evaporation of the ammonia absorbs heat from the storage space of the refrigerator, which results in decreasing temperature inside the refrigerator. When the mixed ammonia and helium vapor gets to the absorber, a small amount of weak ammonia solution is formed at the upper parts of the absorber. While the weak ammonia solution flows through the tube under the force of gravity, it absorbs ammonia from the mixture of ammonia and helium gases in the tube (9a). After the ammonia vapor is absorbed by the weak ammonia solution in the absorber, helium is released back to the evaporator. Helium continues to loop around the system. At the same time, the ammonia solution flows to the reservoir of the absorber (10). Then, it flows onwards to the boiler. This way, the ammonia completes a loop of the system. The system operates as long as the boiler receives heat (1a). The temperature of the storage area is regulated by a thermostat, which controls heat supplied to the boiler. Except for the control unit of the thermostat and fans (in some systems), there are no moving parts in the system. Many systems use electrical units requiring gas and electricity to be used together. Quite low temperatures can be obtained by DARS when ammonia is utilized as the refrigerant. During experiments, cooling chamber temperatures reach approximately 7 to 10 degrees lower than the ambient temperature. The configuration of the system units must be carefully planned so that the pressure difference achieved by the helium can lead to evaporation of ammonia in the evaporator. A representation of DARS taken from a firm's brochure [13] is given in Figure **1**.

3. MATERIALS AND METHOD

3.1. Materials

These types of refrigerators make widespread use of a commercial ammonia/water solution (25% + 75%) fluid pair. Merck supplied the commercial ammonia solution (25%) and the Lithium bromide solution at a concentration of 54% (w/w). Comparison solutions were prepared with distilled water.

3.2. Method

The refrigerant/absorbent pairs in this study were ammonia–water and ammonia–water + LiBr. In this study, different volumes of a LiBr–water and pure water solution were added to the 25% ammonia–water solution, which was the commercial ammonia solution.The amount of refrigerant was kept constant at the same volume for pure water and the LiBr–water added to ammonia solutions in order to observe the effects of absorbents on the performance of the diffusion absorption refrigeration system. Different amounts of additive solutions were used, as shown in the figures below:

Experiment 1: 25% (w) ammonia + 75% water (commercial solution),

Experiment 2: 5% (w) LiBr–water + Ammonia–water solution,

Experiment 3: 7% (w) LiBr–water + Ammonia–water solution,

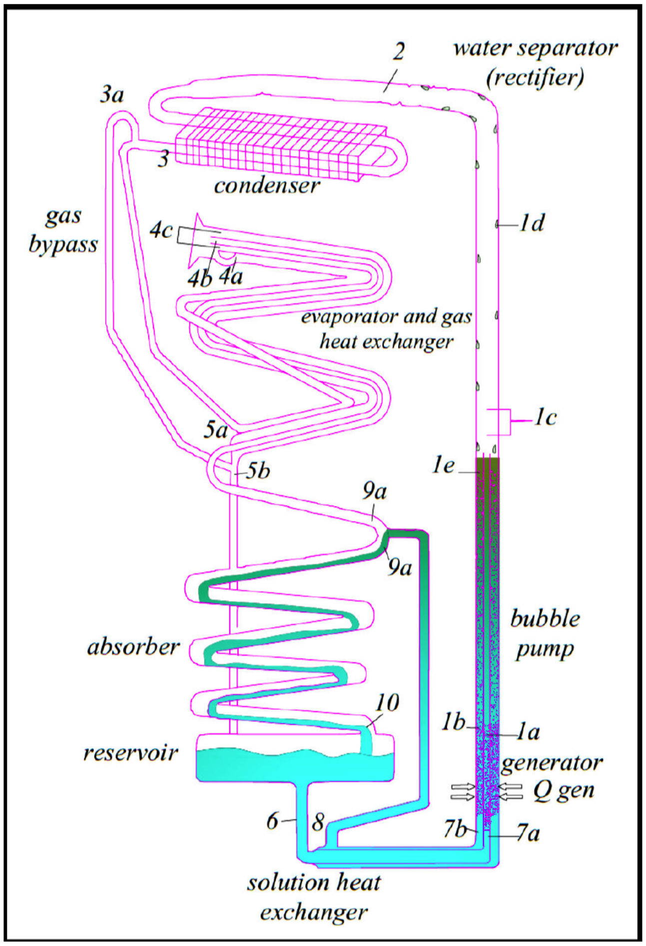

Figure 1: Schematic diagram [13].

Experiment 4: 9% (w) LiBr–water + Ammonia–water solution,

Experiment 5: 5% (w) water + Ammonia–water solution,

Experiment 6: 7% (w) water + Ammonia–water solution

Experiment 7: 9% (w) water + Ammonia–water solution.

The concentrations of ammonia solutions with added LiBr, along with their volume and mass percentages, are shown in Table **1**. The volumes and mass percentages of the comparison fluid prepared by means of an ammonia solution diluted with water, via the addition of a specified volume of water, instead of LiBr are detailed in Table **2**.

The tests were conducted with four kinds of ammonia–water binary solutions and three kinds of ternary solutions with different mass fractions of ammonia, water and LiBr. The solutions used in the study were proportional binary and ternary solutions with a volume of 170 ml. The power of the electrical heater was kept at 75 W throughout the study. The power supply of the system was connected to a wattmeter (Fluke-43b analyzer). Power was measured in watts. Both systems received the same amount of heat.

The DAR system was cleaned by means of pressurized water before each test, so that there were no residual contaminants from the old experiments. After cleaning, the DAR system was vacuumed at a pressure of −1 bar using a pump. The 170 ml of the selected solution was introduced to the DAR experimental set-up by means of a vacuum effect. Following these steps, helium gas was introduced to the system to fix the system pressure at 15 bar. Then, K-type thermocouple probes were placed at defined measuring points on the pipe surface, connected to a data logger. Similarly, a pressure-measuring device was connected to the data logger with a patch cord. Data was recorded using the data logger device and the DALI 08 data program attachment. After these preparations, the DARS generator was operated and the cycle started. All the same procedures were applied for the commercial ammonia solution, the 5%, 7% and 9% volumetric concentrations of LiBr solutions and the H_2O–ammonia solutions, respectively.

Lithium bromide is a lithium salt substance, which is solid under normal conditions. However, lithium

Table 1: LiBr–H_2O Added Ammonia Solution with Mass and Volumetric Mixing Percentage

	LiBr (g) (% w/w)	Ammonia (g) (% w/w)	Water (g) (% w/w)	Additional LiBr–Water(ml) (% v/v)	Ammonia–Water (ml) (% v/v)	Amount of inert gas (g)
Experiment 1	–	39.10 (25)	117.30 (75%)	–	170.00	3.66
Experiment 2	7.35 (4.53%)	37.15 (22.91%)	117.7 (72.56%)	8.50 (5%)	161.50 (95%)	3.66
Experiment 3	10.29 (6.25%)	36.37 (22.11%)	117.90 (71.64%)	11.90 (7%)	158.10 (93%)	3.66
Experiment 4	13.22 (7.93%)	35.58 (21.33%)	118.00 (70.74%)	15.30 (9%)	154.70 (91) %	3.66

Table 2: H_2O Added Ammonia Solution Mass and Volumetric Mixing Percentage

	Ammonia (g) (% w/w)	Total Water (g) (% w/w)	Additional water (ml) (% v/v)	Ammonia/Water (ml) (% v/v)	Amount of inert gas (g)
Experiment 1	39.10 (25%)	117.30 (75%)	-	170.00	3.66
Experiment 5	37.15 (23.65%)	119.94 (76.35%)	(5%)	161.50 (95%)	3.66
Experiment 6	36.37 (23.12%)	121.00 (76.88%)	11.90 (7%)	158.10 (93%)	3.66
Experiment 7	35.58 (22.58%)	122.05 (77.42%)	15.30 (9%)	154.70 (91%)	3.66

bromide salt is highly soluble in fluids. It dissolves in water and forms a lower vapor pressure solution at equilibrium than pure water at the same operating temperature.

Many researchers make wide use of lithium bromide–water solutions (LiBr–H_2O) as working fluid in absorption refrigeration systems because of its non-volatile and non-toxic nature, as well as being environmentally friendly by not contributing to ozone depletion. Employing this solution avoids the use of chlorofluorocarbon (CFC) refrigerants and its consequent environmental damage [14]. In contrast, the low crystallization temperature, high absorption capacity and low viscosity are all advantages of LiBr–H_2O solution as an absorbent [15].

The system with water and the system with LiBr–water were subject to the same experimental conditions and the same ambient temperature. Both systems were run in parallel. Experiments were repeated at least 3 times.

In the experiments, temperature and pressure parameters were measured at various locations (measurements were taken from the numbered points in Figure **1**) on the experimental set-ups since those parameters were the ones that most affect the performance of DARS.

Temperature and pressure at different points are the important parameters affecting the working conditions of the system (Figure **1**). In order to carry out thermodynamic calculations, the boiler region, where heat entered the system, and the rectifier region were separated as shown in Figure **1**. The significant points in terms of thermodynamics are indicated by different symbols.

The uncertainty of the experimental results was determined using the deviation in experimental parameters. The experiments were replicated three times and the average of the temperatures at each test was recorded. K-type thermocouples were used for determining the temperatures. The boiler section was heated by an electrical heater with a nominal power of 75 W, and a wattmeter was used to measure the input power. The uncertainty of the overall thermal conductivity for the experiments can be expressed as:

$$U_m = \sqrt{\frac{\Delta T}{T} + \frac{\Delta Q}{Q}} \tag{1}$$

The accuracy of the thermocouples is ± 0.1 °C. The accuracy of the wattmeter is ± 0.5 W. The uncertainty of the experiments was within ± 3.3% based on equation 1.

4. THEORETICAL STUDY

The energy method is a well-known method for analyzing thermal systems. The analytical thermodynamics mentioned here are based on the following assumptions: (i) System pressure is the pressure measured at point 2. Pressure drops within the pipeline are negligible, (ii) Hydrostatic pressure is negligible, (iii) the liquid solution and the vapor bubbles exit from the capillary and depart the generator at the same temperature (T_{1c}=T_{1e}), (iv) because the generator is thermally insulated, heat loss to the environment is negligible, (v) the refrigerant and inert gas mixture at the entrance to the evaporator is accepted as adiabatic, (vi) there is no flow at point 3a in Figure **1**, (vii) the dead-state temperature is regarded as being equal to the measured ambient temperature, (viii) the temperature difference between the surface measurements of the tubes and the internal flows is negligible. The wall thickness of the tubes does not cause any changes in the temperature, (ix) any negative effect of the inert gas is not significant in the determination of the system characteristics (COP). In the mathematical modeling calculations, it is postulated that there is no inert gas in the cooler and absorber.

In the first step of the thermodynamic analysis, the control volumes of each component of the DARS are selected (Figure **1**). The mass and energy balance equations (including heat losses, gains and capacities for each component of the system) are detailed below. The subscripts of the various properties relate to the locations are indicated in Figure **1**. Electrical resistance, which enables the refrigerant to vaporize and thus become separated from the liquid mixture, and which is also used for pumping the solution towards the bubble pump, provides heat input to the generator.

5. RESULTS AND DISCUSSION

Figures **2** to **6** demonstrate the variations of temperature at the fixed points on the experimental system. Ammonia in the mixture was evaporated by the heat supplied from the boiler in the system. The temperatures at T_{7b} versus time are illustrated in Figure **2**. According to the experimental results, when the solutions with LiBr and water added to ammonia at the same percentage were compared, Figure **2** shows that the solutions with added LiBr have a higher specific heat capacity than the others. For this reason, ammonia solutions with added LiBr had a higher T_{7b} temperature than the ammonia solutions with added water. The pure ammonia solution had the lowest T_{7b} temperature.

As can be seen from Figure **3**, the solutions with added LiBr have lower T_{1b} temperatures. It can be inferred that the LiBr in the working fluid absorbs more water and ammonia as a result of increasing the dipole moment of the fluid. Because the atoms have different electromagnetic forces, the covalent bonds between these atoms have a polarity. The dipole moment is simply the measure of net polarity in a chemical bond. Higher water absorption and dipole moment are the more significant parameters involved in the absorption of ammonia in the ammonia solution with added LiBr at the bubble pump in the system. Yuyuan *et al*. [16] also supported this opinion.

There are parallels between T_{1c} temperatures and T_{1b} temperatures since the same results are observed. T_2 temperatures for ammonia solutions with added water, instead of solutions with added LiBr, are higher than other solutions because water in the vapor mixture produces heat. Thus, the higher absorbed heat has been transferred to the immediate surroundings and to the pure ammonia vapor in the inlet of the condenser. The results obtained are matched by the study of Sathyabhamaa *et al*. [17]. It is possible to see the increasing outlet temperature of the condenser (T_3) from Figure **4**, when an LiBr solution was added instead of water. In contrast, it can be said that the ambient temperature affected the outlet temperature of the condenser. In Figure **5**, the decreasing T_{4a} temperatures in the evaporator have occurred over a shorter period for the ammonia solution with added LiBr. It can be seen from these figures that for an ammonia solution with 5% LiBr solution added, the T_{4c} temperature decreases to −20 °C. As a result of this, there will be reduced switching periods of the thermostat in situations where too much temperature fall is not desired (Figure **5**). In this way, energy is saved.

When the T_5 temperature distribution was determined, the recorded experimental data was similar to the T_3 temperature distribution. Heat transfer occurred from the ammonia solution at the condenser outlet to the ammonia vapor at the evaporator outlet.

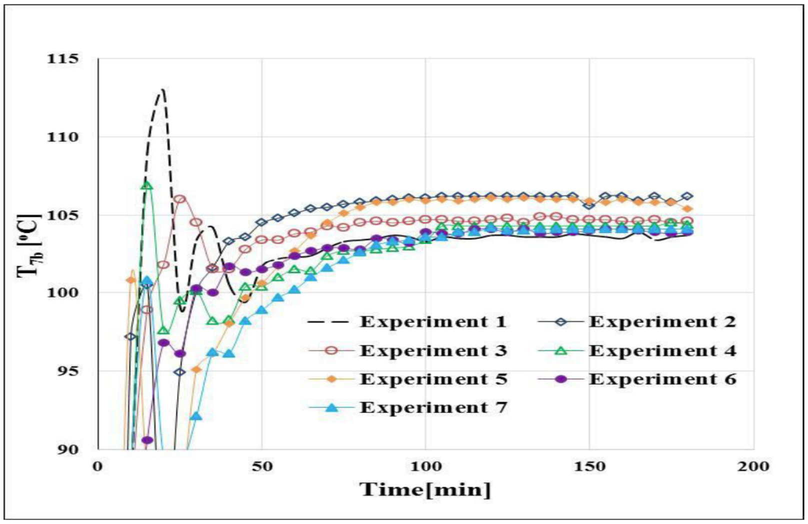

Figure 2: Graph of measured T_{7b} boiler's temperature versus time.

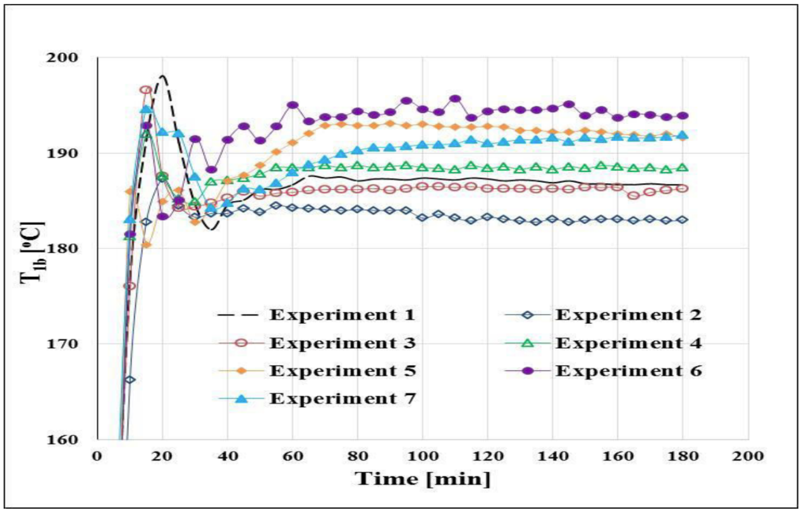

Figure 3: Graph of T_{1b} temperature versus time.

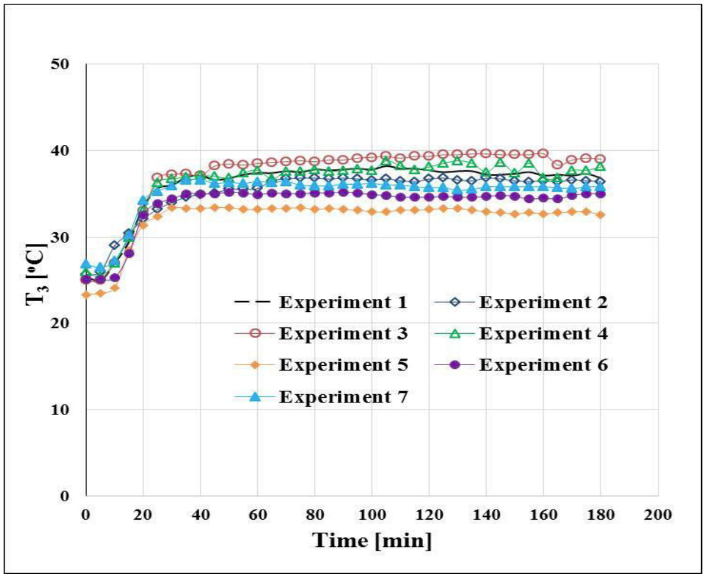

Figure 4: Graph of T_3 outlet temperature of ammonia in condenser versus time.

Table 3: Recorded Data for all Experiments at the 180th Minute

Experiment	T_{7b} (°C)	T_{1b} (°C)	T_{1c} (°C)	T_2 (°C)	T_3 (°C)	T_5 (°C)	T_{4c} (°C)	T_{4a} (°C)	T_{amb} (°C)	P_{sis} (bar)
Exp.1	103.7	186.7	176.4	140.6	36.8	29.2	−17.4	0.6	26.8	16.9
Exp.2	106.1	183	167.6	122.3	35.4	28.6	−19.7	−7.6	26	17.4
Exp.3	96.5	186.3	171.1	127.9	39.0	30.8	−19.9	−2.8	27.1	17.5
Exp.4	104.4	188.5	174.2	123.5	38.1	31.2	−16.7	−1	27	17.6
Exp.5	105.4	191.6	181.4	136.3	32.6	27.4	−15.7	−1.7	23.9	16.9
Exp.6	103.5	193.9	182.7	144.1	35	28.4	−11.6	1.7	25.3	17
Exp.7	104.9	191.9	179.6	139.1	35.8	29.8	−15.5	−1	26.3	16.8

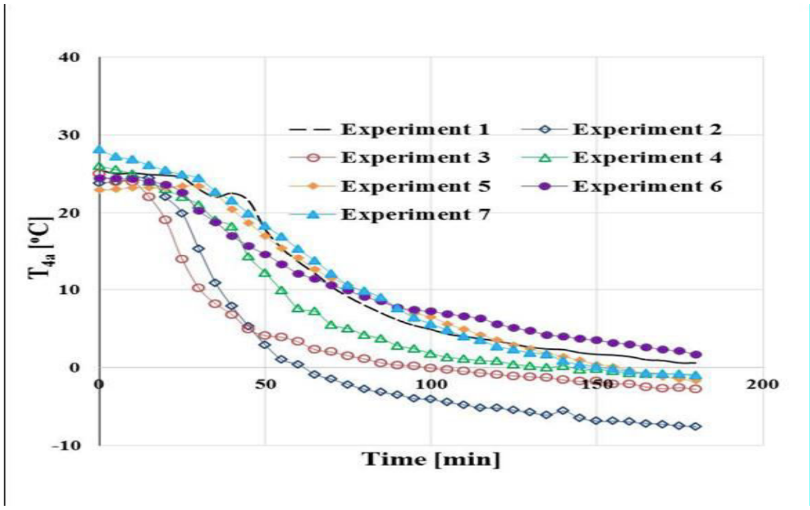

Figure 5: Graph of T_{4a} temperature versus time.

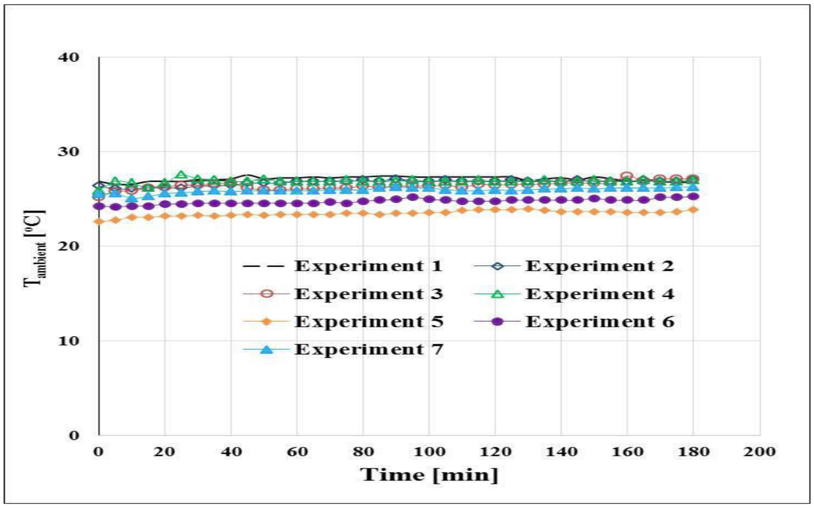

Figure 6: The ambient temperature.

The gas-liquid heat exchanger operates as a countercurrent theory. Eventually, the ammonia liquid is exposed to pre-cooling before reaching the evaporator. Changes in all of the prepared solutions ambient temperature, with respect to time, is represented graphically in Figure **6**. The ambient temperature changed between 22 to 27 °C due to the variation in seasonal temperatures. The system becomes stable in each experiment on average within 40 to 60 minutes. The system temperatures obtained at the 180th minute for each experiment are shown in Table **3**. Fluctuations were observed in the temperatures in Experiment 6 throughout the experiment.

It can be seen from Figure **7**, the distribution of solution pressures versus the operating period has been demonstrated by means of a pressure transmitter. The system pressure has been measured at the entrance to the condenser, at point 2. DARS with LiBr solutions have a higher system pressure compared to DARS with water instead of LiBr, as seen from the graph. The maximum pressure of 17.6 bar in Experiment 4 system was recorded for 180 minutes. The circulation ratio is defined as the ratio between the mass flow rates of the rich solution to that of pure ammonia. The pressure is an important parameter in DARS, since higher pressure results in a higher circulation rate of the working fluids. It is observed that the ammonia solution with added LiBr increases the circulation rate of working fluids from 10 minutes to 180 minutes. The results of this study are as follows: Cooling/absorption fluids containing LiBr solutions and water make it easier to achieve the desired cooling ambient temperature when they are used in mini DARS. Moreover, cooling/absorption fluids using ammonia solutions with added LiBr reach a steady-state temperature more rapidly in mini DARS. As seen in Figure **7**, DARS using ammonia solutions with 5% added LiBr reached 0 °C in the evaporator in 35 minutes, whereas DARS using ammonia solutions with 5% water instead of LiBr decreased to a temperature of 0 °C in 80 minutes. It was observed in the experiments that the solution containing LiBr has, thermodynamically, more capacity for absorbing ammonia compared to solutions with water in place of LiBr. Absorbing more ammonia has been limited due to the changing amount of refrigerant in ammonia solutions with added LiBr or water, which is a limitation that affected the cooling performance. Tiehui *et al*. (32) also expressed this idea.

Theoretical thermodynamic analysis of the systems can be performed by making use of the measured temperature values obtained in the experiments. In this way, the DARS coefficient of performance (COP) can be calculated as follows:

$$COP_{DARS} = \dot{m}_{sf-b} \frac{h_{4c} - h_5}{W_{heater}} \tag{9}$$

The variables h_{4c} and h_5 in (equation 9) are related to T_{4c} and T_5, respectively. They represent the inlet and the outlet enthalpy of the evaporator, respectively. REFPROP 8.0 and Engineering Equation Solver (EES) software was used to calculate h_{4c} and h_5. Considering the measured results, based on the principle of energy conservation given below, the mass flow in (equation 9) was calculated by REFPROP and EES for LiBr and water added to ammonia–water mixtures.

The mass flow of pure ammonia is critical to the performance of the system since ammonia is responsible for cooling activity. Hence, the calculation of the mass flow is required to determine the COP. Figure **8** shows the variations in COP values for DARS. Initial observations from the experiments state the highest COP values. The COP for DARS with a LiBr solution added to ammonia varied between 0.28 and 0.25; whereas, the COP for DARS with water added to

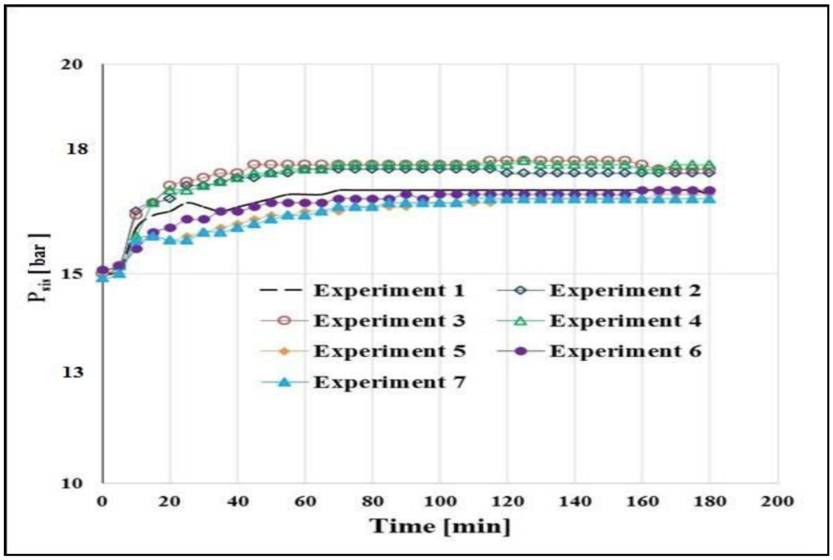

Figure 7: Graph of system pressure versus time.

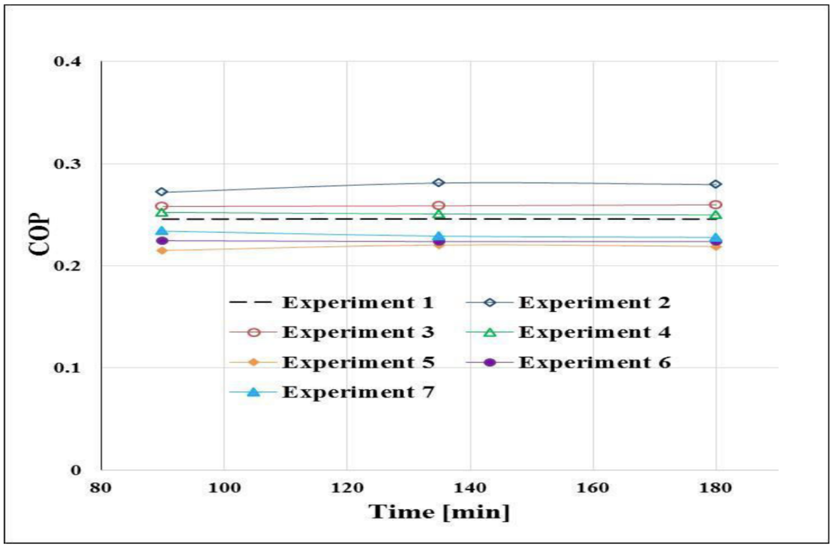

Figure 8: Results of COP analysis.

ammonia solutions varied between 0.23 and 0.22. The COP for DARS with water added to ammonia solutions was found to be lower than the one with LiBr added to the ammonia solution. It was realized that DARS with the LiBr solution obtained the highest COP value, and showed that the LiBr solution had positive effects on the performance of the DARS. The difference in COP values for the same amount of ammonia containing a 5% LiBr solution and a 5% water solution had a beneficial effect of 27% on the performance (Figure **8**). Examining the effects of LiBr on the performance of the bubble pump, it can be said that due to its high ability to take in the absorbent in the absorber, the amount of absorbent carried to the evaporator increases and causes the complete decomposition of ammonia due to the high specific heat and thermal conductivity, and thus cooling capacity increases. This study is important to show that LiBr solutions can be used in DARS to improve thermal efficiency as well as they have been recently able to achieve in many fields.

6. CONCLUSION

It was found that DARS with different absorbents had the best performance – according to experimental analyses of two DARS, one using ammonia with LiBr and one using water with ammonia. The LiBr solution added to the fluids in the absorber improved the absorption process. The improved absorption process contributed to the cooling effect, since the LiBr solutions used have higher ammonia absorption capacity. It was also observed that increasing ammonia concentration in the solution increases the ammonia circulation rate in DARS. There is a triple interaction between LiBr, water and ammonia in DARS. It is known that LiBr absorbs water and water easily absorbs ammonia. It is thought that LiBr absorbs ammonia due to the increasing mass flow of pure ammonia vapor in DARS resulting from extra molecular affinity. Consequently, the thermal performance of a DARS used with a LiBr solution was higher – by up to 12% more – than a DARS operated without a LiBr solution because LiBr has a higher refrigerant absorption capability.

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