M8-027 Study on Absorption Refrigeration Cycle Powered by Low Temperature Heat Source

Phetsaphone Bounyanite[a], I Made Astina[b], and Prihadi S. Darmanto[b]

[a]National University of Laos
Master Student of Institut Teknologi Bandung, Indonesia
E-mail: phetsaphonebounyanite@yahoo.com

[b]Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung
Jalan Ganesha 10, Bandung 40132 West Jawa, Indonesia
E-mail: astina@soon.com

Abstract

Vapor absorption refrigeration system is interesting to be developed in advance due to prospect of this system that could be operated using lower temperature heat source. Two fluid types are normally used in the systems, i.e. one fluid works as refrigerant to transport energy from evaporator to condenser, and a secondary fluid or absorbent is used to circulate the refrigerant. The binary systems of water-lithium bromide (H_2O-LiBr) and ammonia-water (NH_3-H_2O) were well known as working fluid to be applied in absorption refrigeration system. This research is to conduct thermodynamic performance simulation and analysis on single-stage vapor absorption refrigeration system for several varied operational parameters. The operating temperature conditions of the generator, condenser and evaporator are ranged respectively from 60 to 90°C, 20 to 40°C and 2.5 to 12.5°C. For the considered operating conditions, the simulation result of the coefficient of performance (COP) could reach from 0.386 to 0.885 for H_2O-LiBr mixture and from 0.282 up to 0.597 for NH_3-H_2O mixture. It can be concluded that the system using H_2O-LiBr as working fluid gives better performance than that of using NH_3-H_2O.

Keywords: absorption refrigeration, water-lithium bromide, ammonia-water, COP

1. Introduction

In recent years, the absorption refrigeration system has attracted to the researchers due to the two followings reasons. Firstly, the use of ozone-depletion refrigerants can be easily avoided and, secondly, this system can be powered by waste thermal energy, solar energy, geothermal energy or renewable energies. It means that both the electricity demand and the dependency on fossil fuel can be reduced significantly. At the same time the negative impact of conventional energy utilization on environmental aspect can also be decelerated. Many theoretical and experimental researches for developing alternative refrigeration system and finding the better refrigerants applicable for the vapor absorption refrigeration system, such as carbon tetrachloride, methyl chloroform, hydro-chlorofluorocarbons (HCFs), and methyl bromide have been conducted. Vapor absorption refrigeration system is one of the developed systems that can use natural refrigerants which are classified into environment-friendly refrigerant.

The basic thermal principle of the vapor absorption refrigeration system (VARS) is similar with the vapor compression refrigeration system (VCRS). But they have the difference of compressing the refrigerant. A unit consists of absorber, generator, pump, heat exchanger and pressure reducing valve in the absorption refrigeration system replaces the compressor function on vapor compression system.

Due to the possibility of this VARS powered by low temperature heat source, this system can be applied in automotive system where the exhaust gas and/or engine cooling water could be used as main heat source. In the tropical countries where solar energy is available more intensively than other countries, this system could also be applied in combination with solar water heater. It is the aim of this study to simulate thermodynamic performance of absorption refrigeration cycle powered by low temperature heat source with two different refrigerants such as H_2O-LiBr and NH_3-H_2O.

2. Absorption Cycle System

Figure 1 shows the main components in the simple vapor absorption system. High-pressure zone is started since refrigerant vapor leaving from generator (1) up to the condenser. Liquid refrigerant (2) from the condenser passes into the evaporator (4) through an expansion valve (3) where its temperature drops significantly to give refrigeration effect in the evaporator. The liquid refrigerant (3) vaporizes in the evaporator by absorbing heat from the material being cooled and then low-pressure vapor (4) passes to the absorber.

The process in generator and absorber for H_2O-LiBr system are the same as NH_3-H_2O system. Since water evaporated in H_2O-LiBr mixture, the solution in the generator becomes strong solution (8). This solution flows through valve (10) into absorber. The cooling process in absorber causes water vapor from evaporator dissolves to the H_2O-LiBr mixture and the mixture becomes a weak solution. Similarly the process is occurring for NH_3-H_2O where ammonia works as absorber agent.

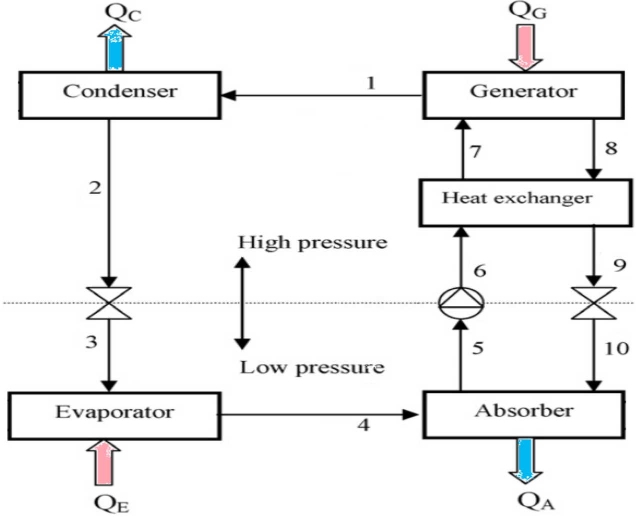

Figure 1: Schematic diagram of vapor absorption refrigeration system

The operation conditions during simulation process conducted in this study are limited and some assumptions are considered. The following assumptions are applied in the study such as hot vapor refrigerant leaving from the generator is pure refrigerant, heat transfer from the system to surrounding or vice versa is neglected. Operating temperature at the generator, condenser and absorber are varied respectively from 60°C to 90°C, 20°C to 40°C and from 2.5°C up to 12.5°C. The different between liquid temperature leaving from the absorber and the generator temperature is assumed around 15°C. The hot liquid temperature leaving from the generator entering into the absorber is 10°C higher than the absorber temperature. Other data and assumptions taken for simulation include:

- mass flow rate of refrigerant is 1.0 kg/s;
- effectiveness of heat exchanger is taken equal to 0.9 and
- isentropic efficiency of pump is assumed equal to 0.7

3. Calculation Procedure

Mass and energy conservation equations are used in the thermodynamic analysis and applied for each component of the cycle. The mass and energy balances for the generator has been derived and the results are given in Eqs. (1) – (4) [1]:

$$\dot{m}_7 = \dot{m}_1 + \dot{m}_8 \Leftrightarrow \dot{m}_{ws} = \dot{m}_{ref} + \dot{m}_{ss} \text{ (LiBr-H}_2\text{O)} \qquad (1)$$

$$\dot{m}_7 = \dot{m}_1 + \dot{m}_8 \Leftrightarrow \dot{m}_{ss} = \dot{m}_{ref} + \dot{m}_{ws} \text{ (NH}_3\text{-H}_2\text{O)} \qquad (2)$$

$$\dot{m}_7 X_7 = \dot{m}_1 X_1 + \dot{m}_8 X_8 \qquad (3)$$

$$Q_{gen} = \dot{m}_1 h_1 + \dot{m}_8 h_8 - \dot{m}_7 h_7 \qquad (4)$$

Flow rates of the strong and weak solutions can be determined by Eq. (5)

$$\dot{m}_8 X_8 = \dot{m}_7 X_7 \qquad (5)$$

The energy balance for the solution heat exchanger is determined by these following Eqs. (6) – (7).

$$Q_{HE} = \eta_{HE} \dot{m}_8 (h_8 - h_9) \qquad (6)$$

$$h_6 = h_7 - \frac{Q_{HE}}{\dot{m}_7} \qquad (7)$$

The energy increase by pumping is:

$$W_{pum,s} = \frac{m_6 (h_{6s} - h_5)}{\eta_{pump}} \cong \frac{m_6 v_6 (P_6 - P_5)}{\eta_{pump}} \qquad (8)$$

Finally, energy balances for the absorber, condenser and evaporator can be written in Eqs. (9) - (10).

$$Q_{abs} = \dot{m}_4 h_4 + \dot{m}_{10} h_{10} - \dot{m}_5 h_5 \qquad (9)$$

$$Q_{con} = \dot{m}_1 (h_1 - h_2) \qquad (10)$$

$$Q_{eva} = \dot{m}_1 (h_4 - h_3) \qquad (11)$$

COP of the system is calculated in accordance with a common definition as written in Eq. (12).

$$COP = \frac{Q_{eva}}{Q_{gen} + W_{Pump}} \qquad (12)$$

The evaluation of thermodynamic properties of the binary mixture as working fluid in VARS is based on the following explanation. The units in the next empirical equations are referred to the citation papers.

Water-Lithium Bromide Properties

The H_2O-LiBr refrigeration system can not operate in temperature less than 0°C because water works as refrigerant while LiBr is the absorbent [6], so that the water will freeze at 0°C. If the concentration of solution is more than 0.7 kg LiBr/kg, the liquid solution will be crystallized; the weak solutions from the absorber go up to the generator by pump or thermo pump, while the strong solutions go down from the generator to the absorber gravitationally. The concentration of LiBr can be found from these following correlations [4]:

$$X_{ss} = \frac{49.04 + 1.125 T_{gen} - T_{con}}{134.65 + 0.47 T_{gen}} \qquad \text{kg LiBr/kg solution}$$

$$X_{ws} = \frac{49.04 + 1.125 T_{abs} - T_{eva}}{134.65 + 0.47 T_{abs}} \qquad \text{kg LiBr/kg solution}$$

When concentration of LiBr in the solution X and temperature are known, enthalpy of LiBr solution can be calculated using Eq. (13) [2].

$$h_{liq}(T, X_a) = \sum_{i=0}^{5} \sum_{i=0}^{2} a_{ij} X_a^i T^j \qquad (13)$$

The refrigerant in the H_2O-LiBr system is water, the relations between enthalpies and temperatures are given in specific mathematical form. Enthalpy for saturated liquid state is evaluated in accordance with

Eq. (14) [6].

$$h_{liq}(T) = 4.19(T - T_{ref}) \qquad (14)$$

Where T_{ref} is the reference temperature.

Enthalpy of the saturated vapor state is evaluated in accordance with Eq. (15) [2].

$$h_{vap}(T) = 2099.3\left(1 + b_1 T_R^{\frac{1}{3}} + b_2 T_R^{\frac{5}{6}} + b_3 T_R^{\frac{7}{8}} + \sum_{i=4}^{8} b_i T_R^{i-3}\right) \qquad (15)$$

$$T_R = \frac{647.3 - T}{647.3} \qquad (16)$$

Ammonia-Water Properties

Ammonia works as a refrigerant and water works as the absorbent in the NH_3-H_2O system. Weak solutions from the generator go down to the absorber, while the strong solutions go up from the absorber to the generator by pump or thermo pump. Concentration of NH_3-H_2O can be found from referring to equation or figure [5]. The relation between the saturation pressure, solution temperature and concentration of ammonia X in the solution is given as Eq. (17) [2]:

$$\log P = A - \frac{B}{T} \qquad (17)$$

with

$$A = 7.44 - 1.767X + 0.9823X^2 + 0.3627X^3$$
$$B = 2013.8 - 2155.7X + 1540.9X^2 + 194.7X^3$$

Temperature of NH_3-H_2O mixture can be determined when pressure and mole fraction of liquid phase are known. The relation is given in Eq. (18). Based on this temperature, enthalpy of saturated liquid can be calculated in accordance with Eq. (19).

$$T_{liq}(P,\overline{X}) = 100\sum_{i=1}^{14} a_i \left(1-\overline{X}\right)^{mi}\left[\ln\left(\frac{2000}{P}\right)\right]^{ni} \qquad (18)$$

$$h_{liq}(T,\overline{X}) = 100\sum_{i=1}^{16} a_i \left(\frac{T}{273.16}-1\right)^{mi}\overline{X}^{ni} \qquad (19)$$

The relation between the ammonia mole fraction and mass fraction is given in Eq. (20).

$$\overline{X} = \frac{17.03X}{17.03X + 18.015\left(1-X\right)} \qquad (20)$$

4. Result and Analysis

Based on evaluation procedure and properties evaluation as mentioned in the previous section, several study parameters were conducted during simulation process. Operating conditions limited by environment that normally used in VARS application are concerned in this research.

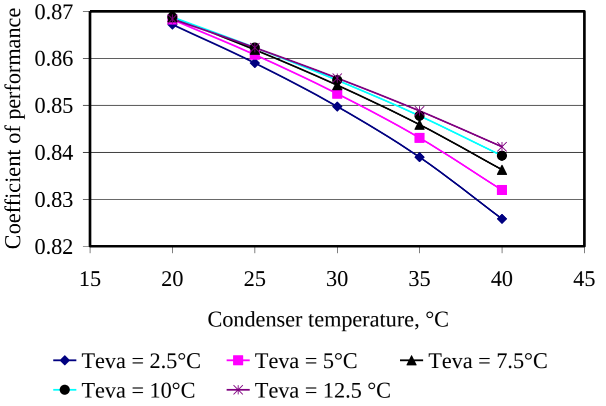

Figure 2: COP characteristics of H_2O-LiBr with respect to condenser temperature at generator temperature of 90°C and absorber temperature of 20°C

Performance of VARS with NH_3-H_2O and H_2O-LiBr is compared and the results are shown Figs. 2 and 3. These comparisons of COP characteristic are obtained for the condenser temperature at 90°C, the evaporator temperature varied from 2.5^{o}C to 12.5^{o}C, and constant absorber temperature at 20°C. When higher condenser temperature and lower evaporator temperature, COP of the system will decrease. Decreasing of condenser temperature and increasing of evaporator temperature cause COP of the VARS increasing.

As shown in Fig. 2 for H_2O-LiBr system, when the condenser temperature is at 20°C, COP is not significantly affected by the evaporator temperature. COP of the system varies from 0.8139 up to 0.8746. Higher condenser temperature will cause COP of the system decreasing.
On the other hand, Fig. 3 shows the result for the performance of the system at the same variation operating condition using NH_3-H_2O. It seems that COP will increase when condenser temperature decreases and evaporator temperature increases. The COP of this NH_3-H_2O can reaches from 0.4905 to 0.5846.

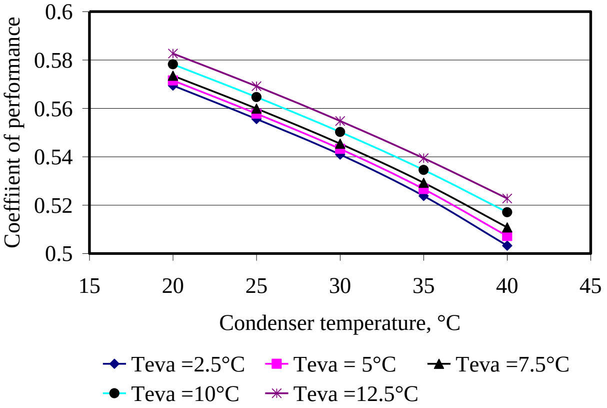

Figure 3: COP characteristics of NH_3-H_2O with respect to condenser temperature at the generator temperature of 90°C and the absorber temperature of 20°

Next two figures, Figs. 3 and 4 show the comparison of the effect of absorber and evaporator temperature on COP. These figures are obtained for the generator temperature maintained at the same condition as mentioned in Figs. 2 and 3 with the variation of the evaporator and the absorber temperatures. The evaporator and absorber temperatures vary from 2.5^{o}C to 12.5^{o}C and 20°C to 40°C, respectively. When absorber and condenser temperatures are low, COP of the VARS increases. Fig. 4 shows for VARS with H_2O-LiBr. It can be seen that COP can reach from 0.7346 up to 0.8714. At the same simulation parameter conditions using NH_3-H_2O, Fig. 5 shows that COP can vary from 0.4386 to 0.5686.

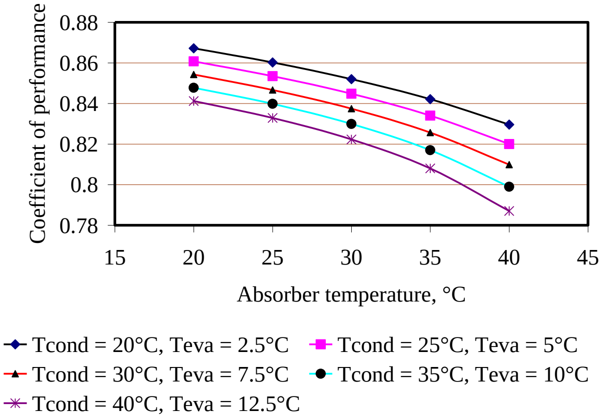

Figure 4: COP characteristics of H_2O-LiBr with respect to absorber temperatures at the generator temperature 90°C

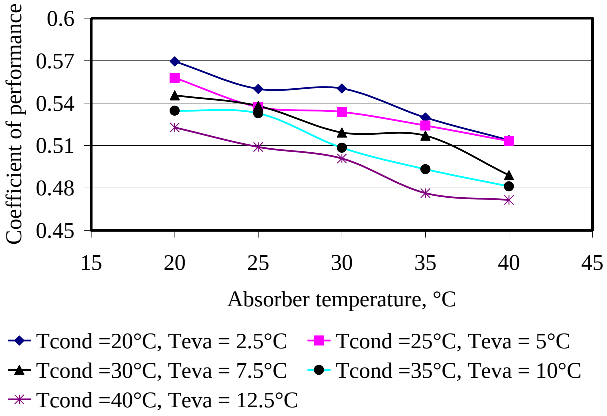

Figure 5: COP characteristics of NH_3-H_2O with respect to absorber temperatures at the generator temperature 90°C

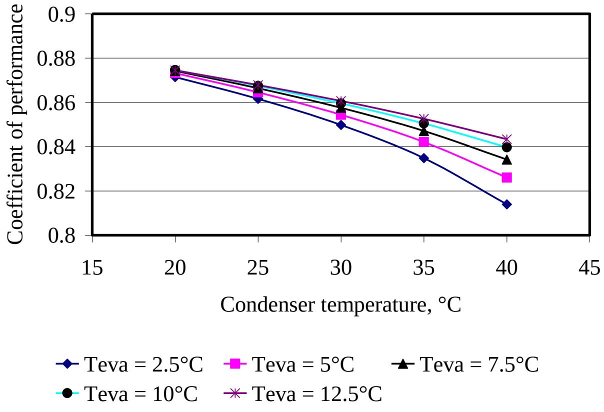

Figure 6: COP characteristics of H_2O-LiBr with respect to condenser temperatures at the generator temperature 80°C and the absorber temperature 20°C

As indicated in Figs. 2 and 3, when generator temperature is higher, COP of the system is also higher. Using lower generator temperature of 80^{o}C with the same other operating conditions, the simulation results of COP characteristic are shown in Figs. 6 and 7 for H_2O-LiBr and NH_3-H_2O systems, respectively. The same behaviors are obtained, but the values of COP are lower at this lower generator temperature.

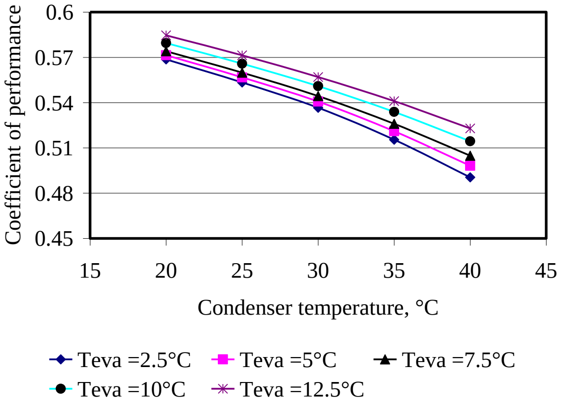

Figure 7: COP characteristics of NH_3-H_2O with respect to condenser temperatures at the generator temperature of 80°C and the absorber temperature of 20°C

Figs. 8 and 9 show the COP characteristics for varied absorber temperature at generator temperature of 80^{o}C. Other parameters are maintained at the same conditions as indicated in Figs. 4 and 5.

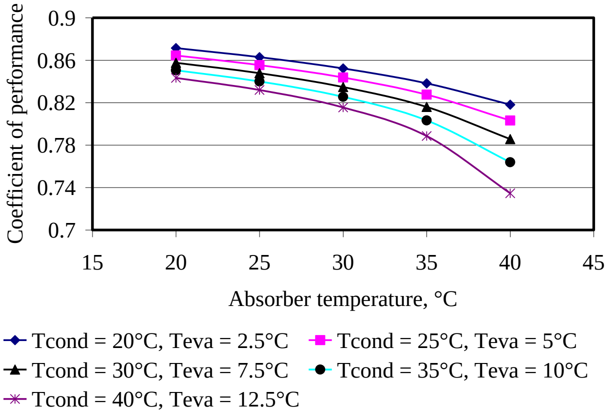

Figure 8: COP characteristics of H_2O-LiBr with respect to absorber temperatures at the generator temperature 80°C

As shown in Fig. 8, when it is compared to the results presented in Fig. 4, the COP at these conditions is higher. Contrary, as shown in Fig. 9, COP of the system becomes lower than that resulted in Fig. 5. As shown in the Figs. 8 and 9, COP of H_2O-LiBr can be performed in the range of 0.7346 to 0.8714, while the values of the COP for NH_3-H_2O are in the range of 0.4386 and 0.5686.

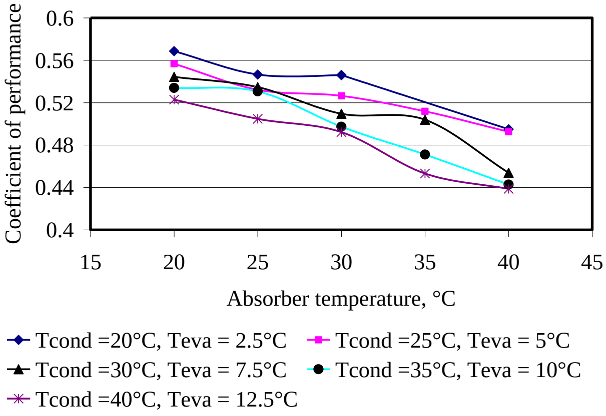

Figure 9: COP characteristics of NH_3-H_2O with respect to absorber temperatures at the generator temperature 80°C

Influence of condenser and evaporator temperatures in COP of the H_2O-LiBr system for constant generator temperature at 70^oC is shown in Fig. 10. Characteristics of COP are influenced by condenser and evaporator temperatures. In case of lower condenser temperature, evaporator temperature does not significantly affect on the COP. In contrary, the variation of evaporator operating temperature will significantly influence in the COP. Higher evaporator temperature will give higher COP of the system. With the evaporator temperature considered at 2.5°C and the absorber temperature at 20°C, the studied system performs of around 0.7616 until 0.8803. It seems that these COP values are lower than that if the temperature of generator is higher than 80^oC.

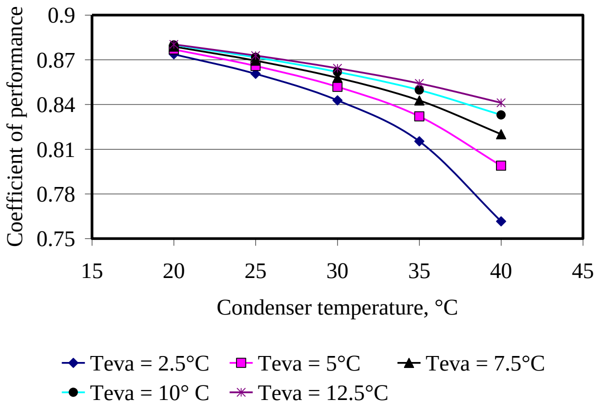

Figure 10: COP characteristics of H_2O-LiBr with respect to condenser temperature at the generator temperature of 70°C and the absorber temperature 20°C

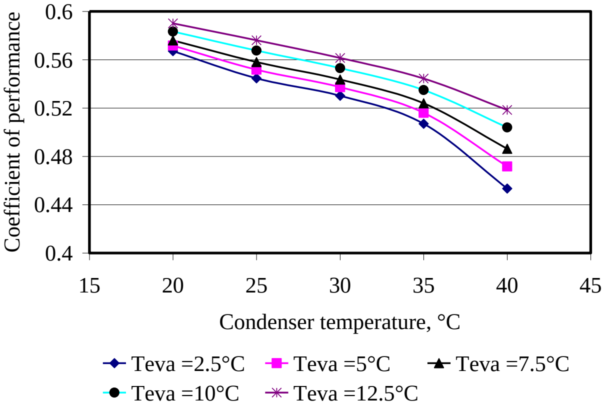

Figure 11: COP characteristics of NH_3-H_2O with respect to condenser temperature at the generator temperature of 70°C and the absorber temperature of 20°C

The same conditions as previous simulation parameters are implemented for NH_3-H_2O system. Detail results are shown in Fig. 11. COP of the NH_3-H_2O system can reach 0.4533 up to 0.5900 depending on evaporator and condenser temperatures.

Fig. 12 shows comparison of COP affected by absorber temperature in which the generator temperature is maintained at 70°C while the other conditions are kept equal to the previous data. Higher condenser temperature and lower evaporator temperatures cause COP of the system to be lower. Some conditions may not work in the system due to concentration of the weak solution is higher than strong solution either for H_2O-LiBr solution and NH_3-H_2O system. As shown in Figs. 12 and 13, the H_2O-LiBr system performs COP ranging between 0.3863 and 08737 while the COP of NH_3-H_2O system reaches 0.2829 to 0.5671.

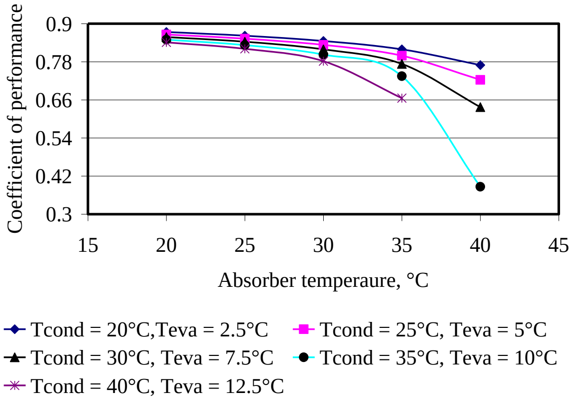

Figure 12: COP characteristics of H_2O-LiBr with respect to absorber temperatures at the generator temperature of 70°C

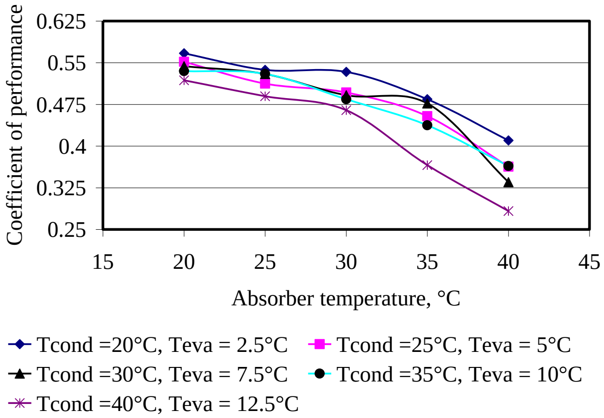

Figure 13: Comparison of the effect of COP of NH_3-H_2O on absorber temperatures at generator temperature 70°C

The generator temperatures are extended to 50^oC in order to get more information of the trend on performance characteristics of these two studied working fluid for VARS. The influence of generator temperature on COP characteristics is especially shown in Figs. 14 to17.

Effect of generator temperatures ranging from 50^oC to 90^oC on COP characteristics are summarized in four last figures, Figs. 14 to 17. Other conditions are maintained at the same values as the previous operating conditions. Higher generator temperature and both lower condenser and absorber temperatures give higher COP. However, at the conditions where the generator temperature is lower while both condenser and absorber temperatures are higher, the system provides lower values of the COP. H_2O-LiBr COP values are obtained in range of 0.685 and 0.873, NH_3-H_2O COP values are in range of 0.228 and 0.569. Detail simulation results showing effect of generator temperatures on COP are given in Figs. 14 to 17.

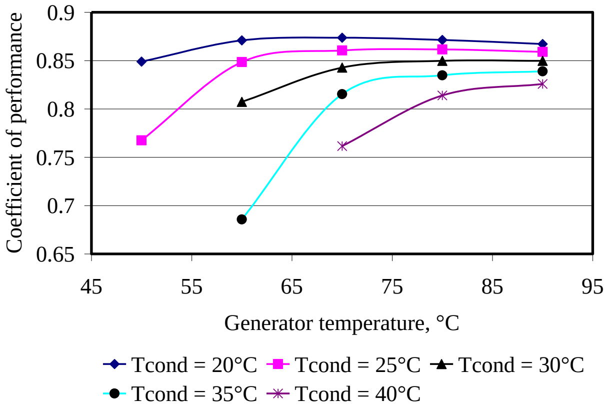

Figure 14: COP characteristics of H_2O-LiBr with respect to generator temperatures at the absorber temperature of 20°C and the evaporator temperature of 2.5°C

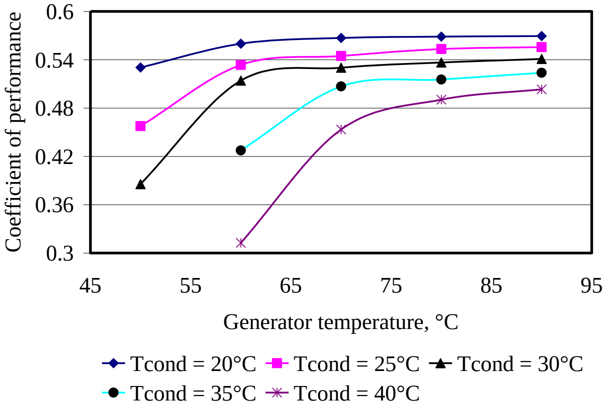

Figure 15: COP characteristics of NH_3-H_2O with respect to generator temperatures at the absorber temperature = 20°C and the evaporator temperature = 2.5°C

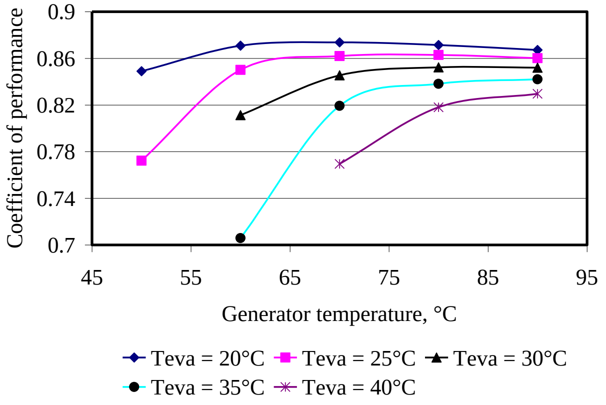

Figure 16: COP characteristics of H_2O-LiBr with respect to generator temperatures at the condenser temperature of 20°C and the evaporator temperature of 2.5°C

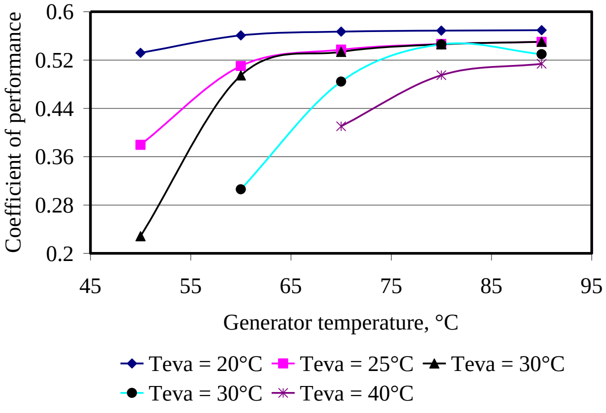

Figure 17: COP characteristics of NH_3-H_2O with respect to generator temperatures at the condenser temperature of 20°C and evaporator temperature of 2.5°C

5. Discussion and Application Opportunity

Based on the simulation results as presented previously, the range of generator temperatures that support the operation of VARS using LiBr-H_2O working fluid are suggested. At condition the evaporator temperature of 2.5°C, the generator temperature should be at least 70°C. However if the evaporator temperature at the range of 5°C to 7.5°C could be accepted, the system can be operated with the generator temperature higher than 60°C. In the case of the evaporator temperature ranging from 10°C to 12.5°C, the system could be operated even when the generator temperature at 50°C or more. In the case of VARS using NH_3-H_2O system, at the conditions where the evaporator temperatures are ranging from 2.5°C to 5°C, the system can be supported normally by the generator temperature of 90°C or more. However if the evaporator temperature are ranging from 7.5°C to 10°C, the generator temperature of 60°C or more could be considered to operate the system. In the case where the evaporator temperature of 12.5°C could be accepted, the system can be operated with the generator temperature of 50°C or more.

It should be noted that in the case where the generator temperatures ranging between 60^oC and 90°C, the COP of VARS using LiBr-H_2O are normally higher than that reached by using NH_3-H_2O. In order to increase the COP of VARS using NH_3-H_2O as working fluid, the system should be operated with the higher generator temperature up to 200°C. It seems that for VARS using LiBr-H_2O as working fluid can be operated with reasonable COP value by generator temperature of about 100°C or lower, which is still acceptable if the system is powered by solar energy or exhaust gas from automobile. Unfortunately, VARS needs large space for installation due to the size of required equipments that are normally bigger than vapor compression system. It is reason why VARS is not convenient to be applied in automobile systems. However this system is still reasonable to be applied for building air conditioning powered by solar energy or exhaust gas from boiler system in the case of hotels or hospitals.

For the tropical climate, the application of studied system is limited by the temperature of ambient for cooling condenser. Normally the operation temperature of condenser should be at least 10^oC higher than ambient temperature. Based on the presented simulation results the condenser temperature higher than 35^oC is seemly still reasonable to apply in tropical climate countries.

6. Conclusion

In order to analyze and optimize the water-lithium bromide and NH_3-H_2O absorption systems, a mathematical model describing the cycle together with equations for calculating the thermodynamic properties of the H_2O-LiBr and NH_3-H_2O binary mixtures based on correlations proposed by Fathi and Quaskit [4] was applied. With the operation conditions varies within the consideration condition that could be supported by exhaust hot gas and solar energy as heat source for operating the system, the simulation results of considered VARS show that for H_2O-LiBr mixture as working fluid gives the values of COP of around 0.386 until 0.885 while for NH_3-H_2O mixture the COP can reach 0.282 up to 0.597. The application of the studied system for domestic or buildings air conditioning powered by solar energy or exhaust gas from boilers is still widely opened especially for LiBr-H2O as working fluid. VARS using NH_3-H_2O as working fluid is more suitable for industrial air conditioning application due to the higher temperature heat source requirement.

Notation

COP	Coefficient of performance
h	Enthalpy, kJ/kg
P	Pressure , kPa
Q	Thermal energy, kJ
X	Concentration of solution, %
T	Temperature, °C
$\dot{m}$	Mass flow rate, kg/s
η_{HE}	Effectiveness of heat exchanger
η_{pump}	Isentropic efficiency of pump

Subscripts

abs	Absorber, absorbent
cond	Condenser
eva	Evaporator
gen	Generator
pump	Pump
HE	Heat exchanger
liq	Liquid phase
vap	Vapor phase
ref	Refrigerant
ss	Strong solution refrigerant
ws	Weak solution refrigerant

Acknowledgements

Thank to AUN/Seed-net scholarship for the opportunity to present this papers in 8th Indonesian Annual National Seminar on Mechanical Engineering.

References

1. Sun, Da-Wen, Computer Simulation and Optimization of Ammonia-Water Absorption Refrigeration Systems, *Energy Sources*, 19(7), 4-6, 1997

2. Sun, Da-Wen, Thermodynamic Design Data and Option, *Applied Thermal Engineering*, 17(3), 21l-221, 1997.

3. Lansing, F.L, Computer Modeling of a Single-Stage lithium bromide-water absorption refrigeration unit, *JPL Deep space network progress report*, 42-32

4. Fathi, R., and Ouaskit, S., Performance of a Solar LiBr - water Absorption Refrigerating Systems, *Rev. Energ. Ren. Journées de Thermique*, 73-78, 2001.

5. http://www.mrc-eng.com/Downloads/NH3&H2O%20 Props%20English.pdf,

6. http://nptel.iitm.ac.in/courses/Webcourse-contents/IIT%20Kharagpur/Ref%20and%20Air%20Cond/pdf/RAC%20Lecture%2015.pdf, p 6

7. http://nptel.iitm.ac.in/courses/Webcourse-contents/IIT%20Kharagpur/Ref%20and%20Air%20Cond/pdf/R&AC%20Lecture%2016.pdf,
8. Abdulateef, J.M., Sopian, K., Alghoul, M.A., Sulaiman, M.Y., Zaharim, A., and Ahmad, I., Solar Absorption Refrigeration System Using New Working Fluid Pairs

9. Kaynakli, O., and Yamankaradeniz, R., Thermo-dynamic Analysis of Absorption Refrigeration System based on Entropy Generation, *Current Science*, 92(4), 472-479, 2007

10. Bula, J.A., Herrera, D.L., Navarro, L.F., and Corredor, L.A., Thermodynamic Simulation of Solar Absorption Refrigeration System Generator-Heat Exchanger

11. He, Y., Hong, R., and Chen, G., Heat Driven Refrigeration Cycle at Low Temperatures, *Chinese Science Bulletin*, 50(5), 485—489, 2005

12. Kaita, Y, Thermodynamic Properties Lithium Bromide-Water Solutions at High Temperature, Int. J. of Refrigeration, 24, 374-390, 2001

13. Kilic, M., and Kaynakli, O., Second Law-Based Thermodynamic Analysis of Water-Lithium Bromide Absorption Refrigeration System, *Energy*, 32, 1505–1512, 2007

14. ASHRAE, Refrigerant properties. In 2005 ASHRAE Handbook, Fundamentals, Chapter 20.