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Thermodynamic Modelling of a 10-kW Ammonia-Water Absorption Machine

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Abstract: Absorption chillers are cooling units usually powered by renewable energy or waste heat. Their performance generally depends on the temperatures of the heat source, the ambient and the medium to be cooled. The present work deals with the thermodynamic study of a 10 kW NH_3/H_2O absorption machine in order to find the COP (coefficient of performance). The first and second laws of thermodynamics were used for the operating conditions. The thermodynamic properties of the NH_3/H_2O mixture were determined using the EES (Engineering Equation Solver) software. The results of the simulation of the machine were validated with the results of the literature. After validation, the program was used to simulate a 10-kW NH_3/H_2O absorption machine for milk conservation/cold storage in northern Senegal. The simulation results of the 10-kW ammonia-water absorption machine give an acceptable COP of 0.521 with a milk storage temperature of 4 ℃.

Key words: Absorption, ammonia-water, COP, EES.

Nomenclature

COP	Coefficient of performance
h	Specific enthalpy (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{n}$	Molar flux (mol.m^{-2}.s^{-1})
P	Pressure (kPa)
$\dot{Q}$	Exchanged heat flux (kW)
S	Specific entropy (kJ/kg.K)
$\dot{S}$	Entropy generated (kW/K)
T	Temperature (℃ (ou K))
U	Internal energy (kJ/kg)
v	Specific volume (m^3/kg)
$\dot{W}$	Pump power (kW)
x	Mass fraction
X	Ammonia molar concentration

Indices

A	Absorber
C	Condenser
D1	Expansion valve 1
D2	Expansion valve 2
E	Evaporator
G	Generator
P	Pump
P	Rectifier
SHX	Solution heat exchanger

Abbreviation

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

1. Introduction

Absorption machines are systems for producing cold (refrigeration and air conditioning). They are environmentally friendly because they use fluids that cause no or minimal depletion of the ozone layer [1-3]. These tri-thermal machines work with heat input. The most commonly used refrigerant-absorbent combinations are lithium bromide-water (H_2O-LiBr) and ammonia-water (NH_3-H_2O). The latter is most often used in refrigeration because it can reach negative temperature values and is environmentally friendly [3, 4]. Several works have been carried out on absorption machines

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using ammonia water as working fluid [3, 5-11] and the COP (coefficient of performance) is used to analyze/characterize the performance of the system. Kong et al. [3] worked on the thermodynamic and experimental analysis of a 2,814 W ammonia-water absorption machine with partial condensation. They developed a mathematical model to investigate the performance of the system and a theoretical COP of 0.424 was found. Vera-Romero and Heard-Wade [5] and Ouadha and El-Gotni [6] also carried out a thermodynamic study of an NH3/H2O absorption machine. The objective of Vera-Romero and Heard-Wade [5] was to analyze the individual and global sensitivity of the components with the help of three models. They found reasonably consistent COP values between the methods. These COPs are around 0.5. Ouadha and El-Gotni [6] examined the feasibility of using waste heat from marine diesel engines to power an NH_3/H_2O absorption machine. The effect of the solution exchanger efficiency on the COP is evaluated. Their results show that the COP increases with the exchanger efficiency. Boudéhenn et al. [7] performed a comparative study of the theoretical and experimental results of a 5-kW NH_3/H_2O absorption chiller. They concluded that the experimental results are far from the numerical results. Another study by Hmida et al. [8] led to a simulation of an NH_3/H_2O absorption chiller to evaluate the cooling capacity required for a cold storage room for food conservation in southern Tunisia. They found a COP of 0.53. Chang et al. [9] worked on a distillation tower as a regenerator to evaluate the COP of the NH_3/H_2O absorption refrigeration cycle. For this, they used a single-stage equilibrium tower with a full condenser and a fixed-bed tower with a partial condenser. Their conclusion was that distillation towers increase the COP. One other study by Rashidi et al. [10] was on an NH_3/H_2O absorption machine for a decentralized trigeneration system. The simulation of the machine and the thermodynamic properties were obtained using the EES (Engineering Equation Solver) software. As result, their COP reached 0.8346 for one cycle. Mansouri et al. [11] simulated the performance of a 3-ton NH_3/H_2O absorption chiller in steady state using Aspen Plus software. They resulted in a COP that agrees with the experimental outcomes of Klein [12] and the simulation results of El May et al. [13]. Keith et al. [14] calculated the performance of a single-acting NH_3/H_2O absorption chiller (example 9.2 in the book) and found a COP of 0.549. By considering these studies in the literature, our purpose in this work is to evaluate the thermodynamic properties and the COP of a 10-kW NH_3/H_2O absorption machine for milk conservation/cold storage in northern Senegal.

2. Materials and Methods

2.1 System Description

The absorption machine is a hermetically sealed unit consisting of different elements through which the NH_3/H_2O fluid flows. Fig. 1 shows the arrangement of a conventional ammonia-water absorption machine.

2.2 Thermodynamic Analysis

The analysis of the theoretical performance of an ammonia-water absorption refrigeration system is complex due to the equations of the thermodynamic properties of the working fluid and the simulation programs. The thermodynamic properties of the NH_3/H_2O mixture are interdependent/linked together and are necessary for the simulation of absorption refrigeration machines. Some properties are obtained from the refrigerant and others from the binary mixture. For each of the components of the elementary machine presented (Fig. 1), the mass, energy, and entropy balances summarized are given in Table 1.

The COP of the absorption machine is given by Eq. (1).

$$COP = \frac{Q_E}{Q_G + W_P} \tag{1}$$

To study the absorption refrigeration machine, assumptions must be made that have to be taken into account for an appropriate approach. These assumptions, taken from ASHRAE [15], are stated as follows:

- The temperatures in the components (boiler, condenser, evaporator, and absorber) are uniform throughout the considered volume;
- The mixture at the outlet of the absorber and the boiler is in a saturated state. Their respective temperatures and concentrations are at equilibrium values corresponding to the pressure in these exchangers;
- The refrigerant leaving the evaporator and condenser is in a saturated state;
- The transformation through the pump is isenthalpic;
- Heat exchange with the environment and pressure drops are assumed to be negligible;
- The boiler and the condenser are at the same pressure;
- The absorber and evaporator are at the same pressure.

2.3 Methodology

To develop the mathematical model, the laws of mass, concentration and conservation of energy (first and second laws of thermodynamics) were applied for each component of the cycle. The indices of the different properties are the relationships with the locations shown in Fig. 1. The model of the single-acting NH_3/H_2O absorption machine is implemented in the EES software [16] and the thermodynamic properties of the NH_3/H_2O mixture were found using the EES software. The calculation of the thermodynamic properties of the different points of the cycle is done in EES using the flowchart in Fig. 2.

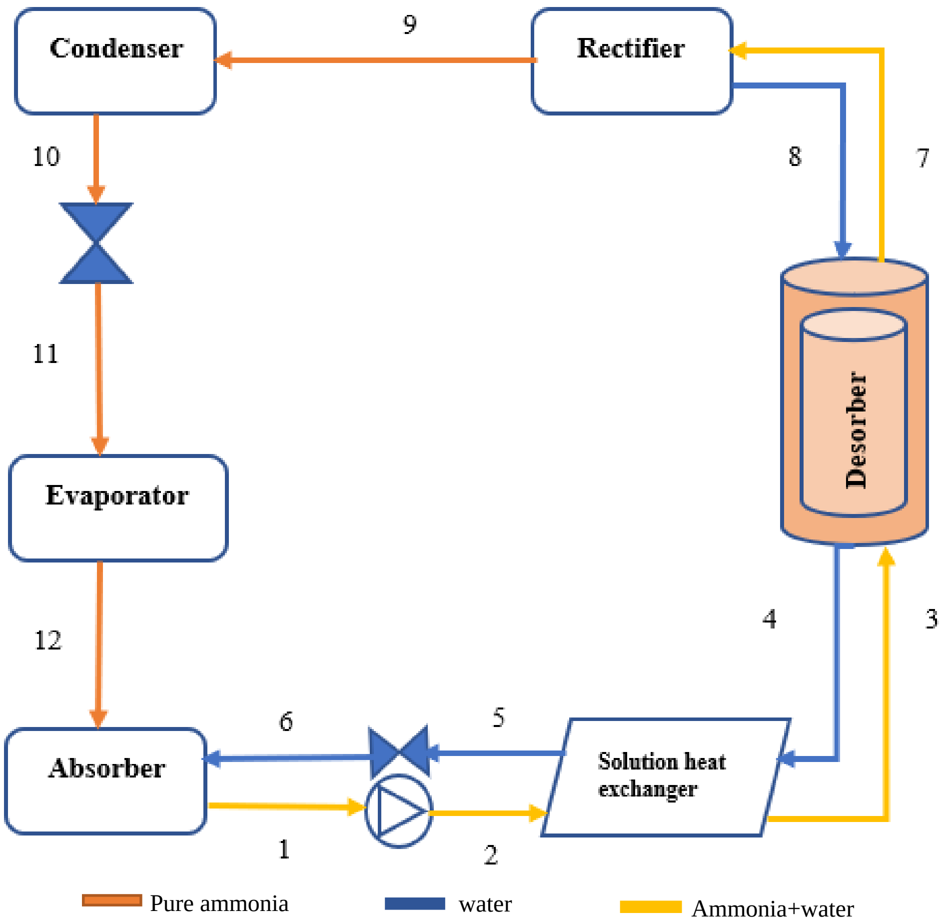


Fig. 1 Ammonia-water absorption machine.

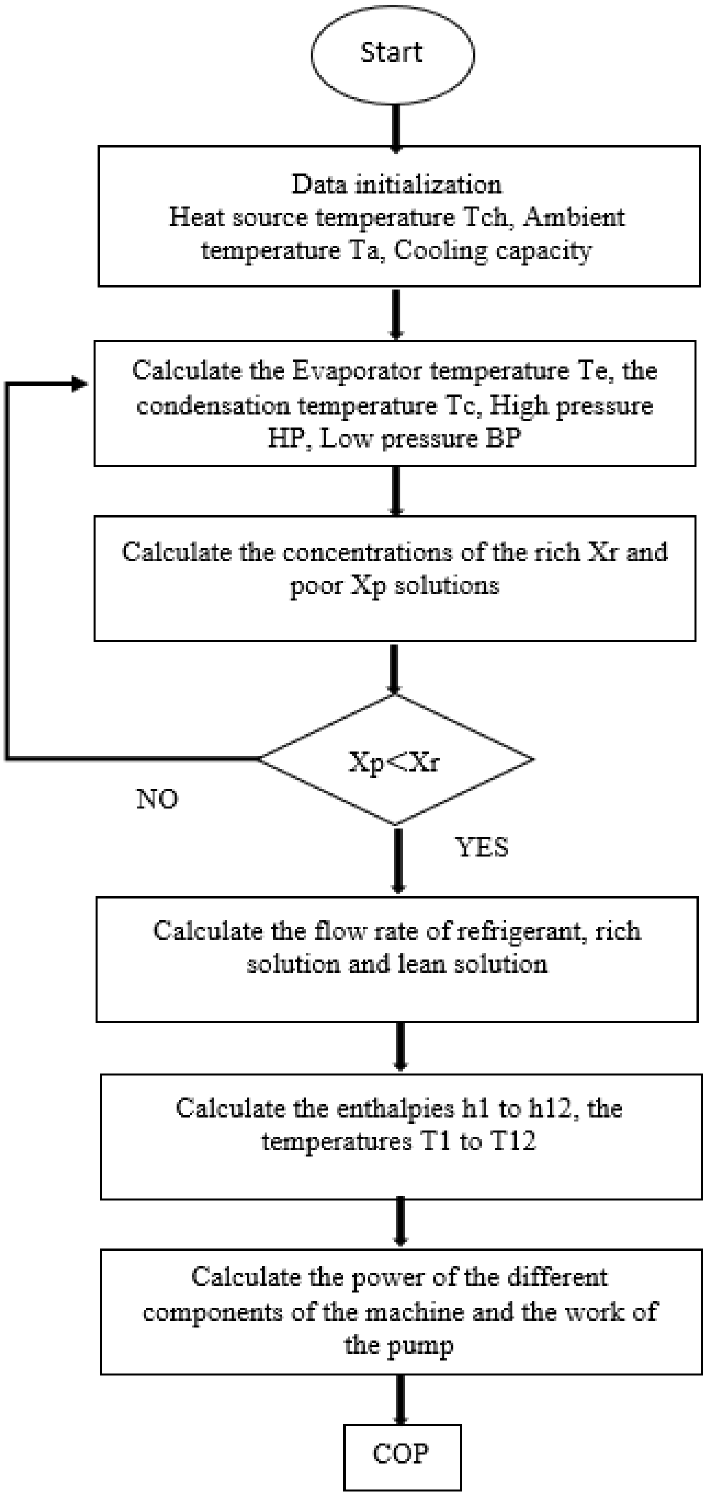


Fig. 2 Simulation flowchart in EES.

Table 1 Expressions of balances.

Components	Mass balance of the mixture	Refrigerant mass balance	Energy balance	Entropy balance
Generator	$\dot{m}_3 + \dot{m}_8 = \dot{m}_4 + \dot{m}_7$	$\dot{m}_3 X_3 + \dot{m}_8 X_8 = \dot{m}_4 X_4 + \dot{m}_7 X_7$	$\dot{Q}_G = \dot{m}_4 h_4 + \dot{m}_7 h_7 - \dot{m}_3 h_3 - \dot{m}_8 h_8$	$\dot{S}_G = \dot{m}_4 s_4 + \dot{m}_7 s_7 - \dot{m}_3 s_3 - \dot{m}_8 s_8 - \frac{\dot{Q}_G}{\dot{T}_G}$
Rectifier	$\dot{m}_8 + \dot{m}_9 = \dot{m}_7$	$\dot{m}_8 X_8 + \dot{m}_9 X_9 = \dot{m}_7 X_7$	$\dot{Q}_R = \dot{m}_7 h_7 - \dot{m}_8 h_8 - \dot{m}_9 h_9$	$\dot{S}_R = \dot{m}_9 s_9 + \dot{m}_8 s_8 - \dot{m}_7 s_7 + \frac{\dot{Q}_R}{T_R}$
Condenser	$\dot{m}_{10} = \dot{m}_9$	$\dot{m}_9 X_9 = \dot{m}_{10} X_{10}$	$\dot{Q}_C = \dot{m}_9 h_9 - \dot{m}_{10} h_{10}$	$\dot{S}_C = \dot{m}_{10} s_{10} - \dot{m}_9 s_{10} + \frac{\dot{Q}_C}{\dot{T}_C}$
Evaporator	$\dot{m}_{11} = \dot{m}_{12}$	$\dot{m}_{11} X_{11} = \dot{m}_{12} X_{12}$	$\dot{Q}_E = \dot{m}_{12} h_{12} - \dot{m}_{11} h_{11}$	$\dot{S}_E = \dot{m}_{12} s_{12} - \dot{m}_{11} s_{11} - \frac{\dot{Q}_E}{T_E}$
Absorber	$\dot{m}_6 + \dot{m}_{12} = \dot{m}_1$	$\dot{m}_6 X_6 + \dot{m}_{12} X_{12} = \dot{m}_1 X_1$	$\dot{Q}_A = \dot{m}_{12} h_{12} + \dot{m}_6 h_6 - \dot{m}_1 h_1$	$\dot{S}_A = \dot{m}_1 s_1 - \dot{m}_6 s_6 - \dot{m}_{12} s_{12} + \frac{\dot{Q}_A}{T_A}$
Solution heat exchanger	$\dot{m}_2 + \dot{m}_4 = \dot{m}_3 + \dot{m}_5$		$\dot{Q}_{ES} = \dot{m}_3 h_3 + \dot{m}_5 h_5 - \dot{m}_2 h_2 - \dot{m}_4 h_4$	
Pump	$\dot{m}_1 = \dot{m}_2$		$\dot{W}_p = v_2 (P_2 - P_1)$	$\dot{S}_p = \dot{m}_2 s_2 - \dot{m}_1 s_1$
Expansion valve D1	$\dot{m}_5 = \dot{m}_6$	$\dot{m}_5 X_5 = \dot{m}_6 X_6$		
Expansion valve D2	$\dot{m}_{10} = \dot{m}_{11}$	$\dot{m}_{10} X_{10} = \dot{m}_{11} X_{11}$		

3. Results and Discussion

To validate our calculation model, we applied the same calculation parameters considered by Keith et al. [14] in the developed EES code. In Table 2, we compare our results of the state points of the absorption machine for the ammonia-water pair with the results by Keith et al. [14] under the same parametric conditions. In Table 3, the different powers of the components of the absorption machine and the COP reported by Keith et al. [14] are compared with the values we obtained.

The results in Tables 2 and 3 show a good agreement between our results of simulation and the values reported by Keith et al. [14]. We can easily notice that in the same conditions as Ref. [14], a better COP value is obtained in our case with the model we developed.

After the validation of the developed EES code, we proceed to the simulation of the 10-kW absorption machine for milk conservation. Tables 4 and 5 show the simulation results of the 10-kW NH_3/H_2O absorption machine.

The condensing temperature depends on the ambient temperature and affects the performance of the system as well as the evaporating temperature and the generator temperature. Fig. 3 presents the variation of the COP as a function of the generator temperature and the condensing temperature for a constant evaporating temperature. It can be seen that the COP decreases as the generator and the condensing temperatures increase. We can say that the increase of the condensation temperature, as well as the increase of the generator temperature, decreases the COP of the system, while the increase of the evaporation temperature increases the COP.

Fig. 4 shows the variation of COP with generator temperature for different condensing temperatures (a) and the variation of COP with condensing temperature (b). As shown in Fig. 3, it can be seen that the COP decreases with increasing condensing temperatures. It can be concluded that the higher the condensation temperature, the lower the COP value, so the warmer the environment of the absorption machine, the lower the COP value.

Table 2 State points of the ammonia-water absorption machine.

State	*h* (J/g)		*m* (kg/s)		*P* (kPa)		Vapor quality		*T* (℃)		*x* (kg/kg)	
	Keith et al. [14]	Our model	Keith et al. [14]	Our model	Keith et al. [14]	Our model	Keith et al. [14]	Our model	Keith et al. [14]	Our model	Keith et al. [14]	Our model
1	-42.3	-42.39	1.00	1	240.2	240.2	0	0	40.0	40.0	0.368	0.3679
2	-39.2	-39.08	1.00	1	1,555	1,555	n/a	-0.001	40.5	40.55	0.368	0.3679
3	306.8	340.8	1.00	1	1,555	1,555	0.022	0.03837	110.7	112.95	0.368	0.3679
4	401.6	400.5	0.863	0.8634	1,555	1,555	0	0	131.0	131.00	0.268	0.2679
5	0.9	1.016	0.863	0.8634	1,555	1,555	n/a	-0.001	40.5	40.55	0.268	0.2679
6	0.9	1.016	0.863	0.8634	240.2	240.2	n/a	-0.001	40.7	40.75	0.268	0.2679
7	1,547	1,547	0.150	0.150	1,555	1,555	1.00	1	108.0	107.95	0.9444	0.9444
8	264.1	263.3	0.013	0.0134	1,555	1,555	0	0	108.0	107.95	0.368	0.3679
9	1,294	1,307	0.137	0.1366	1,555	1,555	1.00	1	44.0	44.00	0.999634	0.9997
10	190.1	190.8	0.137	0.1366	1,555	1,555	0.004	0	40.0	40.00	0.999634	0.9997
11	190.1	190.8	0.137	0.1366	240.2	240.2	0.196	0.1955	-14.5	-14.55	0.999634	0.9997
12	1,264	1,262	0.137	0.1366	240.2	240.2	0.998	1	-10.0	-10.0	0.999634	0.9997

Table 3 Performance evaluation.

	f	Q_{SHX} (kW)	Q_{abs} (kW)	*r*	Q_{rect} (kW)	Q_{des} (kW)	Q_{con} (kW)	Q_{eva} (kW)	W_p (kW)	COP
Keith et al. [14]	7.31	346	216	-	51	268	151	147	3.05	0.549
My results	7.319	376.9	215.6	0.9105	50.2	245.1	152.4	146.3	3.048	0.597

Table 4 State points a 10-kW ammonia-water absorption machine.

State	*h* (kJ/kg)	*P* (bars)	*Qu*	*s* (kJ/kg)	*T* (K)	*u* (kJ/kg)	*v* (m^3/kg)	*x* (kg/kg)
1	-57.49	3.689	0	0.4478	313.2	-57.93	0.001194	0.4398
2	-54.29	15.55	-0.001	0.4535	313.7	-56.14	0.001194	0.4398
3	758.3	15.55	0.282	2.643	402.9	705.7	0.0338	0.4398
4	534.5	15.55	0	1.905	425.2	532.5	0.001235	0.1844
5	48.24	15.55	-0.001	0.5824	313.7	46.55	0.001084	0.1844
6	48.24	3.689	-0.001	0.5865	313.9	47.84	0.001084	0.1844
7	1,477	15.55	1	4.709	366.2	1,314	0.1053	0.9735
8	184.2	15.55	0	1.156	366.2	182.2	0.001283	0.4398
9	1,343	15.55	1	4.323	328.2	1203	0.09017	0.9984
10	189.8	15.54	0	0.6595	313.2	187.1	0.001731	0.9984
11	189.8	3.689	0.1631	0.7206	269.2	169.3	0.05577	0.9984
12	1,264	3.689	1	4.686	269.2	1,141	0.3339	0.9984

Table 5 Power of the components and the cop of the machine.

Parameters	Q_{SHX} (kW)	Q_{abs} (kW)	Q_{rect} (kW)	Q_{des} (kW)	Q_{con} (kW)	Q_{eva} (kW)	W_p (kW)	COP
Values	14.23	14.46	1.249	19.19	10.75	10	0.01416	0.5207

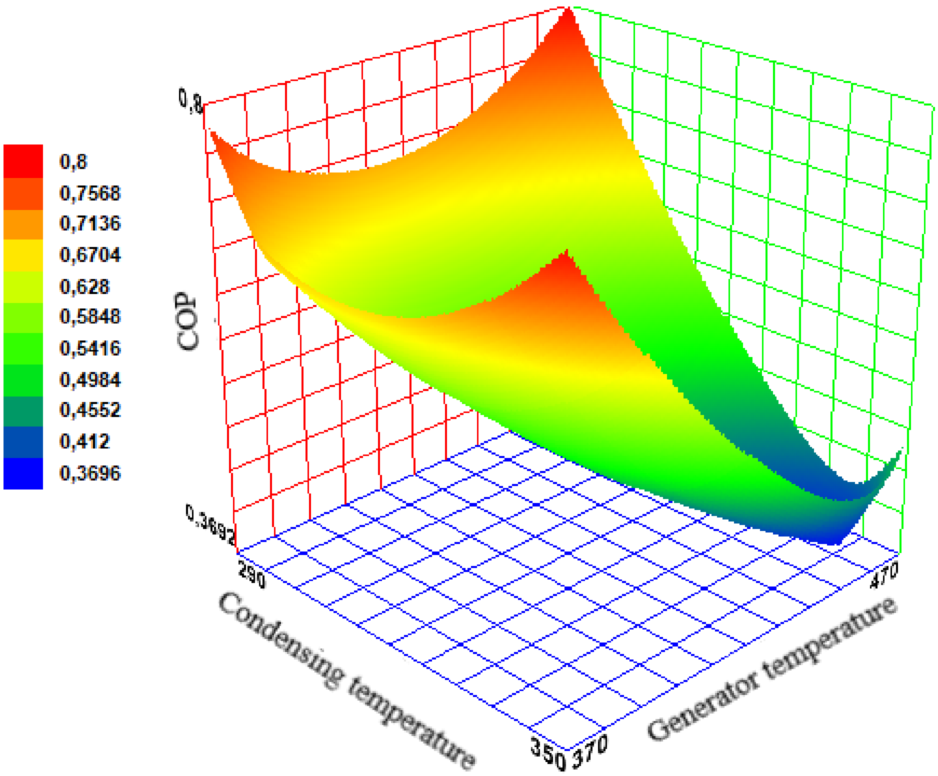
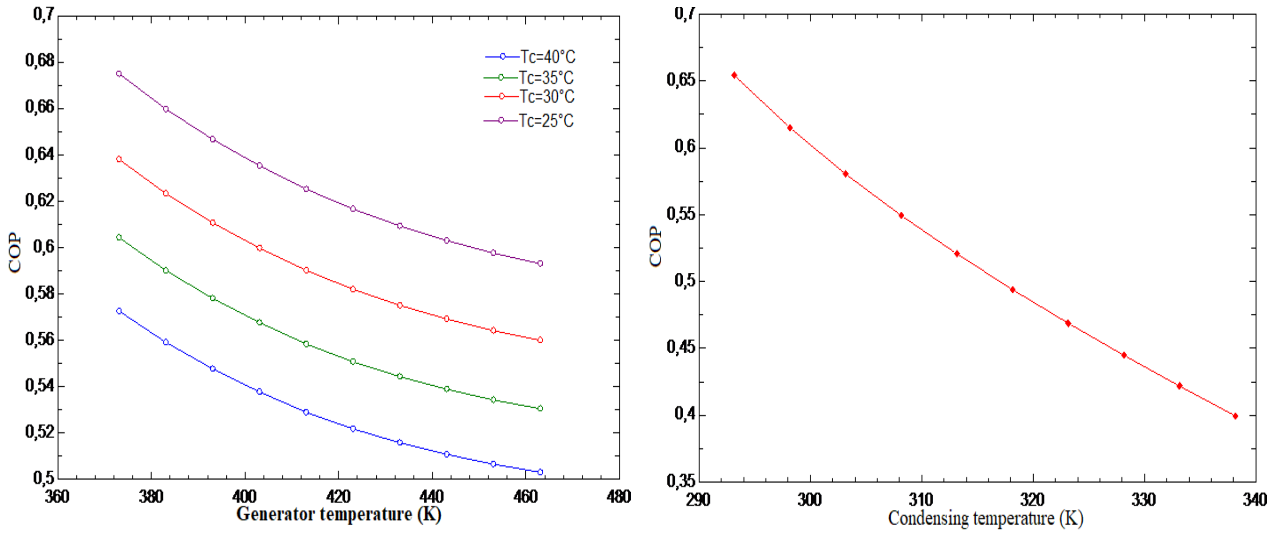


Fig. 3 COP variation as a function of generator temperature and condensation temperature.



(a) (b)

Fig. 4 (a) COP variation as a function of generator temperature for different condensing temperatures; (b) COP variation as a function of condensing temperature.

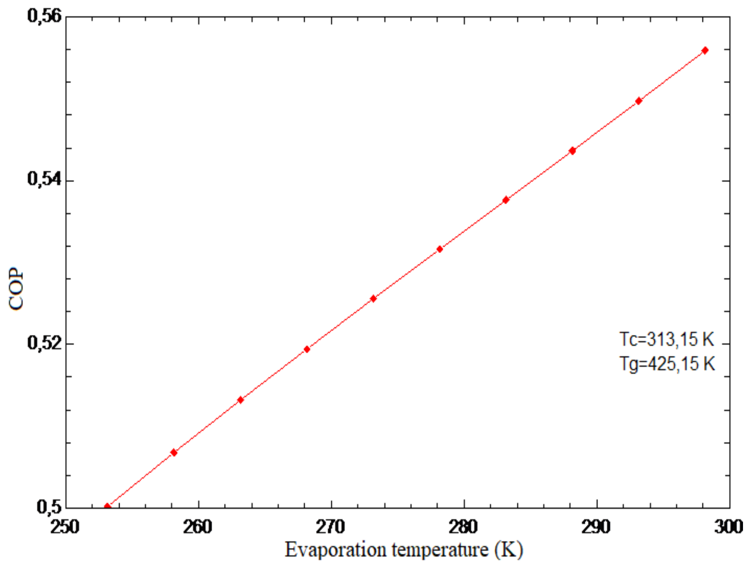


Fig. 5 Variation of COP with evaporating temperature.

Fig. 5 shows the evolution of COP as a function of evaporating temperature for a constant condensing temperature and generator temperature. The increase in evaporating temperature leads to an increase in COP, so it can be said that the evaporating temperature has a positive influence on the system performance.

4. Conclusion

The present study allowed us to carry out a thermodynamic study of a 10-kW ammonia-water absorption machine for milk conservation in northern Senegal. A program was developed and validated under EES to evaluate the COP of the system. The validation results show a good agreement with the literature results. In relation to the temperatures, we can say that it is the condensation temperature that has the most negative influence on the COP of the absorption machine. In the future, we plan to supply the ammonia-water absorption chiller with solar thermal energy, as solar energy is an important potential that can be used to operate the absorption chiller.

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