International Journal of Innovation and Applied Studies
ISSN 2028-9324 Vol. 39 No. 1 Mar. 2023, pp. 401-412

http://www.ijias.issr-journals.org/

Comparative study of the different rectifier in an ammonia-water absorption refrigeration machine

Fatimata Dione[1], Ababacar Thiam[2], Mohamed I. S. Adjibade[3], Djicknoum Diouf[1], and Amadou S. Maiga[1]

[1]LEITER, UFR-SAT, University Gaston Berger, Saint-Louis, Senegal

[2]Department of physics, University Alioune Diop, Bambey, Senegal

[3]Department of Mechanical engineering, Higher Polytechnic School, UCAD, Dakar, Senegal

ABSTRACT: This work deals with the comparative study of different rectification methods on the performance of a 10 kW NH3-H2O absorption refrigeration machine. Three types of rectifiers, namely packed columns, tray columns and partial condensation (single) columns were studied. Numerical simulation of the mathematical model of the absorption machine shows an identical COP profile for the three types of rectifiers. Modification of a 0.43 performance absorption machine previously operating with a single rectifier resulted in 7% and 11% performance improvement for tray column and packed column rectifiers, respectively.

KEYWORDS: Absorption, refrigeration machine, ammonia-water, rectifier, packed column, tray column, coefficient of performance.

1 INTRODUCTION

The most common types of cooling systems are compression and sorption systems [1]. Compression systems are the most common in industrial and domestic applications. Sorption systems consist of absorption and adsorption machines. Sorption systems differ from compression machines by the absence of mechanical parts. They use a binary sorbent/refrigerant couple. When the sorbent is a liquid, it is called an absorbent and an absorption machine, if it is a porous solid, it is called an adsorbent and an adsorption machine. In the case of an absorption refrigeration machine, the thermal coefficient of performance (COP) is between 0.5 and 0.7; that of an adsorption machine varies between 0.4 and 0.6. The performance of an absorption refrigeration system depends mainly on the chemical and thermodynamic properties of the working fluid [2]. Several working fluids have been suggested in the literature, an investigation established by Marcriss et al on fluids showed about 40 potential refrigerants and 200 absorbents [3]. The most commonly used couples are water/lithium bromide and ammonia/water. The NH3-H2O couple can be used with a temperature range of -60 °C to +20 °C. It is most often used in food preservation, chemical industry and ice rinks. The H2O-LiBr pair is more often used in air conditioning and water cooling for the chemical industry. It has a range of use between 4.5 °C and 20 °C. However, the search for new alternative and suitable fluids is still going on. Absorption refrigeration machines operate continuously, whereas adsorption systems operate intermittently. Adsorption refrigeration machines are much more used in air conditioning. In addition, at negative evaporation temperatures, absorption chillers have a better COP than adsorption chillers. In ammonia-water absorption refrigeration systems, a purification process is necessary to ensure good system performance. During this process, the water content of the vapor must be reduced to a minimum, otherwise it tends to accumulate in the evaporator and strongly deteriorates the efficiency of the system [3, 4]

Indeed, at the generator outlet, the steam still contains traces of refrigerant that must be removed to guarantee good overall performance. Several rectification methods exist. Work has been done on rectifiers in order to improve the performance of the ammonia-water absorption machine.

Several works have been carried out in order to make absorption machines very competitive. One of the essential components is the rectifier. It allows to improve the vapor of the absorbent leaving the generator. Research work has been carried out on rectification methods. The most studied are: the rectification by column with packing and by column with plates or the combination of both.

Fernandez Seara et al [5] carried out an experimental study of the effect of the reflux rate on the mass transfer performance of a packed rectifier, designed for an NH3-H2O absorption refrigeration system. For this purpose, a 0.195 m high and 0.08 m diameter column filled with Mellapak Plus 752.Y packing was used. The results show that the ammonia concentration of the rectified vapor increases with the reflux rate. Jaime Sieres et al [6] experimentally studied an NH3-H2O absorption machine using a Pall packed column with a diameter of 10 mm for different operating conditions. They determined the upper ammonia vapor concentration and different mass transfer performance parameters for each set of experimental data. They conclude that by increasing the reflux rate, the column performs better and the ammonia vapor concentration in the vapor phase is higher. Jaime Sieres and José Fernández-Seara [7] developed a stationary model of single-stage NH3-H2O absorption machine with partial and complete condensation. The analysis is based on a mathematical model applied to different column configurations evaluated and compared according to the rate of ammonia purification achieved in each component of the column and the system performance obtained. The results show that the predicted COP values are lower than those of the condensation system.

Jaime Sieres and José Fernández-Seara [8] theoretically analyzed a rectification column with partial condensation for an ammonia-water absorption machine of small power. The analysis was performed by varying the length of the stripping and rectifying sections and the number of turns of each rectifier. The column results predict that water is absorbed into the liquid phase throughout the column. They also found that there is a limiting stripping length over which no further improvement is obtained.

E.W. Zavaleta-Aguilar and J.R. Simões-Moreira [9] analyzed a sieve plate rectification column with segmented weirs for a 17.58 kW ammonia-water absorption refrigeration system. The Ponchon-Savarit method was used to perform mass and energy balances in the distillation column. The results showed that the entrainment section provides a considerable increase in vapor concentration (51%), while the enrichment section increases the vapor concentration only by 1.5% and the rectifier by 2.2%, the latter two parts lead to high purity ammonia vapor. In this paper we focus on modeling of an NH3-H2O absorption machine, making a comparison of rectification methods. The coefficient of performance (COP) will be used to compare the different rectification methods.

This work focuses on the comparative study of rectification methods in an ammonia-water absorption machine and the analysis of the performance of the absorption machine by artificial neural networks (ANN) in the Sahelian zone.

2 DESCRIPTION OF THE SYSTEM

The system studied is a single-acting NH3-H2O absorption refrigeration machine. It is essentially composed of a condenser, a boiler, an evaporator, an absorber, two expansion valves and a pump (Fig 1).

The refrigerant-rich solution (5) receives the amount of heat at the temperature of the hot source, which causes the ammonia-water solution to vaporize. Refrigerant vapour (8) is obtained at the outlet of the boiler (generator or desorber) and the refrigerant-depleted solution (6) returns to the absorber. At the generator outlet, the refrigerant vapour reaches the condenser (8). The ammonia gas condenses (1) at the condensation temperature and pressure in the boiler/condenser unit is expanded before being admitted to the evaporator (2). After expansion, the liquid ammonia is admitted to the evaporator (2). It evaporates (3) by absorbing the amount of heat. The evaporation temperature, and consequently the pressure in the evaporator/absorber unit, is determined by the temperature of the refrigerant or the medium to be cooled. The vapors coming from the evaporator (3) are conveyed to the absorber where they meet the lean ammonia-water solution coming from the boiler (7) after having been expanded. It is absorbed by the lean mixture, causing the solution to be enriched and emerge rich (4). To maintain a pressure difference between the absorber/evaporator (low pressure) and the boiler/condenser (high pressure), the presence of a pump is required as well as the presence of two expansion valves on the refrigerant and lean solution circuits.

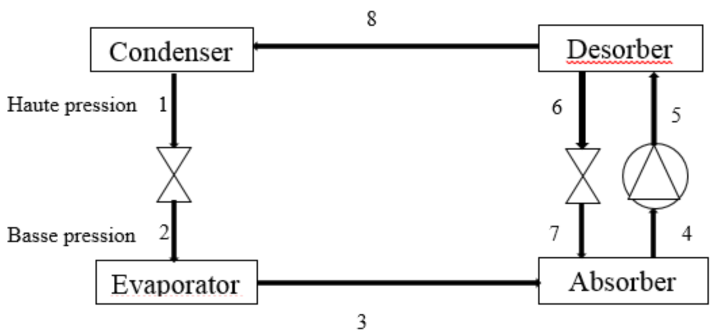


Fig. 1. Absorption refrigeration machine

3 Model Of The NH3-H2O Absorption Machine

The representation of the machine (Fig. 2) is different from the one presented in Fig 1. In this case, in addition to the absorber, the evaporator, the condenser and the generator, we have a solution exchanger and a rectifier. The role of the solution exchanger is to preheat the rich solution using the heat from the lean solution.

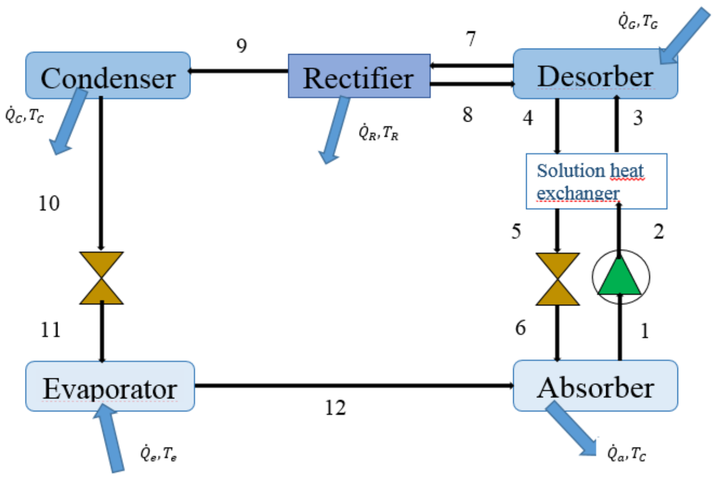


Fig. 2. Model of ammonia-water absorption refrigeration machine

The modeling equations of the different components of the absorption machine with the mass balances and the energy balances of the different components are given by the following equations.

- Mass balance of the mixture: $\sum \dot{m}_{in} = \sum \dot{m}_{out}$
- Mass balance of the refrigerant: $\sum \dot{m}_{in} X_{in} = \sum \dot{m}_{out} X_{out}$
- Energy balance: $\dot{Q} = \sum \dot{m}_{in}\, h_{in} - \sum \dot{m}_{out}\, h_{out}$
- The COP of the system set given by: $COP = \frac{\dot{Q}_E}{\dot{Q}_G + \dot{W}_p}$

To make a thermodynamic study of the absorption refrigeration machine, some assumptions must be taken into account for a proper approach [10]:

- Steady state,
- No pressure change except through flow restrictors and pump;
- The states at points 1, 4, 8 and 10 are saturated liquids;
- States at points 7 and 12 are saturated vapors;
- The flow restrictors are adiabatic;
- The pump is isentropic;
- No heat loss;
- No liquid carryover from evaporator to absorber;
- The steam outlet generator is at equilibrium temperature to enter the solution stream

At the generator outlet, at a certain temperature, water happens to evaporate with the ammonia. The presence of water in the refrigerant decreases the refrigeration production because the traces of absorbent prevent the total evaporation of the refrigerant when the evaporator is set to a conventional superheat level for a thermodynamic machine using pure ammonia. Therefore, the rectifier allows to improve the quality of the refrigerant, by eliminating the major part of the absorbent still contained in the separated gas phase at the exit of the generator.

4 Rectification Columns

A rectification column is a unit for separating a mixture by heating using the difference in volatility. It is composed of a rectification section and a stripping section. These two sections are linked in material and energy flow by a continuous feed. The role of the rectification column is to allow material exchanges between the gas phase and the liquid phase. Fig. 3 shows a simplified schematics of a rectifier column.

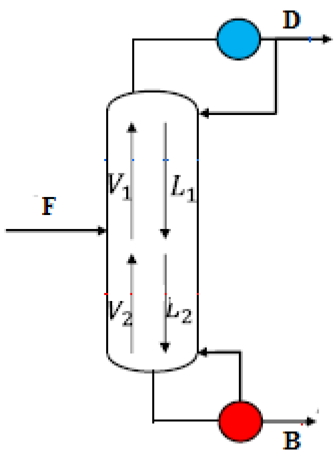


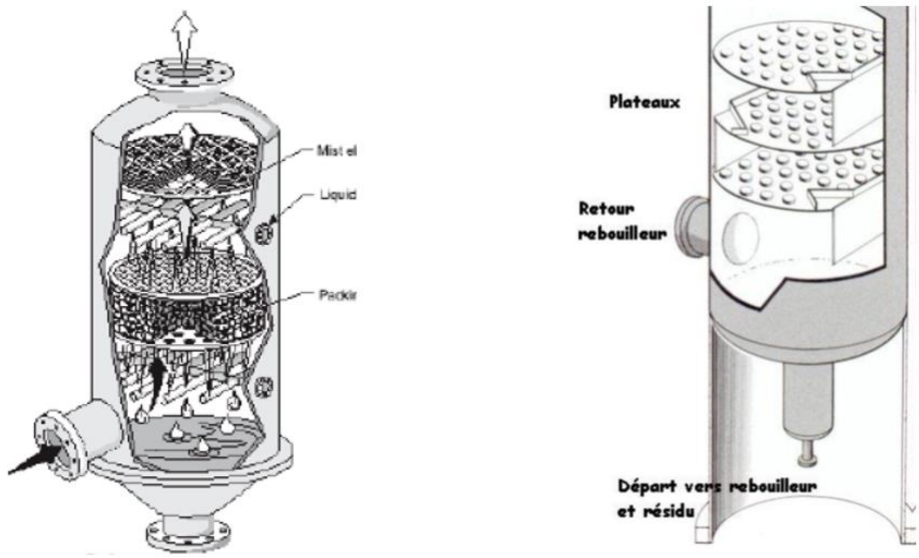
Fig. 3. Simplified schematic of a rectification column

The McCabe-Thiele method is most often used to study the rectification column. The equations that govern the operation of the rectification column are:

$F=B+D$ and $FX^F=DX^D+BX^B$. F, D and B are respectively the molar flow rates of the feed and the distillate.

The columns are differentiated by internals placed inside the column to ensure an intimate contact between the gas and the liquid in order to approach a compositional equilibrium as well as possible (Fig. 4). Thus, we have:

- Packed columns which is filled with objects of a certain shape in a loose or structured form. The packing increases the contact surface between the gas and liquid phase and improves the exchange surface.
- Columns with trays where, the bring liquid descends by gravitation into contact with the rising steam. We have trays with caps, perforated trays and trays with valves (or flaps).



(a) *(b)*

Fig. 4. Packed column (a) and Trays column (b)

5 Modelling And Simulation

This part gathers the different curves after simulation in EES and in MATLAB. The results obtained are grouped in tables and will be appreciated through the curves obtained from the programming software EES and MATLAB.

The optimization problem is defined in the following ranges:

- Evaporation temperature: -10 °C to 10 °C;
- Temperature of the heating medium in the boiler: 80 °C to 195 °C;
- Condensation temperature: 35 °C to 45 °C.

The used flowchart of the simulation is shows Fig 5. We have chosen a method of resolution by scanning the system parameters. The temperature of the hot source is scanned from 80 to 195 °C with a step of 5 °C; the condensation temperature from 35 to 45 °C with a step of 5 °C and the evaporation temperature from -10 to 10 °C with a step of 5 °C. Each state of the system is characterized by the triplet (heat source temperature, condensing temperature and evaporating temperature).

The input and output parameters of the artificial neural networks (ANNs) were obtained from our simulation results in the EES software. These parameters constitute the database of our model. It has been randomly divided into two parts. A part which constitutes 70 % of the data obtained from the simulation software will allow a learning of the behavior of the absorption machine to the network. The remaining 30% will allow to verify if the network understands the operation of the machine. The database used consists of the temperatures of the hot source, condensation, evaporation and the coefficient of performance (COP). The type of neural network used is the multilayer perceptron (PMC).

RNA with back propagation algorithm learns by changing the connection weights and these changes are stored as knowledge. Some statistical methods, such as root mean square error (RMSE) and multiple coefficient of determination (R^2) can be used to compare the predicted and actual values [12]. During learning, the error is estimated by RMSE defined as:

$$\mathrm{RMSE}=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\mathrm{COP_{sme}(i)}\text{-}\mathrm{COP_{sest}(i)}\right)^2}$$

(i) is the i-th measured COP value. (i) is the ith value of the estimated COP. n is the number of measurements considered.

The coefficient of multiple determination is given by: $\mathrm{R}^2=1\text{-}\frac{\sum_{i=1}^{n}\left(\mathrm{COP_{sme}(i)}\text{-}\mathrm{COP_{sest}(i)}\right)^2}{\sum_{i=1}^{n}\left(\mathrm{COP_{sme}(i)}\right)}$

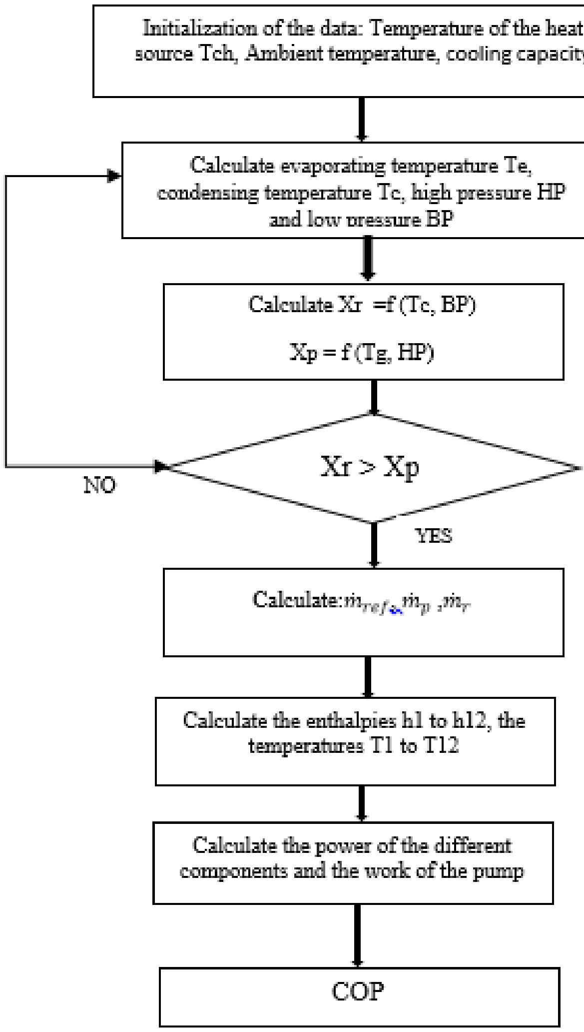


Fig. 5. Flowchart of the simulation under EES

6 Results And Discussion

Table 1 gives the state points of our cycle.

Table 1. The different state points of the system

Points	h (kJ/kg)	P (bar)	Qu	s (kJ/kg.K)	T (K)	u (kJ/kg)	v (m^3/kg)	x
1	-72,72	3,689	0	0,4008	310,2	-73,16	0,0012	0,4578
2	150	14,3	0	1,063	359,1	148,2	0,00128	0,4578
3	173,9	14,3	0	1,127	363,9	172	0,001273	0,4325
4	180	14,3	0	1,143	365,2	178,2	0,001271	0,4264
5	180	14,3	0	1,143	365,2	178,2	0,001271	0,4264
6	180	3,689	0,1101	1,181	328	162,6	0,04735	0,4264
7	1476	14,3	1	4,743	363,9	1313	0,1144	0,9734
8	173,9	14,3	-0,001	1,127	363,9	172	0,001273	0,4325
9	1312	14,3	1	4,262	316	1178	0,09341	0,9996
10	175,8	14,3	0	0,6109	310,2	173,4	0,001717	0,9996
11	175,8	3,689	0,1516	0,664	269,2	156,7	0,05193	0,9996
12	1264	3,689	1	4,686	269,2	1141	0,3339	1

After the simulation of the different models in EES with each time a specific rectifier, the results are presented in the curves (Figures 7, 8 and 9).

Figure 7 shows the effect of the variation of the COP as a function of the internal temperatures of the system operating from a tray column rectifier. For one heat source temperature, increasing the condensing temperature decreases the COP. This is because the increase in condensation temperature leads to an increase in the temperature difference between the cooling medium and the refrigerant in the condenser. It is therefore more sensible to work with condensation temperatures close to the temperature of the medium in which the system is located.

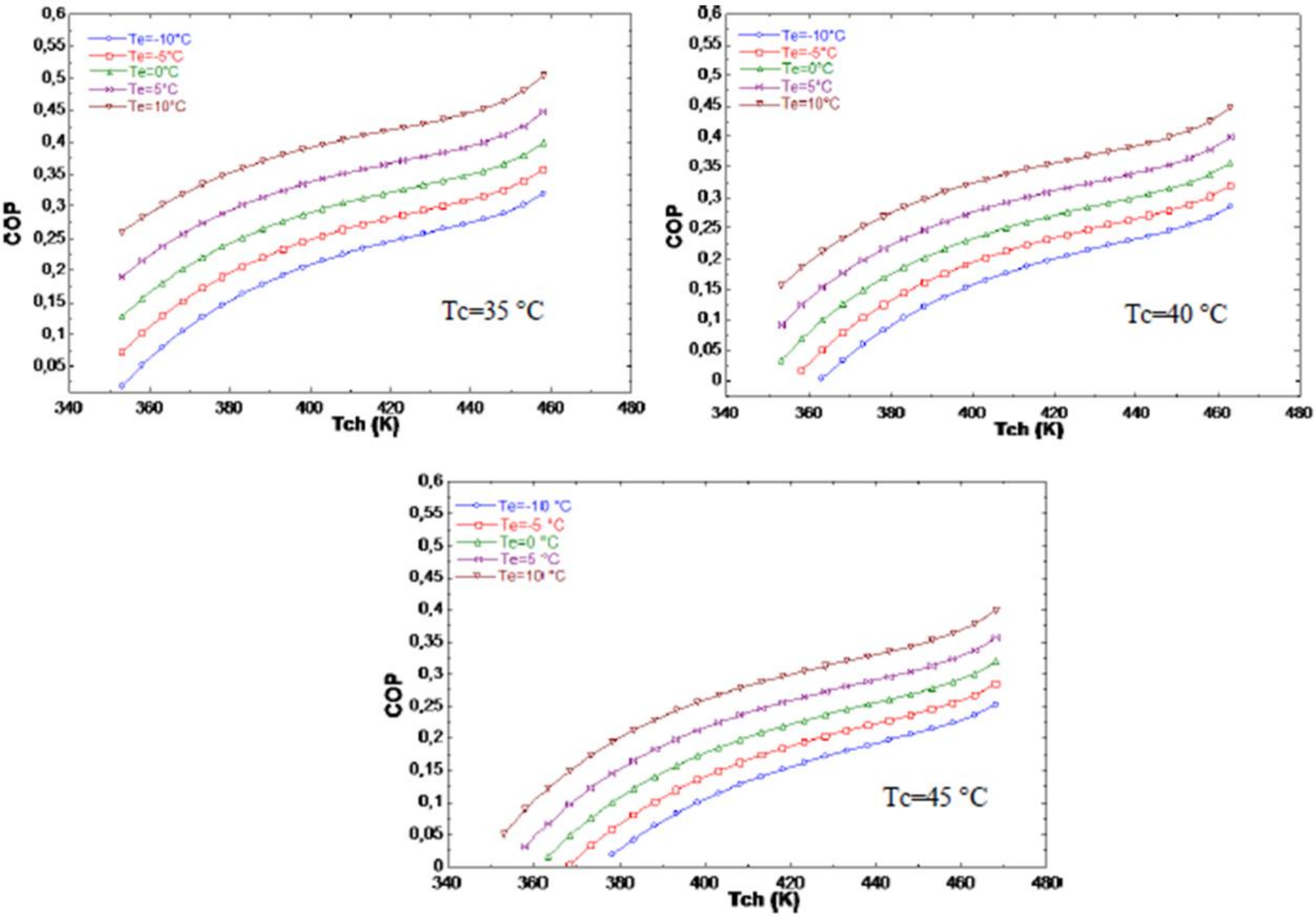


Fig. 6. Variation of COP with heat source temperature for the packed column

Figure 8 shows the evolution of the COP as a function of temperature for the system operating with a packed column rectification. As the heat source temperature increases, the COP increases and reaches a maximum before decreasing. For all the evaporation temperatures studied, the COP is maximal for a heat source temperature of about 440 K. This is due to the fact that above this value, some water vapor has evaporated with the ammonia at the boiler and not all the water vapor has been condensed at the rectifier. The presence of water in the refrigerant will reduce the cooling output which will decrease the COP.

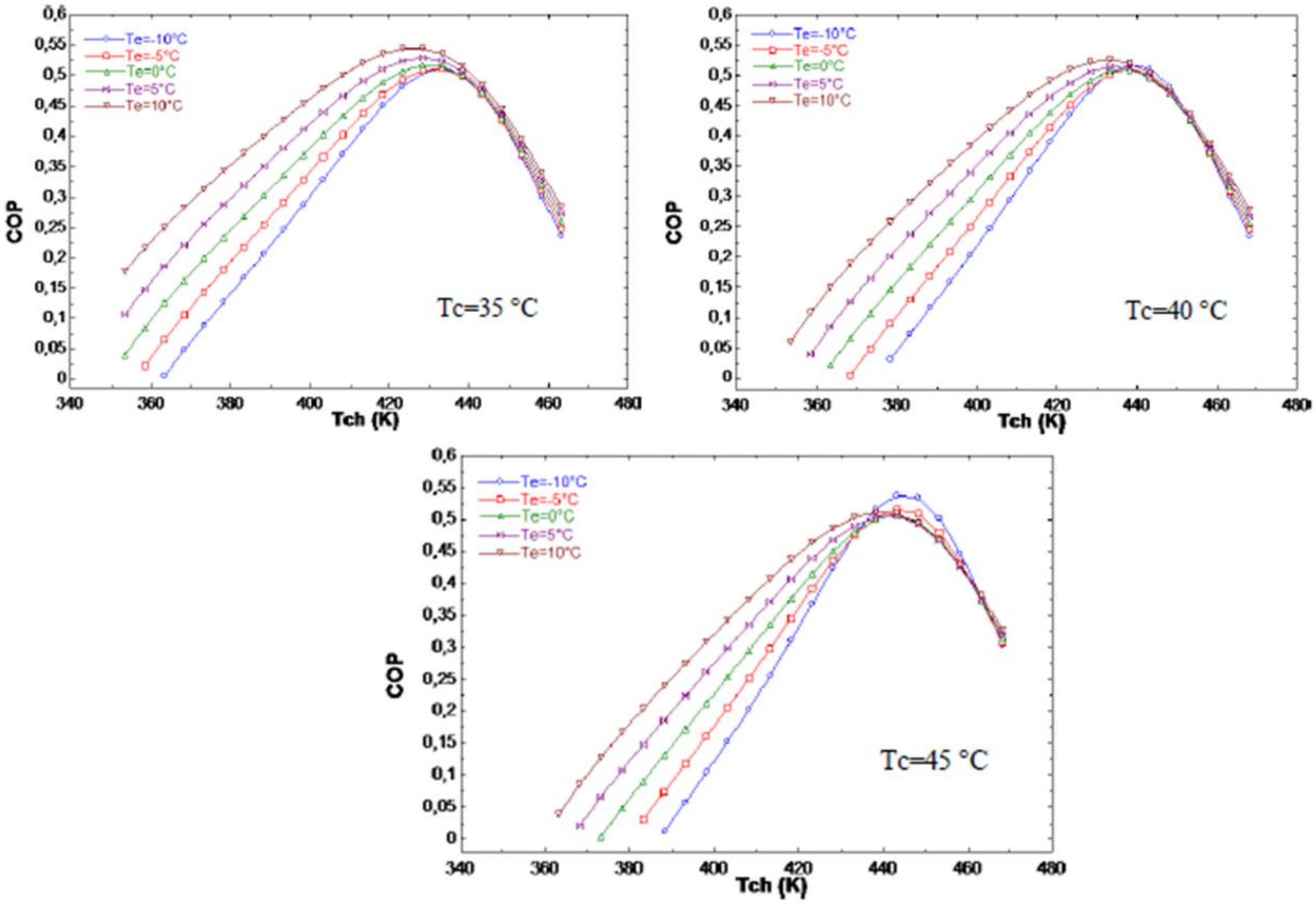


Fig. 7. ***COP variation as a function of heat source for packed column***

Figure 9 shows the evolution of the COP as a function of the temperatures of the system operating with partial condensation rectification. For a condensation temperature and heat source, the variation of the evaporation temperature does not have too much influence on the COP, i.e. a maximum variation of 1.37 %. This shows that the COP does not vary significantly depending on the type of refrigeration application.

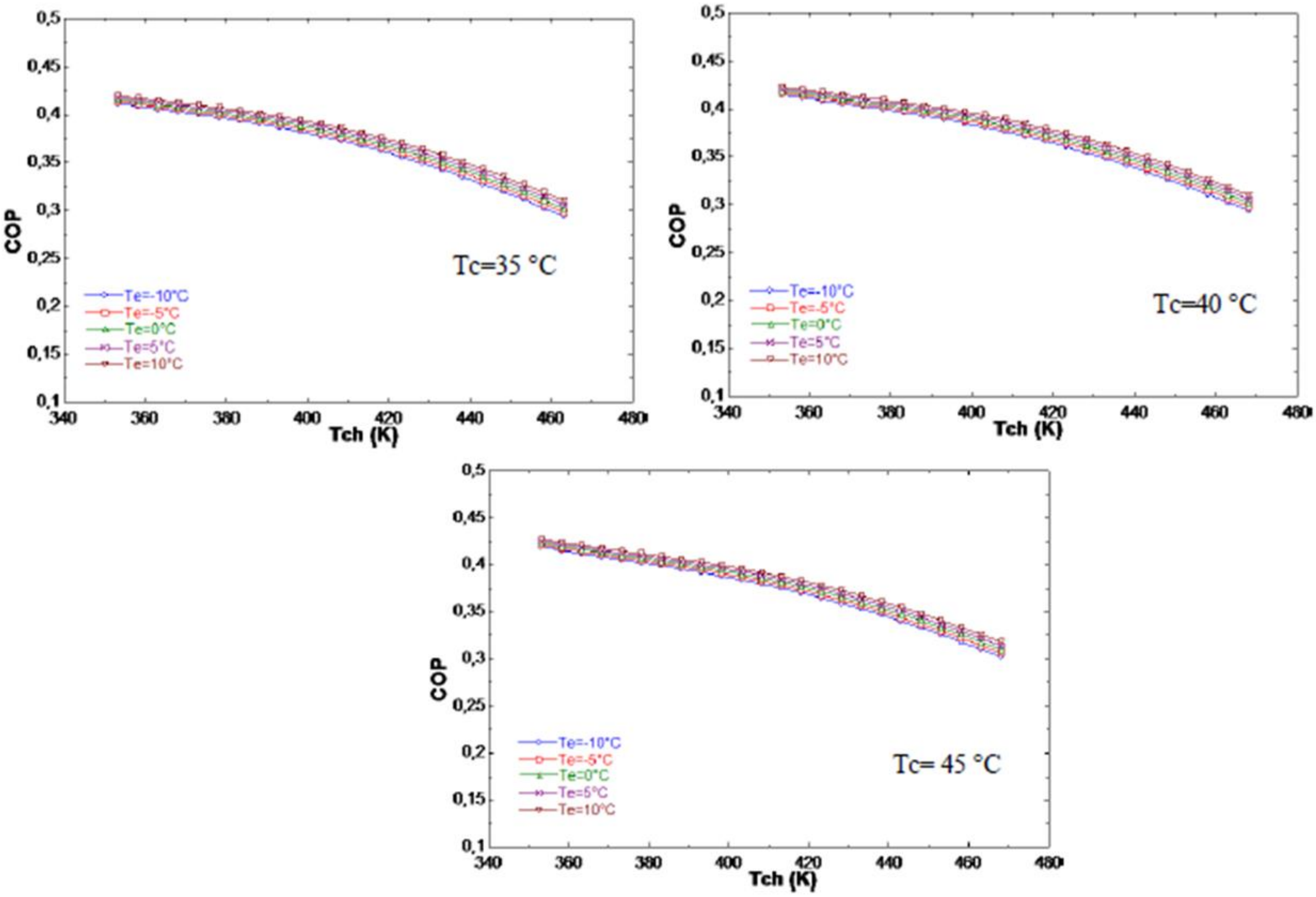


Fig. 8. Variation of the COP according to the temperature of the heat source for simple column

The comparison of the three configurations shows that the packed column has the best COP regardless of the evaporation temperature. The highest COP value obtained is 0.54 for packed column rectification followed by 0.5 for tray column rectification and 0.43 for simple column rectification. However, for high heat source temperatures, above 440 K, the tray column rectification is better, which improves its COP. Similarly, for low heat source temperatures, partial condensation rectification has the best COP. Thus the performance of the different rectification configurations varies according to the temperature of the heat source.

An artificial neural network is a computational model whose design is very schematically inspired by the functioning of biological neurons [13]. The analysis of the model using neural networks has allowed us to highlight the validity of our model. Thus, the root mean square error and the multiple determination coefficient were used to analyze the prediction accuracy of the model. The dynamic program for modeling the grinders is implemented in MATLAB. Figure 10 shows the final architecture of the developed neural network model common to all the studied rectifiers columns.

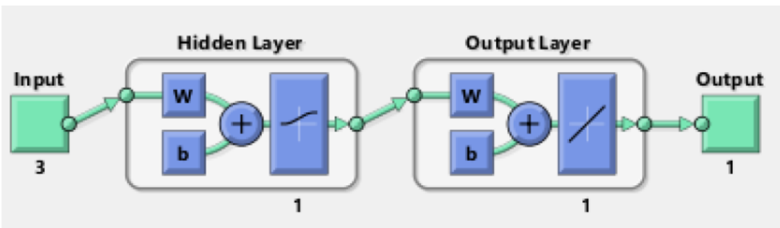


Fig. 9. Final architecture of the developed neural network model

We have three inputs which are: generator temperature, evaporation temperature and condensation temperature and as output the COP.

Table 2 gives the characteristics of the developed model.

Table 2. Summary of the characteristics of the model developed

Characteristic of the model	Value
Number of layers	3
Number of input layers	1
Transfer function	Linear
Number of hidden layers	1
Number of neurons	70
Transfer function	Sigmoid
Number of output layers	1
Transfer function	Linear

Validation of the COP model as a function of evaporation, condensation and heat source temperatures shows that the calculated data are close to the estimated ones with a root mean square error equal to 0.0123 and a multiple coefficient of determination of 0.9982 according to figure 11.

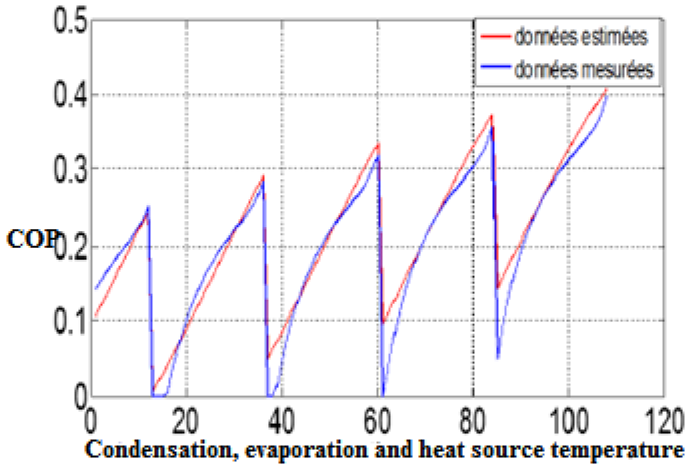


Fig. 10. Correlation between estimated and measured values for tray column

The prediction of the output results is well taken into account by the neural network. Figure 12 shows that the prediction of the COP of the system was done in an acceptable way because the root mean square error is 0.0161 and the multiple determination coefficient is 0.9990.

But on the other hand, the results estimated by the network do not reach 0.5, so the network has assimilated well until about 0.44 and becomes constant. Therefore, it should be noted that the COP of the absorption machine operating from a packed column is 0.44.

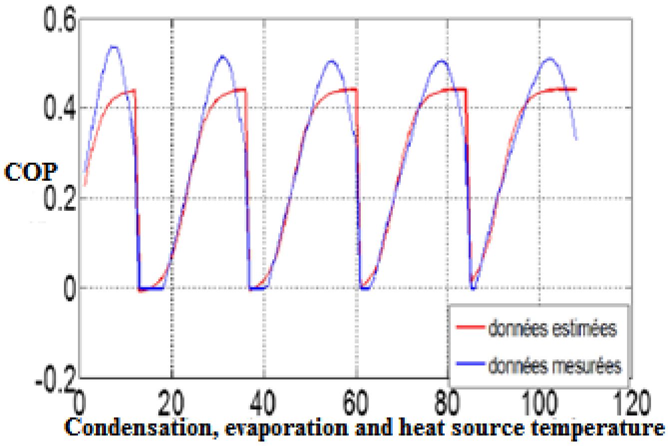


Fig. 11. Correlation between estimated and measured values for packed column

The results were well assimilated by the network because the root mean square error is 0.0014 and the coefficient of multiple determination is 1. Figure 13 shows that the partial condensation rectification method after predicting the results gives a COP of 0.42. This shows the calculated values and the estimated values are close.

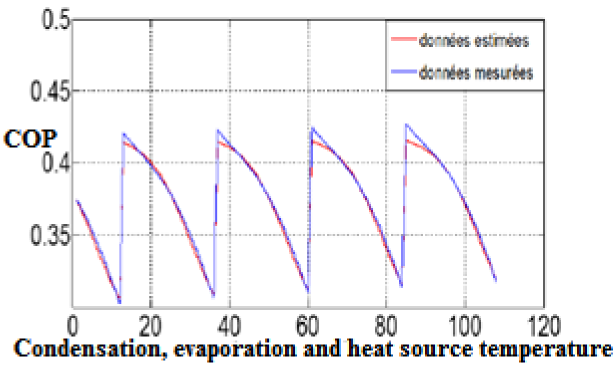


Fig. 12. Correlation between estimated and calculated values simple rectification

The packed column configuration has a coefficient of multiple determination equal to unity while the other two configurations namely tray column and single column rectification have coefficients of multiple determination near unity. The partial condensation rectification method has a lower RMSE value compared to the other two configurations

We can say that the packed column rectification method presents the best prediction results compared to the other two with a root mean square error of 0.0014 and a multiple determination coefficient equal to 0.9999. Table 3 gives a summary of the predictions of the three types of configurations with their RMSE and R^2 values.

Table 3. Comparative study of the different methods studied

Rectification method	RMSE	R^2	Number of iterations
Trays column	0,0123	0,9972	14
Simple column	0,0161	0,9990	18
Packed column	0,0014	0,9999	9

7 CONCLUSION

The study of NH_3-H_2O absorption machines requires a prior understanding of the rectification methods. This comparative study of the different rectifiers, namely tray columns, packed columns and partial condensation, allows to determine the operating conditions of the machines and the evolution of the COP during the cycle.

Thus, the thermodynamic properties of the fluid used have been calculated at each point of the circuit. The temperatures of the hot source, condensation and evaporation were scanned from 80 to 195 °C, from 35 to 45 °C and from -10 to 10 °C respectively; with a step of 5 °C, 5 °C and 5 °C respectively. For this purpose, the system states were simulated under the EES environment. The results of this simulation showed that for an evaporation temperature ranging from -10 °C to 10 °C and a condensation temperature ranging from 35 °C to 45 °C we obtained COPs up to about O.45, 0.43 respectively for the tray column rectification method, the single column rectification method and COPs up to 0.5 before decreasing for the packed column rectification method for a hot source temperature above 177 °C.

These results from the EES simulation were used as a database randomly divided into two parts, 70% for learning and 30% for validation, for a RNA study. The use of the three-layer RNA structure with the number of nodes in hidden layer via Levenberg Marquardt (LM) algorithm gave satisfactory performance in predicting the COP of the system according to the studied types of rectifications.

REFERENCES

[1] Refrigeration. [Online] Available: «https://fr.m.wikipedia.org/wiki/Réfrigération» (September 29, 2022).

[2] Jose´ Fernandez-Seara *, Jaime Sieres. The importance of the ammonia purification process in ammonia–water absorption systems. Energy Conversion and Management 47 (2006) pp.1975–1987.

[3] Marcriss, R. A. J. M. Gutraj and T. S. Zawacki, Absorption fluids data survey, final report on worldwide data, Chicago, Institute of gaz Technology, 1988, ORLN/Sub/8447989/3.

[4] Bogart MJP. Pitfalls in ammonia absorption refrigeration. International Journal of Refrigeration 5 (1982) pp.203–208.

[5] José Fernandez-Seara, Jaime Sieres, Manuel Vazquez, Distillation column configurations in ammonia–water absorption refrigeration systems, International Journal of Refrigeration 26 (2003), pp.28-34.

[6] Jaime Sieres, José Fernandez-Seara, Francisco J. Uhia, Experimental characterization of the rectification process in ammonia-water absorption systems with a large-specific-area corrugated sheet structured packing, International Journal of Refrigeration 32 (2009), pp.1230-1240.

[7] Jaime Sieres, José Fernandez-Seara, Francisco J. Uhıa, Experimental analysis of ammonia–water rectification in absorption systems with the 10mm metal Pall ring packing, International Journal of Refrigeration 31 (2008), pp.270-178.

[8] Jaime Sieres, Jose Fernandez-Seara, Evaluation of the column components size on the vapour enrichment and system performance in small power NH_3-H_2O absorption refrigeration machines, International Journal of Refrigeration 29 (2006), pp.579-588.

[9] E.W. Zavaleta-Aguilar, J.R. Simões-Moreira, Thermal design of a tray-type distillation column of an ammonia/water absorption refrigeration cycle, Applied Thermal Engineering (2012), pp.52-60.

[10] ASHRAE. ASHRAE Fundamentals Handbook, SI Edition. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, 1791, 892.p.

[11] Arzu Sencan, Artificial intelligent methods for thermodynamic evaluation of ammonia–water refrigeration systems, Energy Conversion and Management 47 (2006) pp.3319-3332.

[12] Reseau de neurones artificiels. [Online] Available: «https://fr.wikipedia.org/wiki/Réseau_de_neurones_artificiels» (July 3, 2022).