Impact Study of Thermal Distillation Process on Absorption Refrigerators

Salek Malaine[a] ‡, Najib Ababssi[a], Mohamed Charia[b], Zine El Abidine Bakher[c], Jilali Dardouch[d], Abdellah Boulal[a]

[a] Department of Mechanical and Electrical Engineering, Faculty of Sciences and Techniques, Hassan First University of Settat, Casablanca road, Km 3.5, P.O. Box 577, Settat, Morocco, 26000

[b] Department of Physics, Faculty of Sciences, Team of Thermodynamic and energetic, Mohammed V University in Rabat, 4 Ibn Battouta street, P.O. Box 1014, Rabat, Morocco, 10000

[c] Department of Applied Chemistry and Environment, Faculty of Sciences and Techniques, Hassan First University of Settat, Casablanca road, Km 3.5, P.O. Box 577, Settat, Morocco, 26000

[d] Department of Physics, Faculty of Sciences, Laboratory of Solar Energy and Environment, Mohammed V University in Rabat, 4 Ibn Battouta street, P.O. Box 1014, Rabat, Morocco, 10000

(s.malaine@uhp.ac.ma, nababssi@gmail.com, charia@fsr.ac.ma, z.bakher@uhp.ac.ma, dardouch81@gmail.com, boulalabdellah2020@gmail.com)

‡ Corresponding Author: Salek Malaine, Casablanca road, Km 3.5, P.O. Box 577, Settat, Morocco, 26000, Tel: +212 600 86 1190, s.malaine@uhp.ac.ma

Received: 02.09.2022 Accepted: 16.11.2022

Abstract- This paper numerically investigates the impact of thermal distillation, as an ammonia purification process, on various components forming the absorption refrigerators using ammonia-water pair as a working fluid. A numerical simulation program built-in FORTRAN language describing the real process of the absorption refrigerators functioning was established. Various physical parameters were examined, namely the mass flow rate of the rich solution evacuated by the absorber, the mass title of the vapor emitted by the boiler, and the variation in the quantities of heat exchanged by each element of the refrigeration installation. The results show a significant improvement in the exergetic performances (about 27.79 %) of the frigorific unit equipped with a distiller when compared to the basic refrigeration machine (20.19 %). It is clearly demonstrated how much the thermal distillation process has been adapted to absorption refrigeration for the production of cold at temperatures below -10 °C. The novelty of this research could motivate engineers and manufacturers to develop and construct modern absorption refrigerators equipped with a thermal distiller mechanism.

Keywords: Impact study, Thermal distillation, Ammonia purification process, Absorption refrigerators.

1. Introduction

Today, refrigeration has become increasingly important for preserving and storing food and medical products due to the world's rapid population growth [1]. Absorption refrigeration systems can become the most widely used equipment in residential, commercial, and industrial applications [2]. The ammonia-water absorption refrigeration systems (AWARS) have attracted more attention of several researchers [3] over the last few decades [4-5] due to their operation by environmental-friendly refrigerants [6] and the utilization of low-grade heat [7-8]. In these systems, water droplets are often present with the ammonia-rich vapor produced by the generator. This can affect negatively on the performances of this type of machines. But, the elimination of this water residue constitutes a crucial issue to assure a reliable and efficient functioning of these frigorific machines. To overcome this problem, several techniques and methods have been used by researchers in the literature. J. Mikielewicz et al. [9] suggested a novel analytical model of Liq-Vap separation in view to suppress water droplets that occurs in many industrial devices such as heat pumps, steam turbines, and Organic Rankine Cycle (ORC). To validate this model, experimental databases were used, and the results obtained showed a satisfactory agreement with the data provided in the literature. A 3A molecular sieve module was employed by J. S. Chiou et al. [10] to purify ammonia coming out in form of vapors in aqua-ammonia refrigeration systems. The experimental results of the ammonia enrichment tests showed that, if the molecular sieve modules have been arranged correctly in the installation, the purified ammonia concentration can be increased from about 80% to 99%. Mengkai Xu et al. [5] experimentally investigated the influence of lithium bromide concentration on distillation process, dedicated to eliminate the fraction of residues, integrated into a single-stage AWARS using ternary working fluid (ammonia-water-lithium bromide). It was found that the ternary working fluid ammonia-water-lithium bromide can operate more efficiently in the NH_3 rectification process when compared to conventional NH_3-H_2O working fluid. The experiment results obtained showed that the reduction of rectification cooling load and the distillation tower size can improve the coefficient of performance (COP). Anton N. Petukhov et al. [11] studied the effects of ammonia molecular association with impurities at low concentrations level in ammonia purification efficiency based on distillation process. Jose´ Ferna´ndez-Seara et al. [12] studied theoretically and experimentally the condensation of ammonia–water solutions over a horizontal tube to estimate the vapor mass and heat transfer coefficients. Based on experimental data used in the study, the theoretical investigations demonstrated that ammonia mass transfer throughout the vapor phase has a considerable impact on the vapor phase heat and mass transfer coefficients, and hence on the condensation of the ammonia–water mixture. J. Sieres et al. [13] experimentally reported and tested the ammonia rectification process in AWARS with packed column. Results obtained showed that the volumetric mass transfer coefficient in the vapor phase and the ammonia concentration of the rectified vapor increase with the reflux ratio values (from 0.2 to 1). This results have been employed after that to propose the design and analyze of the packed column integrated in AWARS. E.W. Zavaleta-Aguilar et al. [14] studied and analyzed a distillation process of ammonia-water solution via a sieve-tray distillation column integrated in an ammonia-water absorption refrigeration cycle in order to obtain a high degree of purity ammonia vapor. The study provided a geometrical details to build the distillation column and the results obtained showed that four ideal trays are sufficient for the small absorption refrigeration systems. In another study, E.W. Zavaleta-Aguilar et al. [15] were carried out an experimental analysis based on horizontal tube distiller formed by two parts; the generator and the rectifier, and dedicated to ammonia–water mixtures distillation. The experimental results obtained showed that the maximum concentration of purified ammonia vapor was 0.9974. A novel configuration for distillation and rectification of ammonia–water mixtures through a distillation column incorporated in small-capacity of AWARS was suggested and presented by M. A. Staedter et al. [16]. The designed thermal separation processes in the study are proposed for applications in the chemical industry and thermally driven desalination process. X. Chen et al. [18] proposed and compared an ammonia-water power cycle equipped by a distillation stage with two other Kalina cycles and one ORC. According to this study, the proposed cycle can produce more power about 9% than Kalina cycles at temperature of heat source equal 346 °C. And when the proposed cycle was compared with ORC cycle, the results obtained showed that the amount of net power produced was improved by about 9% at temperature of heat source equal 346 °C. Recently, S. Malaine et al. [3] proposed and investigated the integration of a rectifier as mechanism to purify ammonia as refrigerant in an absorption refrigerator. Two approaches have been employed to analyze the effects of this thermal mechanism on exergy efficiency and exergy loss in this refrigerator. The results obtained showed that the absorption refrigerator was enhanced by increasing its exergetic efficiency and reducing its exergy losses, nevertheless a study of the impact of this thermal mechanism on the overall component of absorption installation was required. It is noted that the most of the studies carried out didn't take into consideration the impact study of ammonia thermal distillation and purification processes on absorption refrigeration systems.

The novelty brought by the present work aims to conduct an impact study of ammonia thermal distillation process on the reliable and efficient operation of an absorption frigorific machine. The goal of this paper is to investigate the effect of distillation as an ammonia purification process on the various heat exchanger in the absorption refrigerators.

2. Materials and Methods

2.1. Description of the Studied Absorption Refrigerators

This section provides a brief overview of the absorption refrigerator that is the focus of this research. Figure 1 (a) illustrates a representative diagram of the basic absorption refrigerating machine operating with ammonia-water pairs; ammonia being the refrigerant [17-18] and water being the absorbent [10]. This type of machine can produce cold by exchanging heat with three sources: the hot source at the temperature T_B, the medium temperature source (which may be the ambient) at T_{AM} and the cold source formed by the medium to be cooled at T_E (T_E is lower than the ambient temperature). Figure 1 (b) schematizes the same installation illustrated in Fig. 1 (a) equipped with a distiller located at the outlet of the boiler. The distiller is fed directly by the vapors produced by the boiler at high pressure and high temperature. Its main role lies in the liq-vap separation to purify the ammonia as much as possible to eliminate the liquid quantity contained in the mixture emanating from the boiler and which can impair the efficient operation of the installation. In addition to the distiller, this absorption refrigeration plant includes the elements mentioned in table 1.

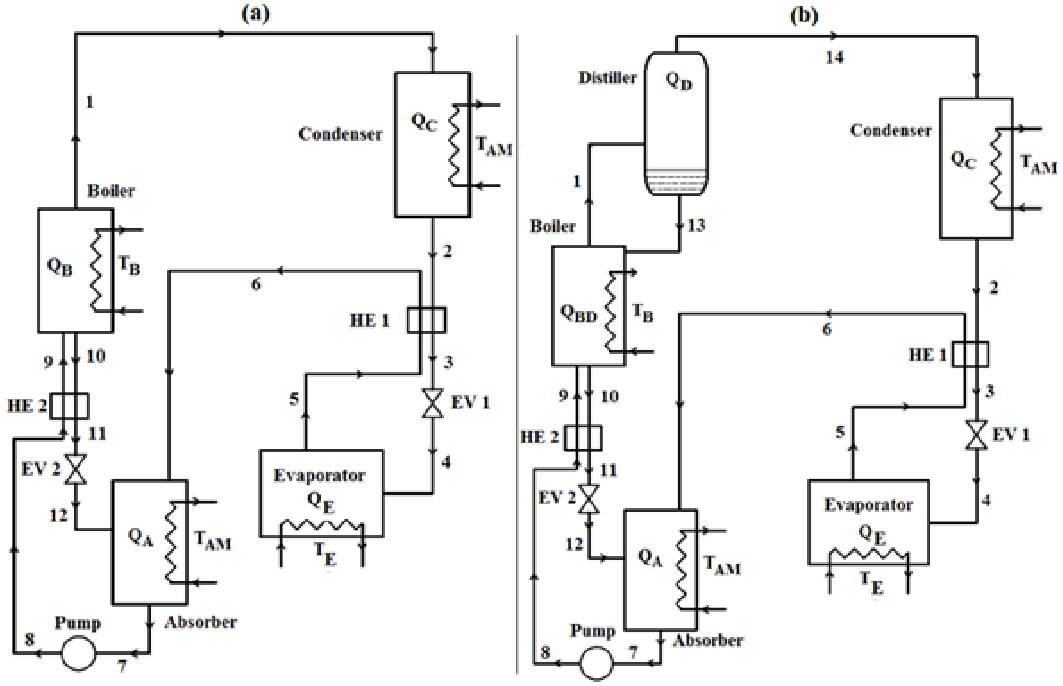


Fig. 1. Schematic representing of single-stage absorption refrigeration system: (a) without distiller mechanism; (b) with distiller mechanism.

Table 1. Each component's role within the basic refrigerator.

Component	Its role
Boiler	The separation of the binary mixture (NH_3-H_2O) by vaporizing ammonia as a refrigerant at high pressure. The rich vapors produced are directed to the condenser, while the lean solution is returned to the absorber.
Condenser	Heat exchanger between the absorption machine and the ambient air at a temperature lower than the condensation temperature of refrigerant. This temperature difference is essential to cause the vapors to condense.
Evaporator	Heat exchanger fed by the liquid refrigerant under a low pressure, such that its boiling point is lower than the temperature of the media to be cooled. This temperature difference causes the refrigerant to boil.
Absorber	Absorbs the vapor coming from the evaporator and enriches the poor solution in refrigerant coming from the boiler.
Pump	Pump the ammonia-rich solution to the boiler (from low to high pressure) [19].
Expansion valves	Bringing the pressure of the liquid leaving the condenser to the pressure of the evaporator and the pressure of the lean solution leaving the boiler to the pressure of the absorber.
Heat exchangers	HE 1's role is to cool and/or heat the refrigerant; HE 2 its role is the cooling and/or heating of the mixture of water-ammonia solution.

2.2. Thermodynamic Model Formulation

Firstly, the process of calculating the heat flows exchanged at the level of each component of the absorption refrigerating machine requires knowledge of the characteristics and physical properties of the fluids or pairs of fluids at different points of the thermodynamic cycles, specifically the enthalpies in liquids and vapors phases [20]. Many researchers utilize EES software, which is a ready-to-use tool [21-22]. The development of a thermodynamic model [23] is designed in the current study to ease those calculations according to the phase considered at various points in the thermodynamic cycle of the investigated refrigerators. The reduced variables of Gibbs free energy in the integral form [24] presented below were suggested to simplify the modeling of thermodynamic parameters. In this regard, the model was built with the following two cases in mind:

1- Case of pure ammonia:

For pure ammonia (as a refrigerant), the formulation of Gibbs free energy in its reduced form is categorized into two phases.

– Gaseous phase:

$$G_r^v = H_{0r}^v - T_r.S_{0r}^v + \int_{T_{0r}}^{T_r} C_{pr}^v dT_r - T_r.\int_{T_{0t}}^{T_r} \frac{C_{pr}^v}{T_r} dT_r + T_r \ln\left(\frac{P_r}{P_{0r}}\right) + C_1(P_r - P_{0r}) + C_2\left(\frac{P_r}{T_r^3} - 4\frac{P_{0r}}{T_{0r}^3} + 3P_{0r}.\frac{T_r}{T_{0r}^4}\right) + C_3\left(\frac{P_r}{T_r^{11}} - 12\frac{P_{0r}}{T_{0r}^{11}} + 11P_{0r}.\frac{T_r}{T_{0r}^{12}}\right) + \frac{C_4}{3}\left(\frac{P_r^3}{T_r^{11}} - 12\frac{P_{0r}^3}{T_{0r}^{11}} + 11P_{0r}^3.\frac{T_r}{T_{0r}^{12}}\right) \quad (1)$$

– Liquid phase:

$$G_r^l = H_{0r}^l - T_r.S_{0r}^l + \int_{T_{0r}}^{T_r} C_{pr}^l.dT_r - T_r\int_{T_{0r}}^{T_r} \frac{C_{pr}^l}{T_r} dT_r + (A_1 + A_2T_r + A_4T_r^2).(P_r - P_{0r}) + \frac{A_2}{2}.(P_r - P_{0r}) \quad (2)$$

Such as:

$$C_{pr}^v = D_1 + D_2.T_r + D_3.T_r^2 \quad (3)$$

$$C_{pr}^l = B_1 + B_2.T_r + B_3.T_r^2 \quad (4)$$

2- Case of ammonia-water pair:

This is the scenario that exhibits, most notably, the ammonia-water pair as a working fluid mixture required for the absorption refrigerator's functioning. Gibbs free energy in its reduced form is also characterized for this sort of pair by the following two phases.

– Gaseous phase:

$$G_r^v = (1 - Y).G_{rH_2O}^v + Y.G_{rNH_3}^v + T_r.[(1 - Y).\ln(1 - Y) + Y.\ln Y] \quad (5)$$

– Liquid phase:

$$G_r^l = (1 - X).G_{rH_2O}^l + X.G_{rNH_3}^l + T_r.[(1 - X).\ln(1 - X) + X.\ln X] + (E_1 + E_2.P_r(E_3 + E_4.P_r).T_r + E_5/T_r + E_6/T_r^2 + [E_7 + E_8.P_r + (E_9 + E_{10}.P_r).T_r + E_{11}/T_r + E_{12}/T_r^2](2X - 1) + [E_{13} + E_{14}.P_r + E_{15}/T_r + E_{16}/T_r^2](2X - 1)^2)X(1 - X) \quad (6)$$

The coefficients in the preceding equations (1-6) are found by the least-squares approach using the experimental values [25].

When generating the above equations in dimensionless form, the following reduced thermodynamic parameters were considered.

$$T_r = \frac{T}{T_b} \quad (7)$$

$$P_r = \frac{P}{P_0} \quad (8)$$

$$C_{pr} = \frac{C_p}{R} \quad (9)$$

$$H_r = \frac{H}{R.T_b} \quad (10)$$

$$G_r = \frac{G}{R.T_b} \quad (11)$$

Where: T_b= 100 °C, P_0= 10 bars, R= 3.3143 kJ/(kmol.K)

Secondly, the thermodynamic simulation model developed is based on establishing the mass and energy balances of the various components in the absorption refrigerator [26] assumed in a steady-state. This model is based on the principles of mass (Eq. 12) and energy (Eq. 13) conservation [27-28].

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (12)$$

$$\sum_i Q_i + W = \sum_{out} \dot{m}_{out}.h_{out} - \sum_{in} \dot{m}_{in}.h_{in} \quad (13)$$

Where: $\dot{m}$, Q_i, W and h are the mass flow rate (kg/s), heat transfer rate (kW), mechanical power (kW), and enthalpy (kJ/kg) values, respectively. The acronyms in and out signify the system's input and output.

Finally, the various thermodynamic variables provided in the current work, based on the vapor (Eq. 14) and liquid (Eq. 15) enthalpies, may be computed using differentiation procedures applied to the Gibbs free energy expressions. In this respect, these computations can be done using the following equations.

$$H^v = -T^2\left(\frac{\frac{G^v(T,P,Y)}{T}}{\partial T}\right)_{P,Y} \quad (14)$$

$$H^l = -T^2\left(\frac{\frac{G^l(T,P,X)}{T}}{\partial T}\right)_{P,X} \quad (15)$$

The exergy efficiency of the absorption refrigeration cycle is measured in terms of the exergetic coefficient of performance (ECOP) expressed as [29]:

$$\eta_{ex} = \left|\frac{Q_E\left(1 - \frac{T_0}{T_E}\right)}{Q_B\left(1 - \frac{T_0}{T_B}\right) + \dot{W}_p}\right| \quad (16)$$

2.3. Hypotheses and operating constraints

Before starting the numerical simulation of the thermodynamic system operation pertaining to the refrigeration machine, it is necessary to consider the following assumptions and operating constraints:

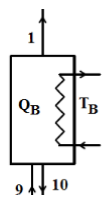
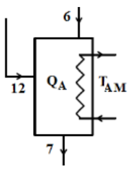
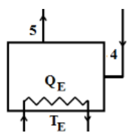
- Operation of the absorption refrigeration machine thermodynamic cycle in the steady state [30-31].
- Expansion valves are considered isenthalpic [32].
- Heat recuperators-exchangers are considered ideal [33].
- Absorber is considered ideal [34].
- Isentropic pump [35-36].
- Heat losses between the system and its environment [36] are considered negligible [37].
- Variations in kinetic and potential exergy are ignored [38].
- Except in the absorber, where the value (P_E-P_7/P_E) = 0.05 has been fixed, pressure drops have been ignored throughout the refrigeration cycle.
- Pinch temperatures ΔT at the main heat exchangers are taken into count:

$\Delta T_B = \Delta T_C = \Delta T_{HE\,1} = \Delta T_{HE\,2} =$ 10 °C and $\Delta T_E = \Delta T_A =$ 5 °C

2.4. Numerical Simulation Methodology

The approach conducted in this research intends to carry out a numerical simulation program, developed in FORTRAN language, describing the thermodynamic cycle of the absorption refrigerating machine. Initially, this program made it possible to calculate the thermodynamic state of the physical variables (T, P, X, Y) at any point in the refrigeration cycle, depending on the phase considered (liquid or vapor). Then, using SCHULTZ's analytical formulas of the Gibbs free energy and the equations of Antoine, this program was able to estimate and compute the enthalpies at various points in the refrigerating circuit. Secondly, using the mass and energy balances, this software was able to determine the amounts of heat transferred at the level of each element in the absorption refrigerator under study (as seen in tables 2 and 3). Taking into account the flexibility of the established simulation program, various parameters characterizing the thermodynamic cycle can be calculated, namely the evolution of the flow rate of the rich solution emanating from the absorber, the vapor flow rate leaving the boiler, the quantity of heat supplied to the boiler, the cooling capacity of the evaporator, as well as the coefficient of performance (see flowchart in Fig. 2).

Table 2. Mass and energy balances modeling of the basic absorption refrigerator (without a distiller).

Elements	Mass balances; mass concentration; energetic balances
Boiler 	$\dot{m}_1 + \dot{m}_{10} = \dot{m}_9$ (17) $\dot{m}_1.Y_1 + \dot{m}_{10}.X_{10} = \dot{m}_9.X_9$ (18) $Q_B = \dot{m}_1 h_1 + \dot{m}_{10} h_{10} - \dot{m}_9 h_9$ (19)
Absorber 	$\dot{m}_7 = \dot{m}_6 + \dot{m}_{12}$ (20) $\dot{m}_7.X_7 = \dot{m}_6.Y_6 + \dot{m}_{12}.X_{12}$ (21) $Q_A = \dot{m}_7.h_7 - \dot{m}_6.h_6 - \dot{m}_{12}.h_{12}$ (22)
Evaporator 	$\dot{m}_4 = \dot{m}_5 = \dot{m}_1$ (23) $Q_E = \dot{m}_1.(h_5 - h_4)$ (24)
Condenser	$\dot{m}_1 = \dot{m}_2$ (25) $Q_C = \dot{m}_1.(h_2 - h_1)$ (26)

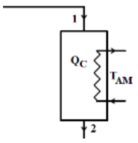
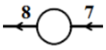
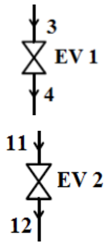
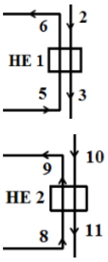
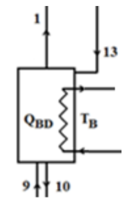
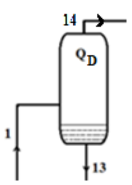
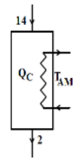
	
Pump 	$\dot{m}_7 = \dot{m}_8$ (27) $\dot{W}_P = \dot{m}_7.(h_7 - h_8)$ (28)
Expansion valve 	$\dot{m}_3 = \dot{m}_4$ (29) $\mathrm{h}_3 = \mathrm{h}_4$ (30) $\dot{m}_{11} = \dot{m}_{12}$ (31) $\mathrm{h}_{11} = \mathrm{h}_{12}$ (32)
Heat exchanger 	$\dot{m}_2 = \dot{m}_3$ (33) $\dot{m}_5 = \dot{m}_6$ (34) $\dot{m}_6.(\mathrm{h}_6 - \mathrm{h}_5) = \dot{m}_2.(\mathrm{h}_2 - \mathrm{h}_3)$ (35) $\dot{m}_8 = \dot{m}_9$ (36) $\dot{m}_{10} = \dot{m}_{11}$ (37) $\dot{m}_9.(\mathrm{h}_9 - \mathrm{h}_8) = \dot{m}_{10}.(\mathrm{h}_{10} - \mathrm{h}_{11})$ (38)

Table 3. Mass and energy balances modeling of the absorption refrigerator with a distiller.

Elements	Mass balances; mass concentration; energetic balances
Boiler 	$\dot{m}_1 + \dot{m}_{10} = \dot{m}_{13} + \dot{m}_9$ (39) $\dot{m}_1.\mathrm{Y}_1 + \dot{m}_{10}.\mathrm{X}_{10} = \dot{m}_{13}.\mathrm{X}_{13} + \dot{m}_9.\mathrm{X}_9$ (40) $\mathrm{Q}_{\mathrm{BD}} = \dot{m}_1.\mathrm{h}_1 + \dot{m}_{10}.\mathrm{h}_{10} - \dot{m}_{13}.h_{13} - \dot{m}_9.\mathrm{h}_9$ (41)
Distiller 	$\dot{m}_{14} + \dot{m}_{13} = \dot{m}_1$ (42) $\dot{m}_{14}.\mathrm{Y}_{14} + \dot{m}_{13}.\mathrm{X}_{13} = \dot{m}_1.\mathrm{Y}_1$ (43) $\mathrm{Q}_{\mathrm{D}} = \dot{m}_{14}.\mathrm{h}_{14} + \dot{m}_{13}.\mathrm{h}_{13} - \dot{m}_1.\mathrm{h}_1$ (44)

Condenser 	$\dot{m}_{14} = \dot{m}_2$ (45) $Q_C = \dot{m}_{14}.(h_2 - h_{14})$ (46)

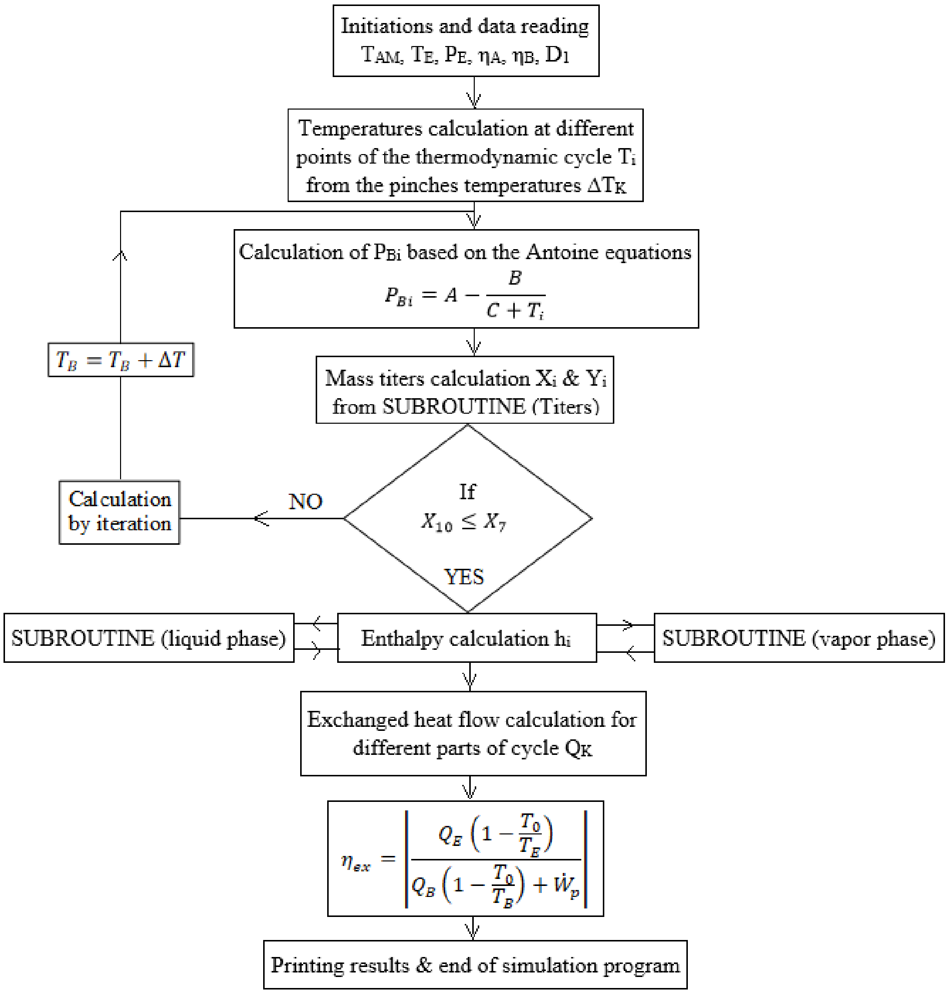


Fig. 2. Flowchart representing the different simulation steps.

3. Results and Discussion

The following parameters were considered:

T_E= -10 °C for the cold source; T_{AM}= 20 °C for the ambient temperature; η_A=η_B= η_P = 0.7 for the absorber's, boiler's, and pump's efficiencies, respectively.

3.1. Thermal Distillation Impact on Mass Flow Rates and Vapor Mass Titer

The effect of distillation on the evolution of the flow of the rich solution emanating from the absorber (f_{rs}), in the absorption refrigerator, can be seen in Figure 3. We note that the flow rate of the rich solution emanating from the absorber in the refrigerator without distiller decreases rapidly compared to the flow rate of the refrigerator with distiller depending on the temperature of the hot source. We find that the thermal distillation process can decelerate the fast decrease in the flow rate of the rich solution leaving the absorber.

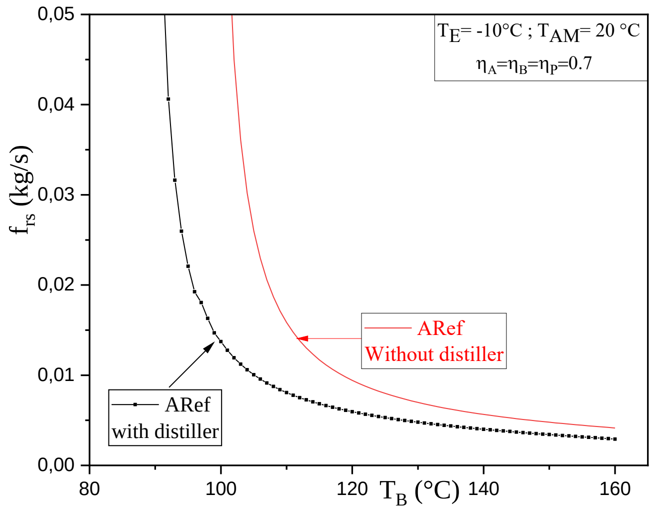


Fig. 3. Influence of thermal distillation process on the flow rate of rich solution coming out from the absorber.

Figure 4 represents the influence of thermal distillation as an ammonia purification process on the evolution of the vapor titer leaving the boiler (Y_{VB}) in the absorption refrigerator. We notice that the vapors content values in the refrigeration system with a distiller are higher than those in the system without a distiller, particularly at higher hot source temperatures. We can also see that the distillation helps to increase the evolution of the titer mass flow of the vapor exiting the boiler.

According to Fig. 3 and Fig. 4, it can be concluded the technical importance that must be attributed to the absorber and the boiler yields, and consequently to the design and construction of the two latter.

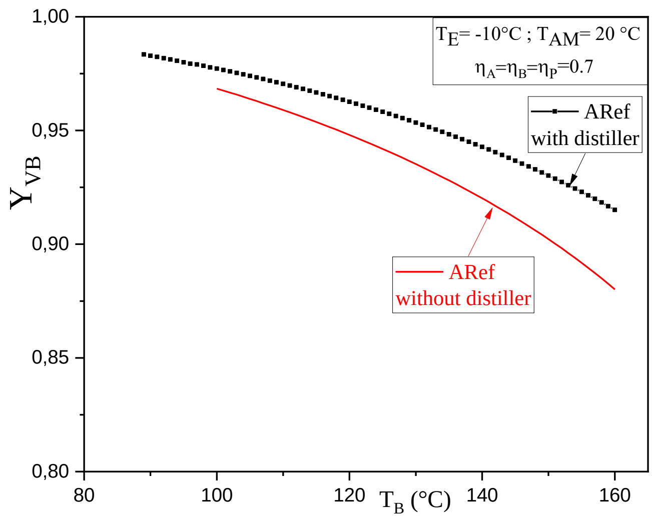


Fig. 4. Influence of thermal processes on the vapor concentration coming out from the boiler.

3.2. Assessment of Thermal Distillation Impact on Various Heat Exchangers

This section discusses the impact of the thermal distillation process on the different heat fluxes exchanged by the main components of the absorption plant.

Figure 5 (a) depicts the evolution of heat exchanged quantity by the condenser. It should be noted that the quantities of heat exchanged by the condenser in the case of the absorption refrigerator with a distiller are lower than those for the refrigerator without a distiller. For the highest temperatures T_B, it can be seen a decrease in heat quantities at the condenser level in the absorption system with a distiller against an increase in these quantities without a distiller. Therefore, the distiller can contribute to reducing the quantity of heat necessary to be exchanged by the condenser with the external environment. This is due to the vapor flow feeding the condenser (see Fig. 4 (b)).

Figure 5 (b) explains the variation in the quantity of heat exchanged by the evaporator as a function of T_B for the two systems analyzed. For the two refrigeration systems analyzed, the quantity of heat transferred by the evaporator diminishes as the temperature T_B increases. We note that the absorption refrigerator with a distiller has a higher refrigerating effect as compared to the refrigerator without a distiller. This is refer to the equality in the mass titer of the liquid solution feeding the evaporator and the mass titer of the vapor evacuated by the boiler. We can conclude that the distillation contributes to the improvement of the cooling capacity in the studied system.

The quantity of heat extracted at the absorber level is depicted in Fig. 5 (c). It should be highlighted that the distillation system has succeeded in minimizing the amount of heat to be extracted by the absorber, and that can facilitate the ammonia absorption phenomena.

Figure 5 (d) shows the impact of distillation on the evolution of the quantity of heat required by the boiler in the examined system. It is noted that the heat fluxes exchanged by these two systems analyzed decrease with the increase in the temperature of the hot source T_B. It can be seen that the heat flux exchanged by the boiler in the absorption machine with a distiller is lower than that of the machine without a distiller. We can say that the distillation aids the machine in reducing the quantity of heat required for the absorption chiller's functioning.

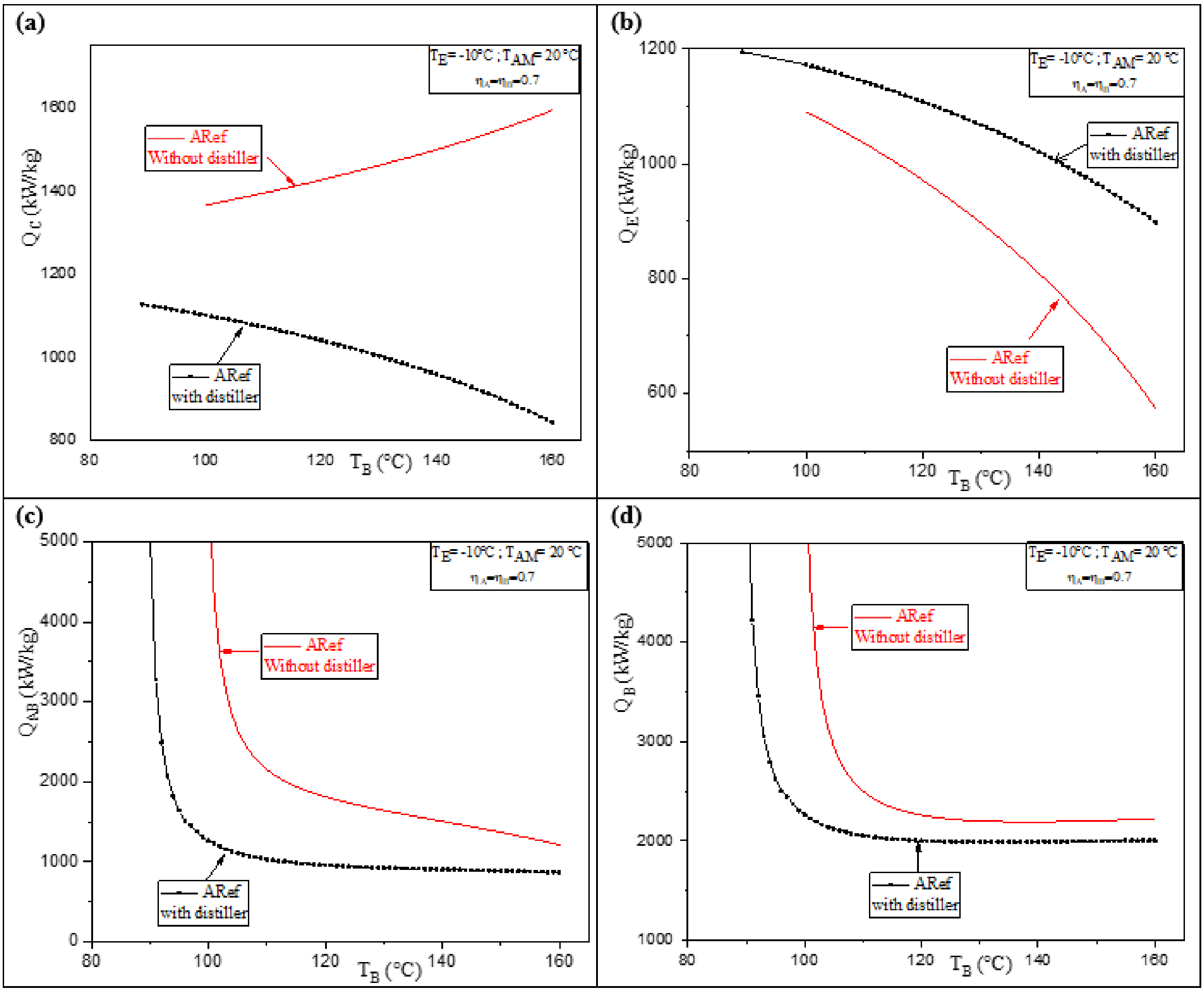


Fig. 5. Effect of distillation on the different quantities of heat exchanged by the absorption system's heat exchangers.

3.3. Evaluation of Thermal Distillation Impact on Exergy Performances

This section analyses the influence of incorporating a thermal distiller as a refrigerant purification mechanism into the basic absorption refrigerator cycle. Figure 6 provides an overview of the impact of the distillation process on the absorption refrigerator's exergy efficiency (η_{ex}) in question. It's worth noting that the curve relying on the exergy efficiency of the absorption machine equipped with a distiller is greater than the curve of the machine without it. In addition, the machine equipped with a distiller commences its operation from the temperature of T_B=89 °C, and its exergy efficiency begins to increase until it reaches a maximum value, equal to 27.79 % at 103 °C, then it continues to decrease. While the absorption machine without a distiller can only start working if the temperature reaches T_B=99 °C, then it exergy efficiency (η_{ex}) rises until it peaks, equal to 20.19 % at 112 °C, after which it began to drop. We have demonstrated that the distiller helps the absorption refrigerator to improve its energetic performance and, as a result, to improve its operation.

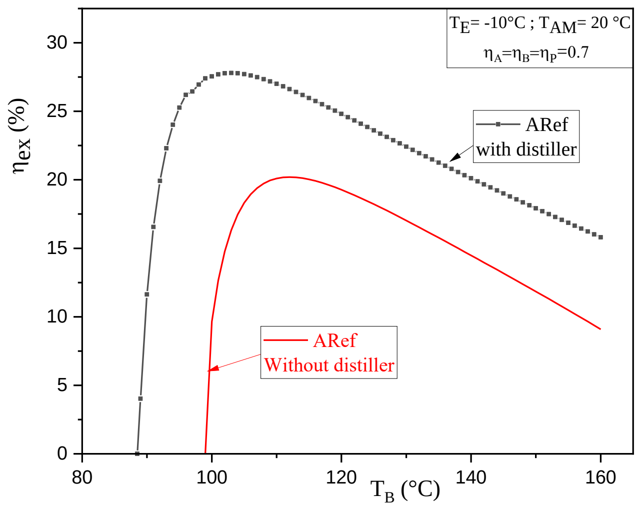


Fig. 6. Evolution of the exergy efficiency for the two absorption refrigerators analyzed (with and without distiller).

3.4. Discussion

In this research, the distiller, which was introduced as a purification mechanism for ammonia in the absorption refrigerator, played a key role in diminishing the droplets contained in the fraction vaporized at the boiler's outflow. This allowed for a large increase in the vapor titer Y that could be provided to the condenser, causing a rise in condensation pressure and, therefore, the contribution to the reduction in the amount of heat required for condensation. A heat exchanger-recovery HE 1 cooled the fluid exiting the condenser. The cooled liquid undergoes an isenthalpic expansion via EV 1 with the same vapor flow (condenser inlet), creating a lowering in the temperature at the beginning of the evaporation. This caused an increase in the cooling effect produced by the evaporator. Thus, the vapor leaving from the latter preheated by HE 1, then it was directed to the absorber, where it was absorbed on one side by the poor ammonia solution. On the other side, the lean liquid that exits the boiler at its boiling point at the highest temperature, in the refrigeration cycle, was cooled by a heat exchanger-recovery HE 2 before being fed back into the absorber via isenthalpic expansion EV 2. This exothermic recombination was necessitated to extract the heat at the absorber level. So this permitted to dispose of a colder low-ammonia liquid feeding the absorber and enhancing the absorption process. A pump conveyed the ammonia-rich solution from the absorber to the boiler. Heat exchanger HE 2 preheated this solution, which must be heated, after that, by the boiler to reach its boiling point. As a result, the quantity of heat delivered to the boiler (Q_B) was significantly lowered. Finally, the vapors discharged by the latter are gathered in the distiller, restarting a new cycle. Consequently, the distiller was able to achieve the absorption refrigerator a higher exergy efficiency while operating at lower temperatures.

4. Conclusion

In this paper, inserting a thermal distiller into the absorption refrigerator (NH_3-H_2O) as a mechanism to purify the ammonia has a favorable influence on its proper functioning, particularly on the improvement of its exergetic performances. The main benefit brings by the thermal distillation process to the absorption refrigerator remains in maximizing the liquid-vapor separation of the ammonia-water fluid mixture. The distiller aided the refrigerator to reduce the water droplets coupled with the gas emitted by the boiler at high pressures and temperatures, resulting in an ideal flow rate of vapor enriched with pure ammonia fluid. Consequently, this allowed for lowering the amount of energy required by the boiler even while improving the refrigerator's cooling capability. The obtained results showed a remarkable increase in the exergetic efficiency of the absorption refrigeration machine equipped with a distiller (about 27.79 %) compared to the simple refrigeration machine (20.19 %). The originality of this work can motivate engineers and manufacturers to develop and construct new absorption frigorific machines that incorporate a thermal distiller.

Future research will focus on the energy optimization of a solar absorption refrigerator equipped with a distiller. A dynamical simulation of absorption frigorific installation equipped with a distiller will also be performed.

Nomenclature

AFM	Absorption Frigorific machine	ECOP	Exergetic coefficient of performance [%]
ARM	Absorption refrigeration machine	f_{rs}	The rich solution flow [kg/s]
ARef	Absorption refrigerator	G_r^l	Reduced Gibbs free energy in the liquid state
AWARS	Ammonia-water absorption refrigeration systems	G_r^v	Reduced Gibbs free energy in the vapor state
		h	Specific enthalpy [kJ/kg]
EV 1- EV 2	Expansion valve number 1 & 2	H_r^l	The reduced enthalpy in the liquid state
HE 1- HE 2	Heat exchanger number 1 & 2	H_r^v	The reduced enthalpy in the vapor state
LiBr-H_2O	Lithium bromide-water pair	$\dot{m}$	Mass flow rate [kg/s]
NH_3-H_2O	Ammonia-Water pair	Q_A	Heat exchanged by absorber [kW/kg]
ORC	Organic Rankine Cycle	Q_B	Heat exchanged by the boiler [kW/kg]
Variables and parameters		Q_{BD}	Heat exchanged at the boiler with distiller

COP	Coefficient of performance [%]		[kW/kg]
Q_C	Heat exchanged by the condenser [kW/kg]	T_{AM}	Ambient Temperature [°C]
Q_E	Heat supplied to evaporator [kW/kg]	W	Mechanical power [kW]
Q_D	Heat exchanged by the rectifier [kW/kg]	X	Liquid mass titer
S_r^l	The reduced entropy in the liquid state	Y	Vapor mass tilter
S_r^v	The reduced entropy in the vapor state	Y_{VB}	Vapor titer exiting the boiler
T	Temperature [°C]	η_{ex}	Exergy efficiency [%]

References

[1] S. S. Franco, J. R. Henríquez, A. A. V. Ochoa, J. A. P. da Costa, and K. A. Ferraz, "Thermal analysis and development of PID control for electronic expansion device of vapor compression refrigeration systems", Applied Thermal Engineering, DOI: 10.1016/j.applthermaleng.2022.118130, vol. 206, p. 118130, April 2022.

[2] F. Panahizadeh, M. Hamzehei, M. Farzaneh-Gord, and A. Villa, "Thermo-economic analysis and optimization of the steam absorption chiller network plant", Therm sci, DOI: 10.2298/TSCI200619058P, vol. 26, No. 1 Part A, p. 95-106, 2022.

[3] S. Malaine, N. Ababssi, M. Charia, and A. Boulal, "Enhancing benefits by rectification in the absorption refrigeration systems", International Journal of Thermodynamics, DOI: 10.5541/ijot.927046, p. 29-37, January 2022.

[4] A. M. Abed, M. A. Alghoul, K. Sopian, H. Sh. Majdi, A. N. Al-Shamani, and A. F. Muftah, "Enhancement aspects of single stage absorption cooling cycle: A detailed review", Renewable and Sustainable Energy Reviews, DOI: 10.1016/j.rser.2016.11.231, vol. 77, p. 1010-1045, September 2017.

[5] M. Xu, S. Li, Z. Jin, W. Jiang, and K. Du, "Experimental investigation of the effect of LiBr on the high-pressure part of a ternary working fluid ammonia absorption refrigeration system", Applied Thermal Engineering, DOI: 10.1016/j.applthermaleng.2020.116521, vol. 186, p. 116521, March 2021.

[6] H. Lv, H. Ma, N. Mao, and T. He, "Boiling heat transfer mechanism of environmental-friendly refrigerants: A review", International Journal of Refrigeration, vol. 133, p. 214-225, 2022.

[7] A. Saeed, M. Zubair, F. A. Khan, F. Mairaj, M. Siddique and A. Shiwlani, "Energy Savings through Ammonia Based Absorption Chiller System: A proposed Strategy," 7th International Conference on Renewable Energy Research and Applications (ICRERA), DOI: 10.1109/ICRERA.2018.8566805, pp. 168-173, 2018.

[8] M. H. Ahmed, A. Giaconia and A. M. A. Amin, "Effect of solar collector type on the absorption system performance," IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), DOI: 10.1109/ICRERA.2017.8191284, pp. 304-309, 2017.

[9] J. Mikielewicz, O. Dolna, and R. Kwidziński, "Diffusive–inertial droplet separation model from two-phase flow", Archives of Thermodynamics, DOI: 10.24425/ATHER.2021.138113, vol. 42, No. 3, p. 159-172, 2021.

[10] J. S. Chiou, T. M. Lin, K. Y. She, and W. M. Chen, "Enrichment of ammonia concentration from aqua-ammonia vapors by using 3A molecular sieve", Energy conversion and management, vol. 50, No. 10, p. 2665-2669, 2009.

[11] A. N. Petukhov, D. N. Shablykin, A. V. Vorotyntsev, I. V. Vorotyntsev, and V. M. Vorotyntsev, "Effects of association with impurities in ammonia purification", Fluid Phase Equilibria, DOI: 10.1016/j.fluid.2015.07.034, vol. 406, p. 163-167, November 2015.

[12] J. Fernández-Seara, F. J. Uhía, and J. Sieres, "Research on the condensation of the ammonia–water mixture on a horizontal smooth tube", International Journal of Refrigeration, DOI: 10.1016/j.ijrefrig.2007.05.004, vol. 31, No. 2, p. 304-314, March 2008.

[13] E. W. Zavaleta-Aguilar and J. R. Simões-Moreira, "Thermal design of a tray-type distillation column of an ammonia/water absorption refrigeration cycle", Applied Thermal Engineering, DOI: 10.1016/j.applthermaleng.2011.12.009, vol. 41, p. 52-60, August 2012.

[14] E. W. Zavaleta-Aguilar and J. R. Simões-Moreira, "Horizontal tube bundle falling film distiller for ammonia–water mixtures", International Journal of Refrigeration, DOI: 10.1016/j.ijrefrig.2015.07.022, vol. 59, p. 304-316, November 2015.

[15] M. A. Staedter and S. Garimella, "Design and modeling of a microscale diabatic distillation column for small capacity ammonia–water absorption systems", International Journal of Refrigeration, DOI: 10.1016/j.ijrefrig.2018.06.018, vol. 94, p. 161-173, October 2018.

[16] X. Chen, R. Z. Wang, L. W. Wang, and S. Du, "A modified ammonia-water power cycle using a distillation stage for more efficient power generation", Energy, DOI: 10.1016/j.energy.2017.07.023, vol. 138, p. 1-11, November 2017.

[17] A. C. Rosa, Ivenio T.de Souza, Alexandre Terra, Ahmed WA.Hammad, Leandro Torres Di Gregório, ElaineVazquez, Assed Haddad, "Quantitative risk analysis applied to refrigeration's industry using computational modeling", Results in Engineering, DOI: 10.1016/j.rineng.2021.100202, vol. 9, p. 100202, March 2021.

[18] A. A. S. Lima, Gustavo de N. P. Leite, Alvaro A. V. Ochoa, Carlos A. C. dos Santos, José A. P. da Costa, Paula S. A. Michima, and Allysson M. A. Caldas, "Absorption Refrigeration Systems Based on Ammonia as Refrigerant Using Different Absorbents: Review and Applications", Energies, DOI: 10.3390/en14010048, vol. 14, No. 1, December 2020.

[19] K. Qiu and E. Thorsteinson, "An organic Rankine cycle system for solar thermal power applications," IEEE International Conference on Renewable Energy Research and Application (ICRERA), DOI: 10.1109/ICRERA.2014.7016545, pp. 138-141, 2014.

[20] A. Şencan, S. Gök, and E. Dikmen, "Prediction of Liquid and Vapor Enthalpies of Ammonia-water Mixture", Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, DOI: 10.1080/15567030903397891, vol. 33, No. 15, p. 1463-1473, May 2011.

[21] A. Khaliq, M. A. Alharthi, and S. Alqaed, "Energetic and exergetic analyses of a solar powered combined compression-absorption refrigeration system", International Journal of Exergy, vol. 34, No. 4, p. 448-474, 2021.

[22] C. F. Okwose, M. Abid, and T. A. H. Ratlamwala, "Performance analysis of compressor-assisted two-stage triple effect absorption refrigeration cycle for power and cooling", Energy Conversion and Management, DOI: 10.1016/j.enconman.2020.113547, vol. 227, p. 113547, January 2021.

[23] C. Naranjo-Mendoza, D. R. Rousse and G. Quesada, "Modeling of a solar absoprtion cooling system for Guayaquil, Ecuador," International Conference on Renewable Energy Research and Applications (ICRERA), DOI: 10.1109/ICRERA.2013.6749870, pp. 853-856, 2013.

[24] S. Kherris, M. Makhlouf, D. Zebbar, and O. Sebbane, "Contribution study of the thermodynamics properties of the ammonia-water mixtures", Therm sci, DOI: 10.2298/TSCI110206083K, vol. 17, No. 3, p. 891-902, 2013.

[25] S. Malaine, N. Ababssi, M. Charia, J. Dardouch, et A. Boulal, « Advanced exergetic study to assess the effects of rectification and distillation on absorption refrigerators », Therm sci, DOI: 10.2298/TSCI220402147M, 2022.

[26] S. Mazouz, H. Dardour, and A. Bellagi, "System Modeling and Parameter Effects on Design and Performance of a New Refrigeration Machine", International Journal on Energy Conversion (IRECON), DOI: 10.15866/irecon.v2i3.3939, vol. 2, No. 3, May 2004.

[27] H. Ganjehsarabi, M. Asker and A. K. Seyhan, "Energy and exergy analyses of a solar assisted combined power and cooling cycle," IEEE International Conference on Renewable Energy Research and Applications (ICRERA), DOI: 10.1109/ICRERA.2016.7884511, pp. 1141-1145, 2016.

[28] H. Tan and A. EriŞen, "Novel Design and Thermodynamic Analyses of Cascade Refrigeration System at Ultra-Low Temperature", International Journal of Thermodynamics, DOI: 10.5541/ijot.1017282, p. 1-9, January 2022.

[29] B. Huirem and P. Kumar Sahoo, "Thermodynamic Modeling and Performance Optimization of a Solar-Assisted Vapor Absorption Refrigeration System (SAVARS)", International Journal of Air-Conditioning and Refrigeration, DOI: 10.1142/S2010132520500066, Vol. 28, No. 1 (2020) 2050006 (18 pages).

[30] B. M. Goortan, F. Baba, , A. A. Alemrajab, and M. Mostajaboddava, "Direct Effects of Solar Irradiance on a Concentrated Solar Powered Water-Ammonia Absorption Refrigerator", International Journal of Renewable Energy Research, Vol.9, No.1, p. 384-392, Mar. 2019.

[31] M. Vallès, M. Bourouis, and D. Boer, "Solar-driven absorption cycle for space heating and cooling", Applied Thermal Engineering, DOI: 10.1016/j.applthermaleng.2019.114836, vol. 168, p. 114836, March 2020.

[32] M. A. Satyro, F. Schoeggl, and H. W. Yarranton, "Temperature change from isenthalpic expansion of aqueous triethylene glycol mixtures for natural gas dehydration", Fluid Phase Equilibria, DOI: 10.1016/j.fluid.2011.03.011, vol. 305, No. 1, p. 62-67, June 2011.

[33] A. Fakheri, "Heat Exchanger Efficiency", Journal of Heat Transfer, DOI: 10.1115/1.2739620, vol. 129, September 2007.

[34] A. Ebrahimi, B. Ghorbani, H. Lohrasbi, and M. Ziabasharhagh, "Novel integrated structure using solar parabolic dish collectors for liquid nitrogen production on offshore gas platforms (exergy and economic analysis)", Sustainable Energy Technologies and Assessments, DOI:

10.1016/j.seta.2019.100606, vol. 37, p. 100606, February 2020.

[35] G. Guzmán, L. De Los Reyes, E. Noriega, H. Ramírez, A. Bula, and A. Fontalvo, "Thermal Optimization of a Dual Pressure Goswami Cycle for Low Grade Thermal Sources", Entropy, DOI: 10.3390/e21070711, vol. 21, No. 7, July 2019.

[36] A. Kuczyńska and W. Szaflik, "Absorption and adsorption chillers applied to air conditioning systems", Archives of Thermodynamics, DOI: 10.2478/v10173-010-0010-0, vol. 31, No. 2, p. 77-94, July 2010.

[37] J. Fernández-Seara and J. Sieres, "The importance of the ammonia purification process in ammonia–water absorption systems", Energy Conversion and Management, DOI: 10.1016/j.enconman.2005.09.002, vol. 47, No. 13, p. 1975-1987, August 2006.

[38] A. R. Noorpoor and S.Heidararabi, "Exergoeconomic Assessment, Parametric Study and Optimization of a Novel Solar Trigeneration System", International Journal of Renewable Energy Research, DOI:10.20508/ijrer.v6i3.3777.g6862, Vol.6, No. 3, 2016