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Study of an Absorption Refrigeration Machine Improved with Distillation Column

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- *Thermodynamic properties.*

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Abstract

We propose in this article the study of the single-stage absorption refrigeration machine functioning with the fluids mixture of water - ammonia equipped with a distillation column to eliminate the water vapor in the refrigerant. Because the presence of the water vapor in the refrigerant enormously reduced the refrigeration effect of the machine and thus the improvement of thermodynamic of performance coefficient of the machine while reducing the operating temperature. We conceived a simulation program in FORTRAN language allowing the calculation of performance of the refrigeration machine. The study of this machine equipped with distillation column shows a clear improvement of the coefficient of performance which exceeds the (30%) compared to a simple machine without distillation column. The study shows also a rather important reduction in the operating temperature of the hot source, which makes this absorption refrigeration machine equipped with a distillation column better-adapted to solar energy (use of simple plate collector).

1. Introduction

The absorption refrigeration machine uses a clean mixture of fluid from the environmental stand point (H_2O-NH_3, H_2O-LiBr…) [1-3], for its operation which does not contain chlorofluorocarbons (C.F.C) [4-6], which destroy the ozone layer and contribute to the greenhouse effect [7].

Our study relates to the study of absorption refrigeration machine which is operating with the fluids mixture of water-ammonia. The presence of the water vapor in the refrigerant (ammonia) reduces the performances of the absorption refrigeration machine. To eliminate this water vapour in the fluids refrigerant we equipped the machine with a distillation column [3,7].

Thereafter we carried out a simulation program which enabled us to make a parametric study of the absorption refrigeration machine, with and without distillation column [3,7]. This enabled us to highlight the performances of these two machines and to compare them.

2. Description and principle of operation of the absorption refrigeration machine

The absorption refrigeration machine functions between three heat sources (Figure 1), the hot source at the temperature T_B at the generator, the average source T_M at the absorber and the condenser, and the cold source T_F at the evaporator [8,9]. For its operation the machine uses the mixture of fluids water-ammonia [10]. The absorption refrigeration machine functions between two pressure levels low; pressure P_F and high pressure P_B [9,10].

The contribution of heat at the generator Q_G allows a partial evaporation of the rich solution coming from the absorber, the poor solution outgoing is retained in the absorber, where as the produced vapors are directed towards the condenser. The Condensation is done in the room temperature T_M with a heat emission Q_C. The outgoing refrigeration liquid of the condenser in point 2 is retained to supply the evaporator with the pressure of evaporation P_F [11]. The contribution of heat Q_F at the evaporator, at the temperature of cold source T_F causes refrigerant to boil (it is the useful effect). The produced vapors are absorbed by the low solution in ammonia which comes from the generator in the absorber. Absorption is an exothermic reaction whose heat released Q_{AB} is evacuated by a coolant circuit at T_M. The rich solution obtained on the outlet side of the absorber is pumped to supply the generator for a second cycle. The exchangers recuperators E_1 and E_2 make it possible to improve the machine's performance [8].To purify the refrigerant we equipped the absorption refrigeration machine with a distillation column, which makes it possible to obtain a pure fluid at the exit (Figure 2)

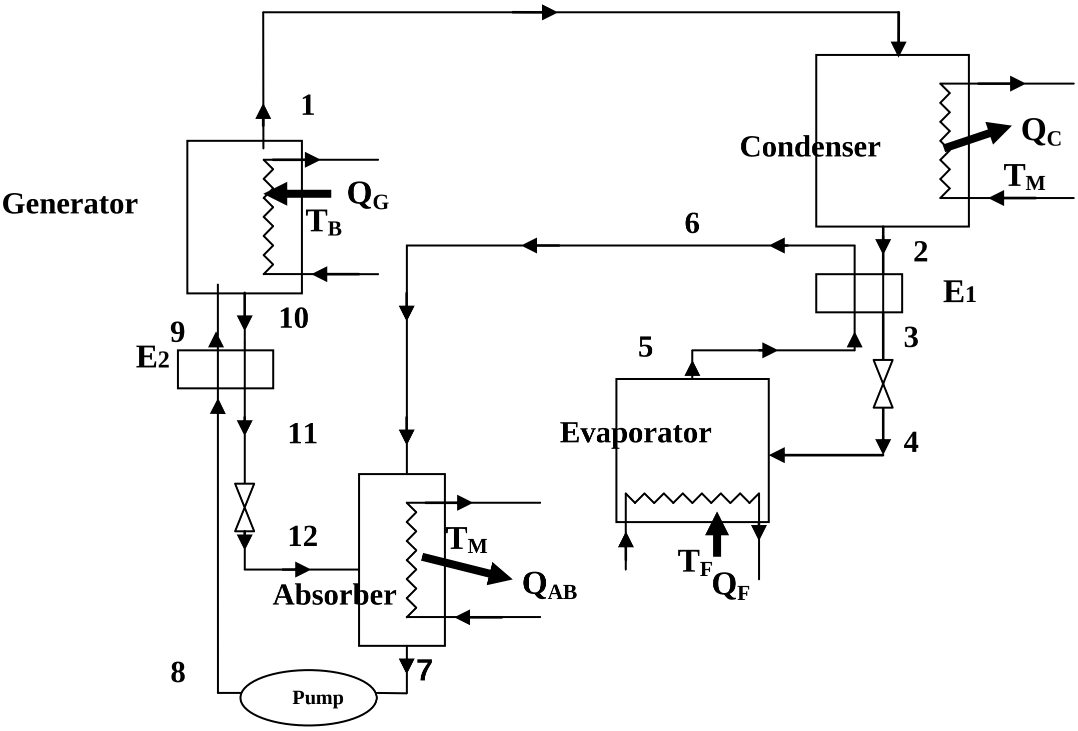

Figure 1: *Diagram of the absorption refrigeration machine simple*

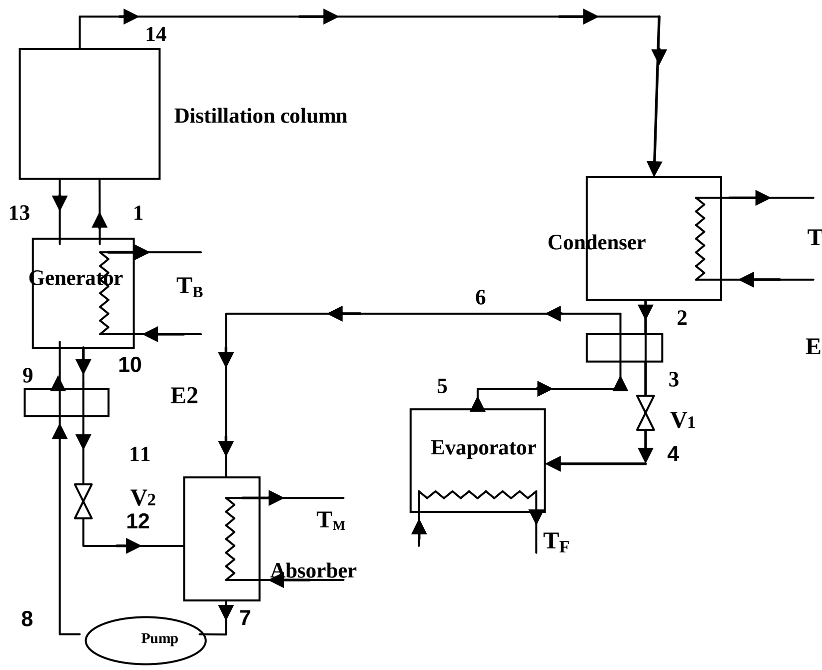

Figure 2: *Diagram of the absorption refrigeration machine with a distillation column*

3. The Simulation program of absorption refrigeration machine

To simulate the operation of the machine, a program was used in FORTRAN language [12]. This simulation program relates to the development of a mathematical model based on the mass and energy balances of the various organs of the machine, supposed in stationary regime, the thermodynamic properties of the couple of fluids water-ammonia and the real assumptions of operation machine [13,14].

3.1. Mass and energy balances of the various elements of the machine

3.1.1. In the distillation column

The conservation of the total mass is given by:

$$qm_{14} + qm_{13} - qm_1 = 0$$

The conservation of the mass by element is expressed as follows:

$$qm_{14} \cdot Y_{14} + qm_{13} \cdot X_{13} - qm_1 \cdot Y_1 = 0$$

The assessment enthalpic of distillation column is given by:

$$qm_{14} \cdot h_{14} + qm_{13} \cdot h_{13} - qm_1 \cdot h_1 = Q_{DC}$$

With

- Q_{DC} : quantity of heat exchanged by the distillation column.
- qm_i : mass flow in point i.
- h_i : mass enthalpy in point i.

This system of equations gives:

$$\begin{cases} qm_{13} = qm_1 \left(\dfrac{Y_{14} - Y_1}{Y_{14} - X_{13}} \right) \\[2ex] qm_{14} = qm_1 \left(\dfrac{Y_1 - X_{13}}{Y_{14} - X_{13}} \right) \\[2ex] Q_{DC} = qm_1 \left[(h_{14} - h_1) + (h_{13} - h_{14}) \cdot \left(\dfrac{Y_{14} - Y_1}{Y_{14} - X_{13}} \right) \right] \end{cases}$$

3.1.2. At the generator

$$\begin{cases} qm_1 + qm_{10} - qm_{13} - qm_9 = 0 \\[2ex] qm_1 \cdot Y_1 + qm_{10} \cdot X_{10} - qm_{13} \cdot X_{13} - qm_9 \cdot X_9 = 0 \\[2ex] qm_1 \cdot h_1 + qm_{10} \cdot h_{10} - qm_{13} \cdot h_{13} - qm_9 \cdot h_9 = Q_G \end{cases}$$

The resolution of this system of equations gives:

$$\begin{cases} qm_{10} = qm_1 \cdot \left[\dfrac{X_9 - Y_1}{X_{10} - X_9} + \left(\dfrac{Y_{14} - Y_1}{Y_{14} - X_{13}} \right) \cdot \left(\dfrac{X_{13} - X_9}{X_{10} - X_9} \right) \right] \\[2ex] qm_9 = qm_1 \cdot \left[\dfrac{X_{10} - Y_1}{X_{10} - X_9} + \left(\dfrac{Y_{14} - Y_1}{Y_{14} - X_{13}} \right) \cdot \left(\dfrac{X_{13} - X_{10}}{X_{10} - X_9} \right) \right] \\[2ex] Q_G = qm_1 \Big[(h_1 - h_9) + \left(\dfrac{Y_{14} - Y_1}{Y_{14} - X_{13}} \right) \cdot \left(\dfrac{Y_1 - X_{13}}{X_{10} - X_9} \right) \cdot h_9 + \left[\dfrac{X_9 - Y_1}{X_{10} - X_9} + \left(\dfrac{Y_{14} - Y_1}{Y_{14} - X_{13}} \right) \cdot \left(\dfrac{X_{13} - X_9}{X_{10} - X_9} \right) \right] h_{10} + \\ \left(\dfrac{Y_{14} - Y_1}{Y_{14} - X_{13}} \right) \cdot h_9 \Big] \end{cases}$$

3.1.3. At the condenser

$$\begin{cases} qm_{14} = qm_2 \\ qm_{14} = qm_1\left(\frac{Y_1 - X_{13}}{Y_{14} - X_{13}}\right) \\ Q_C = qm_{14}(h_2 - h_{14}) \\ Q_C = qm_1\left(\frac{Y_1 - X_{13}}{Y_{14} - X_{13}}\right)(h_2 - h_{14}) \end{cases}$$

3.1.4. At the heat exchanger I

$$h_6 - h_5 = h_2 - h_3$$

3.1.5. At the expansion valves I

$$h_3 = h_4$$

3.1.6. At the evaporator

$$\begin{cases} qm_{14} = qm_5 = qm_4 \\ qm_{14} = qm_1\left(\frac{Y_1 - X_{13}}{Y_{14} - X_{13}}\right) \\ Q_F = qm_{14}(h_5 - h_4) \\ Q_F = qm_1\left(\frac{Y_1 - X_{13}}{Y_{14} - X_{13}}\right)(h_5 - h_4) \end{cases}$$

3.1.7. At the absorber

$$\begin{cases} qm_7 - qm_{12} - qm_{14} = 0 \\ qm_7 \cdot X_7 - qm_{12} \cdot X_{12} - qm_{14} \cdot Y_{14} = 0 \\ qm_7 \cdot h_7 - qm_{12} \cdot h_{12} - qm_{14} \cdot h_{14} = Q_A \end{cases}$$

This gives:

$$\begin{cases} qm_{12} = qm_1\left[\frac{X_{10} - Y_1}{X_{10} - X_9} + \left(\frac{Y_{14} - Y_1}{Y_{14} - X_{13}}\right) \cdot \left(\frac{X_{13} - X_{10}}{X_{10} - X_9}\right) - \left(\frac{Y_{14} - X_{13}}{Y_{14} - X_{13}}\right)\right] \\ qm_{14} = qm_1 \cdot \left(\frac{Y_1 - X_{13}}{Y_{14} - X_{13}}\right) \\ qm_7 = qm_1 \cdot \left[\frac{X_{10} - Y_1}{X_{10} - X_9} + \left(\frac{Y_{14} - Y_1}{Y_{14} - X_{13}}\right) \cdot \left(\frac{X_{13} - X_{10}}{X_{10} - X_9}\right)\right] \\ Q_{AB} = qm_1\Big[\left[\frac{X_{10} - Y_1}{X_{10} - X_9} + \left(\frac{Y_{14} - Y_1}{Y_{14} - X_{13}}\right) \cdot \left(\frac{X_{13} - X_{10}}{X_{10} - X_9}\right)\right] \cdot h_7 + \left(\frac{Y_1 - X_{13}}{Y_{14} - X_{13}}\right) \cdot h_{14} + \\ \left[\frac{X_{10} - Y_1}{X_{10} - X_9} + \left(\frac{Y_{14} - Y_1}{Y_{14} - X_{13}}\right) \cdot \left(\frac{X_{13} - X_{10}}{X_{10} - X_9}\right) - \left(\frac{Y_{14} - X_{13}}{Y_{14} - X_{13}}\right)\right] h_{12} \Big] \end{cases}$$

3.1.8. At the pump

$$P_{pump} = qm_7 . V_7 \cdot \frac{(P_8 - P_7)}{\eta_P}$$

3.1.9. At the heat exchanger II

$$qm_9(h_9 - h_8) = qm_{10}(h_{10} - h_{11}).$$

3.1.10. At the expansion valves II

$$h_{12} = h_{11}$$

3. 2. Real assumptions of operation of the machine

For our study we chose the following variables independent [15, 13]:

- T_B temperature of the hot source,
- T_M temperature of the average source (ambient),
- T_F temperature of the cold source,

As well as the assumptions of operation described below.

3.2.1. Variations in temperatures

The transfers of heat in a real machine impose the existence of variations in temperature. We used the following values [15,13]:

- Absorber :

$$\Delta T_A = T_7 - T_M = 5K$$

- Generator :

$$\Delta T_G = T_B - T_{10} = 10K$$

- Condenser :

$$\Delta T_C = T_2 - T_M = 10K$$

- Exchanger I :

$$\Delta T_{E_1} = T_3 - T_5 = 10K$$

- Exchanger II :

$$\Delta T_{E_2} = T_{11} - T_8 = 10K$$

- Evaporator :

$$\Delta T_F = T_F - T_5 = 5K$$

3.2.2. Pressure loss

The pressure losses were negligible everywhere except in the absorber, where the value was fixed [15]

$$\frac{\Delta P}{P} = \frac{(P_F - P_7)}{P_F} = 0.05$$

3.2.3. Output of the absorber, the generator and the pump

The sizes of liquid balance vapor of binary water ammonia are calculated starting from the equation of Peng Robinson and the coefficient of K_{ij} interaction characterizing the mixture of fluid [16, 17].The parameters of balance thus calculated are however not reached in a real machine. The variations are characterized by outputs. For our study we used the following values [18]:

- For the absorber :

$$\eta_{AB} = \frac{(X_7 - X_{12})}{(X_{S7} - X_{12})} = 0.7$$

- For the generator:

$$\eta_G = \frac{(X_G - X_{10})}{(X_9 - X_{10})} = 0.7$$

Where X_G is the title of the fictitious liquid phase in balance with the outgoing vapour of the generator and Xs_7 is the title of the solution saturated as in point 7 [19].

- For the pump:

$$\eta_P = 0.7$$

The pump is characterized by an isentropic output. The increase in the temperature between the entry and the exit of the pump is negligible [15].

3.3. Constraints of operation of the machine

- High pressure

The pressure of the condenser, which is the same one as that of the generator, is taken equal to the saturated vapour pressure of the liquid solution leaving the condenser at the temperature T_2, The high pressure P_B is calculated by the formula of Antoine [15]:

$$\ln p_B = A - \frac{B}{C + T_2}$$

- Low pressure:

The low pressure in the evaporator is equal to the saturated vapour pressure of the pure cooling agent at the temperature T_5. In this machine with distillation column the evaporator is supplied by a pure fluid (ammonia), low pressure P_F is given by the formula of Antoine [15]:

$$\ln p_F = A - \frac{B}{C + T_5}$$

- Rich title :

The rich title X_7 solution rich in ammonia, outgoing of the absorber must be higher than that of X_{10} poor solution [21].

3.4. Thermodynamic properties

The calculation of the thermodynamic properties (temperature, pressure, composition, enthalpy, entropy, specific volume, vapor title and liquid), of the pair of water-ammonia fluid is based on the sizes of balance (temperature, pressure, composition) determined by using the equation of state of Peng-Robinson and coefficient of K_{ij} interaction characterizing the mixture of fluids [16, 14].

Specific volume, and the entropy and the enthalpy in each point of the cycle of the machine are calculated by using the analytical expression of the free energy of Gibbs given by Ziegler [16, 17].The high and the low pressure which are calculated by the formula of Antoine [15].

3.5. Coefficient of performance

The coefficient of performance is given by the quotient of refrigeration effect Q_F, on the contribution at the generator Q_G [20, 22]:

$$COP = \frac{Q_F}{Q_G}$$

4. Results of the numerical simulation

The simulation program of the operation of the absorption refrigeration machine developed at the point allows us to observe the influence of the various parameters on the operating conditions and the performances of the machine with and without distillation column.

4.1. Absorption refrigeration machine with distillation column

4.1.1. Influence of the temperature of the hot source, T_B, on the coefficient of performance for various values of the average source T_M

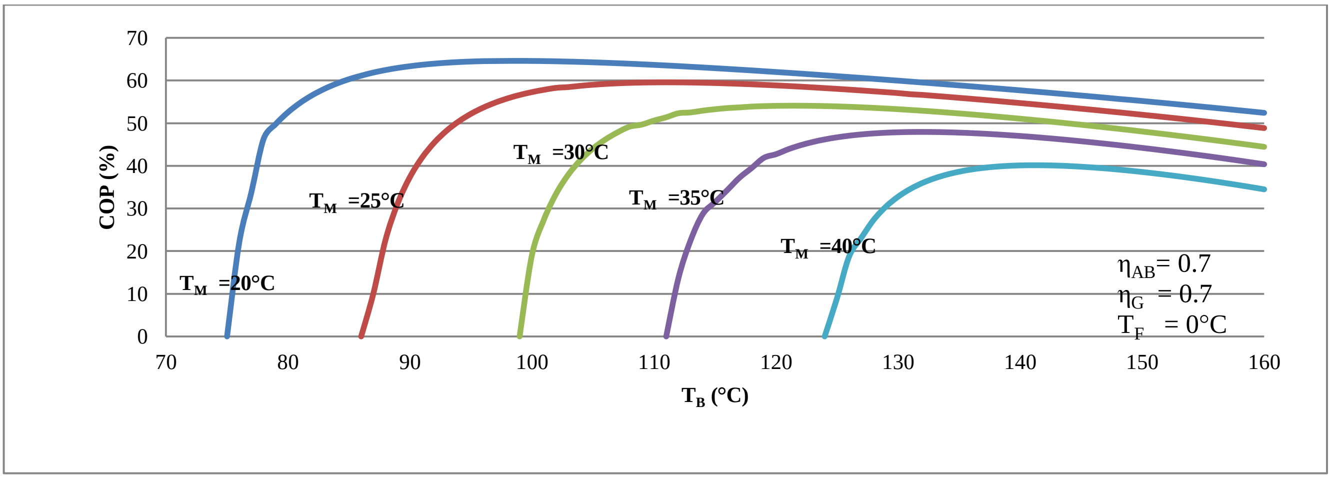

Figure 3: *Evolution of the coefficient of performance according to the temperature of the hot source T_B(°C) for various values of the average temperature T_M (°C)*

(Figure 3) illustrates the coefficient of performance COP according to the temperature T_B for different value from the average temperature T_M and T_F= 0°C
We note that:

- Coefficient of performance COP reaches its maximum capacity according to the temperature of the hot source T_B.
- Coefficient of performance COP reaches its maximum value of (65%) for T_M= 20°C and T_F= 0°C and T_B = 99°C.
- As the average temperature T_M increases value of the coefficient of performance COP decreases.
- The temperature threshold of operation beginning of the machine, the hot source, T_B, which corresponds to a (0%) COP, increases as well as the average temperature of the increases (75°C for T_M=20°C and 86°C for T_M=25°C).

4.1.2. Influence of the temperature of the hot source, T_B, on the coefficient of performance for various values of the cold source T_F

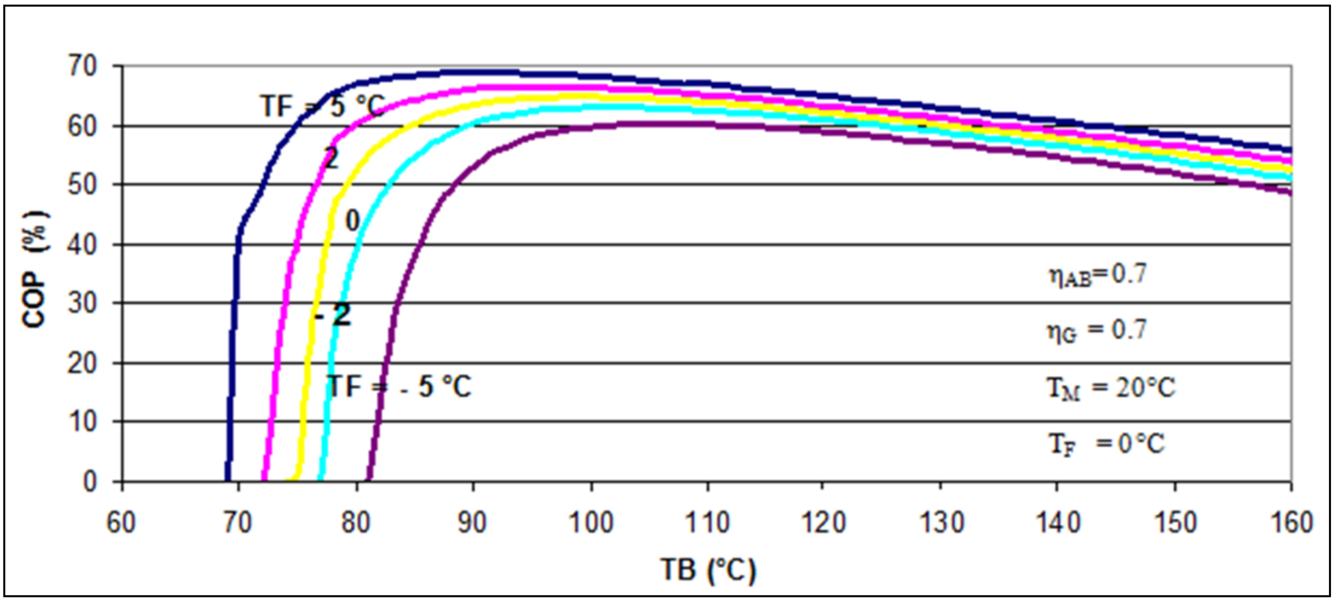

Figure 4: *Evolution of the coefficient of performance according to the temperature of The hot source T_B (°C) for various values of the temperature of the cold source T_F (°C)*

(Figure 4) represents development of COP according to the temperature of the hot source T_B, for various values of T_F the temperature of the average source is fixed T_M=20°C.

We note that:

- The temperature threshold of operation T_B, which corresponds to a (0%) COP increases when T_F decrease,
- As the cold temperature T_F increases the value of the coefficient of performance COP increases.
- For T_F = 5°C, which corresponds to the temperature of conservation of fruits, vegetables and vaccines, optimum of operation, which corresponds to a maximum of COP, which is for a temperature of the hot source T_B of about 75°C. This clearly shows that the absorption refrigeration machine functioning under these conditions can be supplied with simple plane collector with a better output.

4.1.3. Flow of the rich solution

(Figure 5) represents the variation of the flow of the rich solution according to the temperature of the hot source T_B for a flow of vapor emitted by the generator equal to the unit (qm_1= 1 kg/s), T_M = 20°C and T_F =0°C.
According to the figure we note a rapid decrease of the flow of the rich solution when the temperature increases of the hot source T_B.

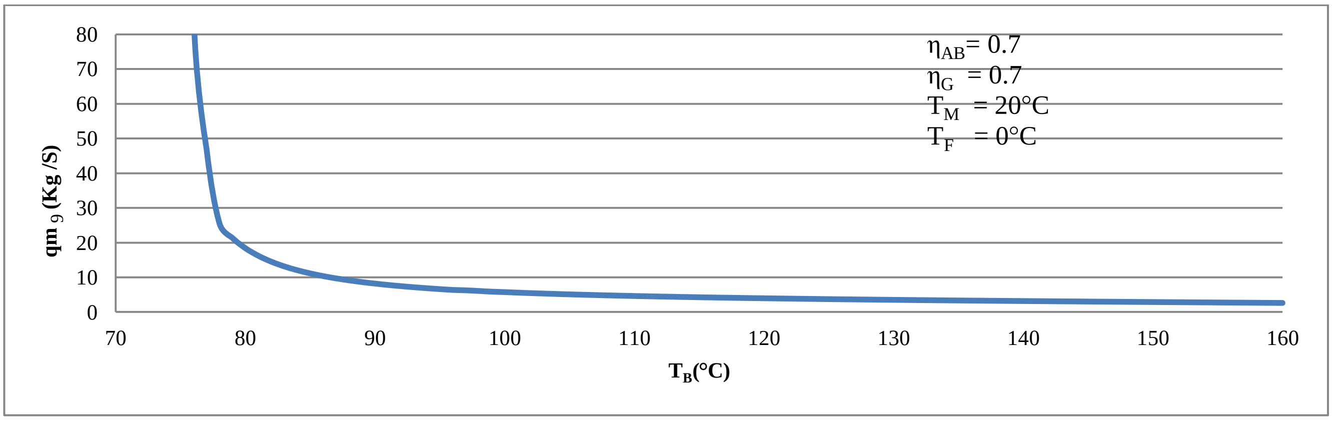

Figure 5: *Evolution of the flow of the rich solution qm_9 according to the temperature hot source T_B (°C)*

4.1.4. Heat flows exchanged by the different elements of the machine

The (Figure 6) represents the heat flows exchanged by the various elements of the absorption machine (generator, absorber. condenser, evaporator) according to the temperature of the hot source for T_F =0°C, T_M = 20°C and(qm_1=1 kg/S).

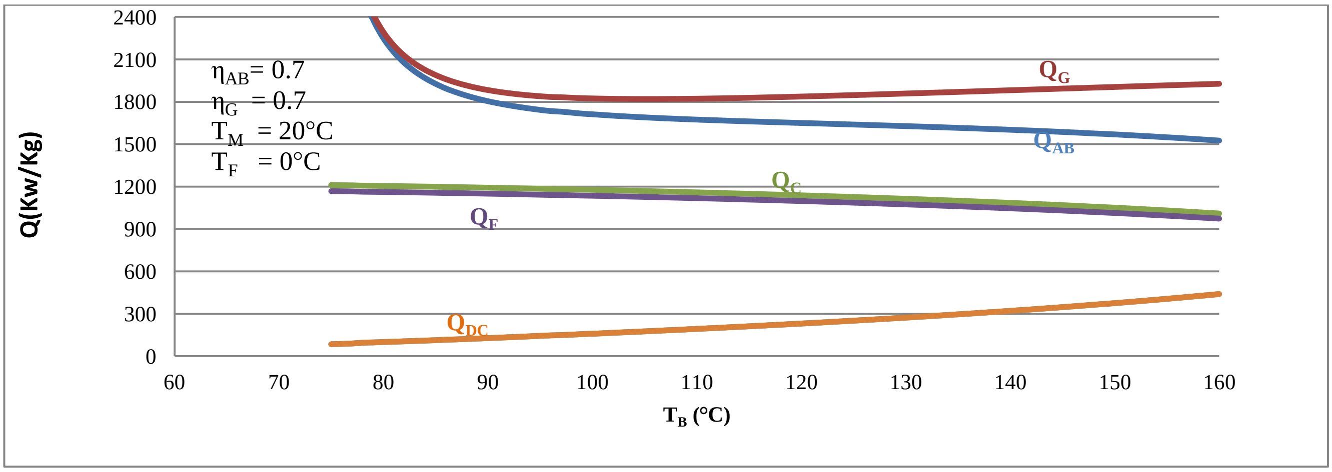

Figure 6:*Heat flows exchanged at different organs of the single-stage absorption machine with a distillation column according to the temperature from the hot source T_B (°C) with T_M =20°C,T_F = 0°C*

We note that:

- The heat flows exchanged at generator Q_G, and the absorber Q_{AB}, decrease with the temperature of the hot source T_B.
- The heat flows exchanged at the condenser Q_C, and at the evaporator Q_F remain almost constant when the temperature increase of the hot source T_B.

- Heat flow exchanged at the distillation column Q_{DC}, augment with the temperature of the hot source T_B.

5. Comparative study of the absorption refrigeration machine with and without a distillation column

Thanks to the flexibility of the simulation program established, we compared the performances of the absorption refrigeration machines single-stage with and without a distillation column.

5 .1.Comparison of the coefficients of performance

5.1.1. First case T_M =20°C and T_F = 0°C

(Figure 7) represents the coefficient of performance COP, of the two absorption refrigeration machines, with and without distillation column, according to T_B for T_M =20°C and T_F = 0°C.

We note according to this curve that the use of distillation column improves the performances of the installation notably, the increase in the COP varies from (30%) to (70%) according to T_B, and that the temperature threshold of operation T_B decreased by approximately 25°C (75°C), which enables us to use simple plane collectors which are available and less expensive.

We can also observe that the coefficient of performance COP, decreases quickly according to the temperature of the hot source T_B, in the case of the machine without a distillation column that in the case of the machine with a distillation column.

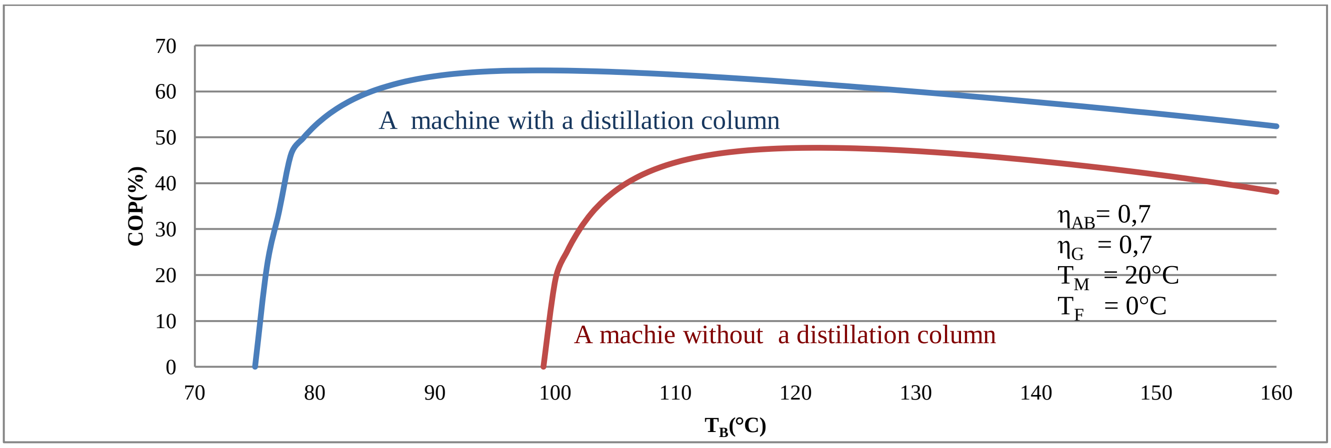

Figure 7: *Evolution of the coefficient of performance for the two machines with and without a distillation column according to the temperature T_B*

5.1.2. Second case T_M =25°C and T_F = 0°C

The (Figure8) represents the COP of the two machines, with and without distillation column, according to T_B for T_M =25°C and T_F =0°C.It is apparent that, for the two machines, when the temperature of the hot source is increased, the coefficient of performance decreases, but the difference between the simple machine and the machine with distillation column is maintained and that the temperature threshold of operation T_B increases.

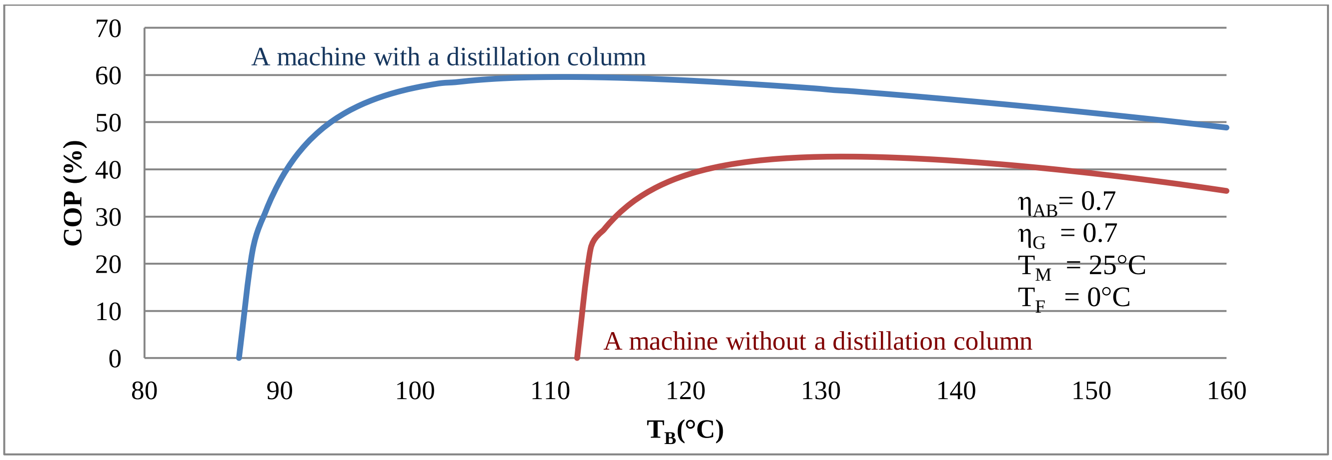

Figure 8: *Evolution of the coefficient of performance for the two machines with and without distillation a column according to the temperature T_B*

5.1.3. Third case T_M =20°C and T_F = 5°C

The (Figure 9) represents the COP of the two machines, with and without distillation column, according to T_B for T_M =20°C and T_F = 5°C.We note that, for the two machines, when the temperature of the hot source increases, the coefficient of performance increases, but the difference between the simple machine and the machine with distillation column is maintained and that the temperature threshold of operation T_B decreases.

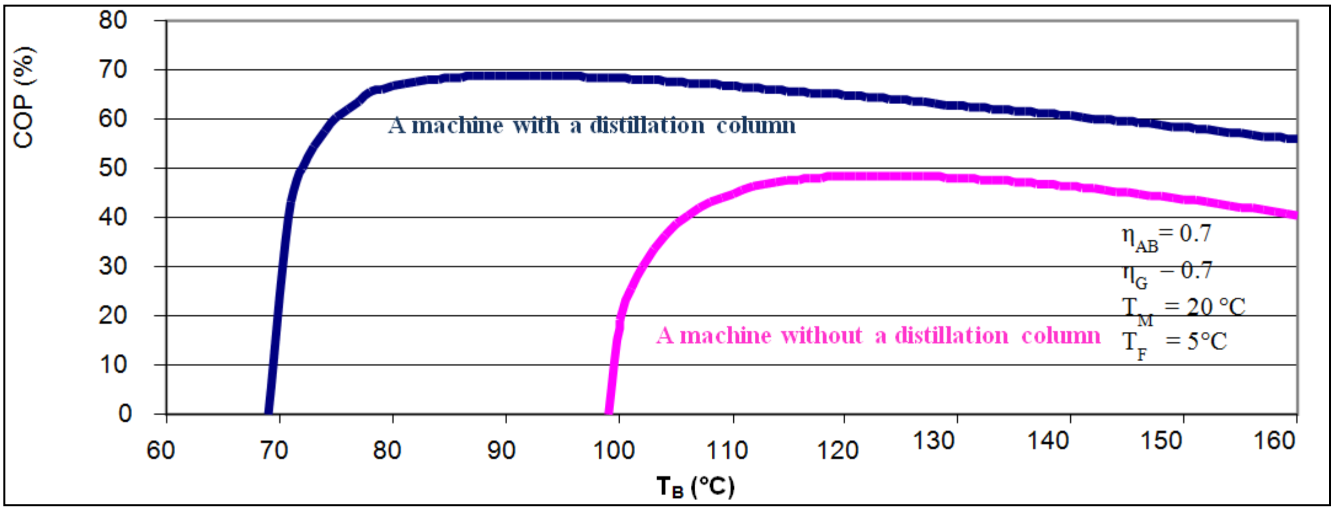

Figure 9: *Evolution of the coefficient of performance for the two machines with and without distillation a column according to the temperature T_B*

5.2. Comparison of the heat flows exchanged by the different elements of the machine

5.2.1. At the generator

The (Figure10) represents the heat flows exchanged by the generator according to T_B for T_F=0°C and T_M= 20°C. For the two machines, we note that the heat flow Q_G decreases when the temperature T_B increases. However, it is noted that the heat flow exchanged is lower than that of the simple machine.

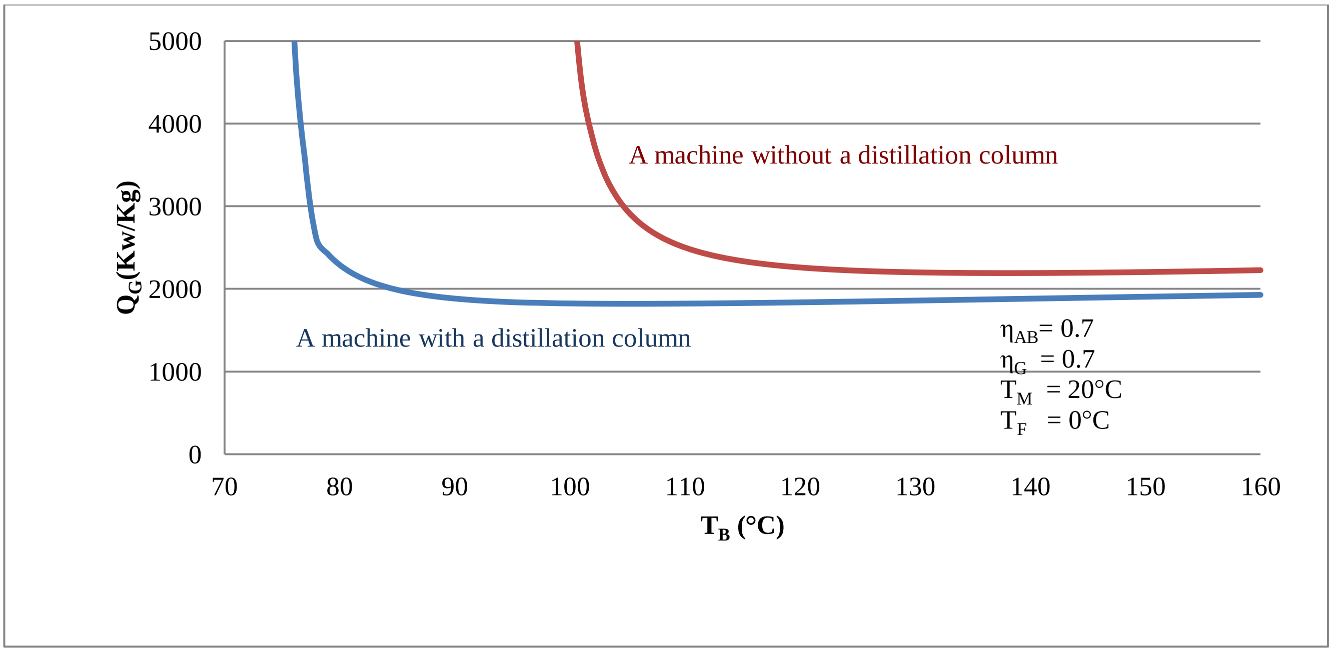

Figure 10: *Comparison of the heat flows exchanged in the generator of the two machines with and without a distillation column according to the temperature of the hot source*

5.2.2. At the evaporator

The figure represents the heat flows exchanged by the evaporator according to T_B for T_F=0°C and T_M= 20°C. For the two machines, we note that the heat flow Q_F decreases when the temperature of the hot source increases. However we observe that the simple machine's refrigeration effect is the most influential.

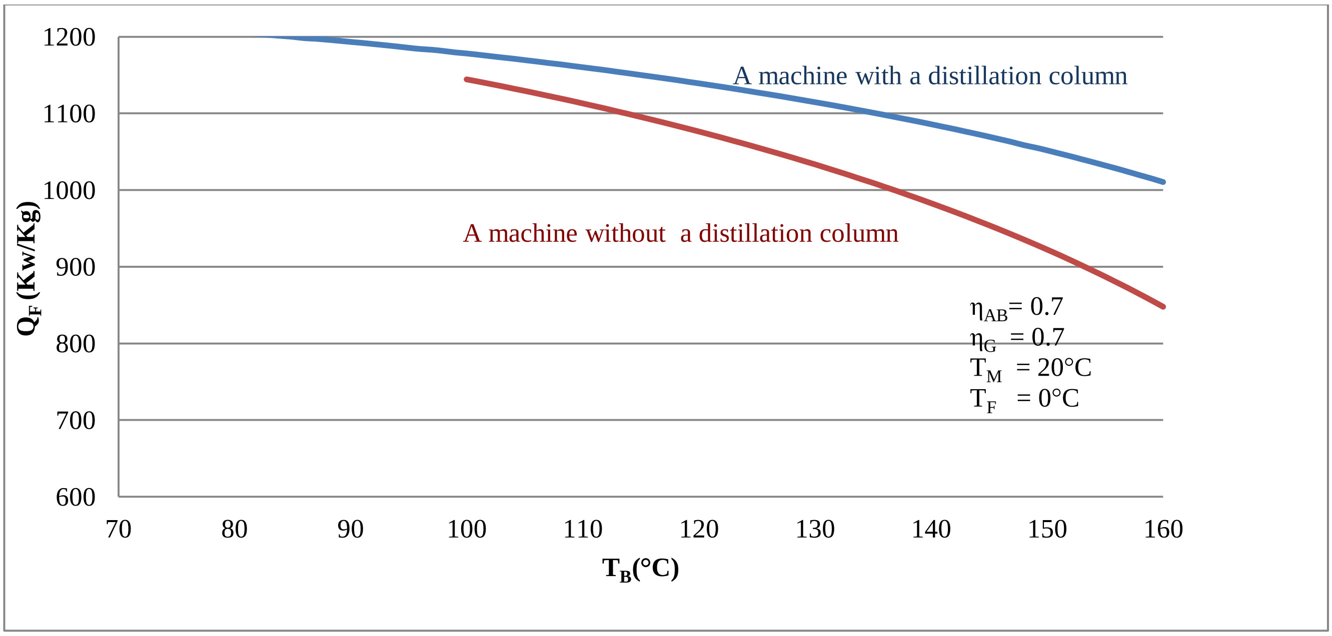

Figure 11: *Comparison of the heat flows exchanged with the evaporator of the two machines with and without a distillation column according to temperature of the hot source*

5.2.3. At the absorber

The figure represents the heat flows exchanged by the absorber according to T_B for T_F=0°C and T_M= 20°C. The heat flow is yielded by the absorber at the same pace in the two machines with the exception of the machine with distillation column the flow is recorded at a slightly higher temperature for the hot source.

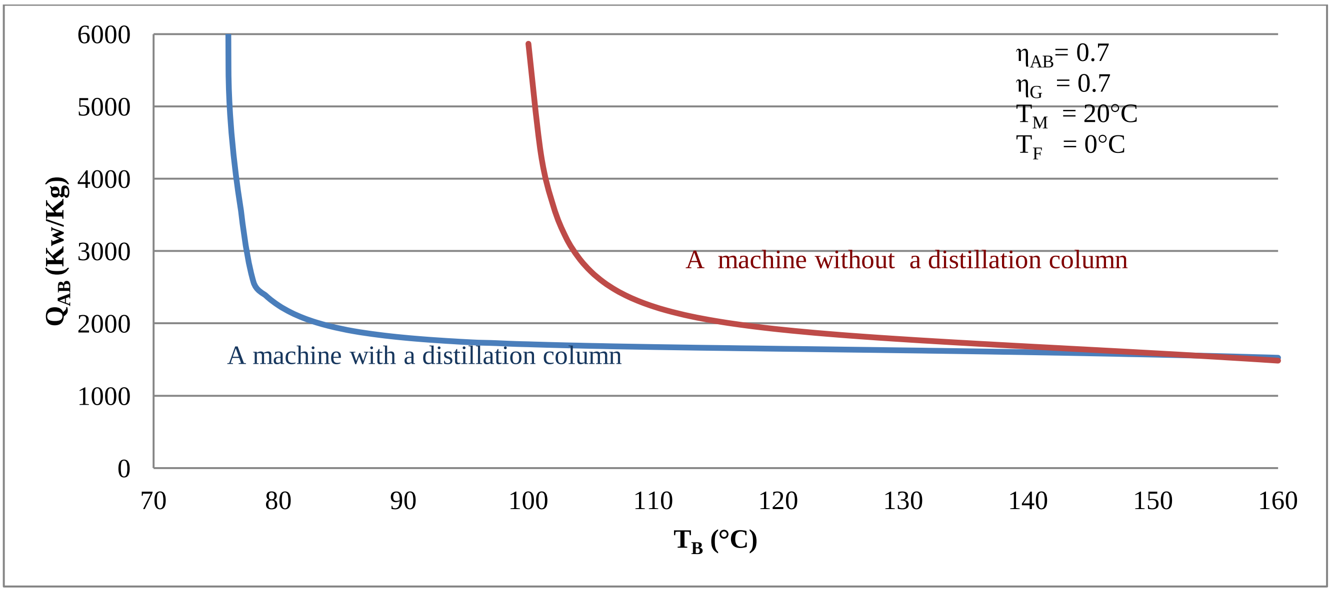

Figure 12: *Comparison of the heat flows exchanged in the absorber of the two machines with and without a distillation column according to the temperature of the hot source*

5.2.4. At the condenser

The figure represents the heat flows exchanged by the condenser according to the temperature of the hot source for T_F=0°C and T_M= 20°C. For the two machines, we note that the heat flow decreases when the temperature of the hot source increases.

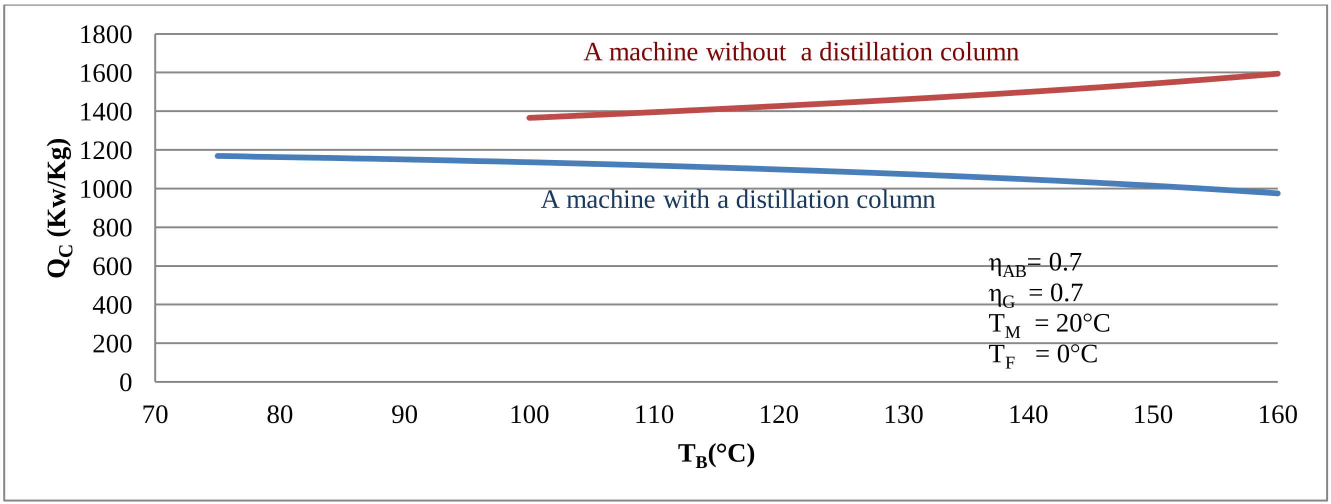

Figure 13: *Comparison of the heat flows exchanged in the condenser of the two machines with and without a distillation column according to the temperature of the hot source*

Conclusion

The results obtained show a clear improvement of the coefficient of performance of this machine, an increase which exceeds (30%).The results show also a notable reduction in the temperature threshold of operation of the hot source, which has an impact on the choice of the solar collectors. And instead of using vacuum sensors in the machine with simple absorption, it is possible to use simple plane collectors in this machine equipped with a distillation column. This has an effect on the equipments economic aspects and it's availability on the market.

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