24th COBEM - 2017

24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-2858
VIABILITITY STUDY OF AN ABSORPTION CHILLER FOR THE CLIMATIZATION OF A SHOPPING CENTER IN TERESINA, PIAUÍ

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Abstract. *The objective of this work is to perform an analysis of a single-effect water-lithium bromide absorption chiller with indirect burning of LPG (Liquified Petroleum Gas) for a thermal load of 1758,43 kW of a Shopping in Teresina, Piauí. To carry out the viability of using an absorption chiller, the energy analysis was developed to determine the required heat and mass transfers and the coefficient of performance (COP). Also was developed the exergetic analysis, to define the irreversibilities and the efficiency of Second law of each component. It was observed that the flow of chilled water influences the internal and external heat flows transferred in the heat exchangers. The COP found was 0.7301. The exergetic efficiencies of the components present satisfactory values as well. The mass flow rate of LPG required to provide heat to the hot water was calculated and, also, the cost of this fuel for an absorption chiller of 1758,43 kW. It has been verified that due to the high LPG cost, although the system has a good energetic performance, the use of this fuel for refrigeration systems with a big capacity is not attractive economically.*

Keywords: *absorption, chiller, energy analysis, exergy analysis)*

1. INTRODUCTION

Air conditioning systems are essential for human comfort and has been widely used in residential, commercial and industrial environments. Electricity has been utilized to power these systems in the past decades (Patel *et al,* 2016). Parallel to this, the population growth in conjunction with the great use of technology led to the raise of the energy consumption (Mohammadi *et al*, 2017). Along with that, according to Al-Sulaiman *et al* (2010), the decrease of the fossil fuel sources resulted in a search for other sources of energy.

Besides that, the energy obtained through fossil fuel has a considerable environmental impact, such as the emissions of greenhouse gas (Khaljani *et al*, 2015). In this context, absorption refrigeration systems have been a great alternative, considering that its electricity consumption of the power grid and its emissions of greenhouse gas are very low (Arrieta *et al,* 2016).

Absorption chillers uses different energy sources, such as solar energy, waste byproduct heat, geothermal, biomass and other fuels, like the natural gas and LPG (Liquified Petroleum Gas). Although, these systems have a lower coefficient of performance (COP), a larger size and a high capital cost (Gupta *et al*, 2015) than the vapor compression system, they operate with better environmental conditions (Kilic and Kaynakli, 2007).

The analysis of this system is performed by the first and second law of thermodynamic. The first law only provides a quantative measurement, showing the COP, the heat removed and the power input. The second law describes the quality of the energy, evaluating the exergy losses due to the irreversibilities, the exergetic efficiency and the entropy generation (Gogoi and Talukdar, 2014).

In order to reduce the electric power costs of the mall object of the study and to increase the efficiency of the refrigeration system, will be carried out an exergy analysis to identify the irreversibilities to improve the system and to verify the viability analysis of the replacement of a 1758,1 kW compression chiller for an absorption chiller, considering that the current thermal load of the mall is 4396 kW. The cooling fluid will be the water-lithium bromide pair and the system will be triggered by the indirect burning of LPG.

2. SYSTEM DESCRIPTION

The operation of an absorption refrigeration system is based on the characteristic of some fluids being sorbed by another solution or other liquids. In the absorber, the refrigerant (water) goes out the evaporator in the saturated vapor condition and mixes with the absorbent (strong solution in lithium bromide) from the generator. The solution in point 1 indicated in Fig.1 has a high concentration of water (weak solution in lithium bromide) and is pumped to increase its temperature and pressure. To improve the COP, it is included a heat exchanger between the generator and the absorber in order to occurs the heat recovery from the strong solution to the weak solution as pointed out by Villa *et al*, 2011.

After pumping the weak solution, there is a heat exchange in the regenerator and the solution goes to the generator, where occurs desorption. With the supply of heat from the burning of LPG, water evaporates, dissociating from lithium bromide. At 7, the water vapor, with a high temperature and pressure goes to the condenser. At 4, the strong solution is directed to the heat exchanger and its reduced pressure through a valve to return to the absorber.

The fluid in 8 leaves the condenser as a high pressure saturated liquid and goes to an expansion valve, where there is a reduction of the fluid pressure and its temperature in 9. At this stage the fluid is a mixture of liquid and vapor. In the evaporator, the refrigerant is now a saturated steam resulted by the phase change that occurred due to the heat exchange with the chilled water.

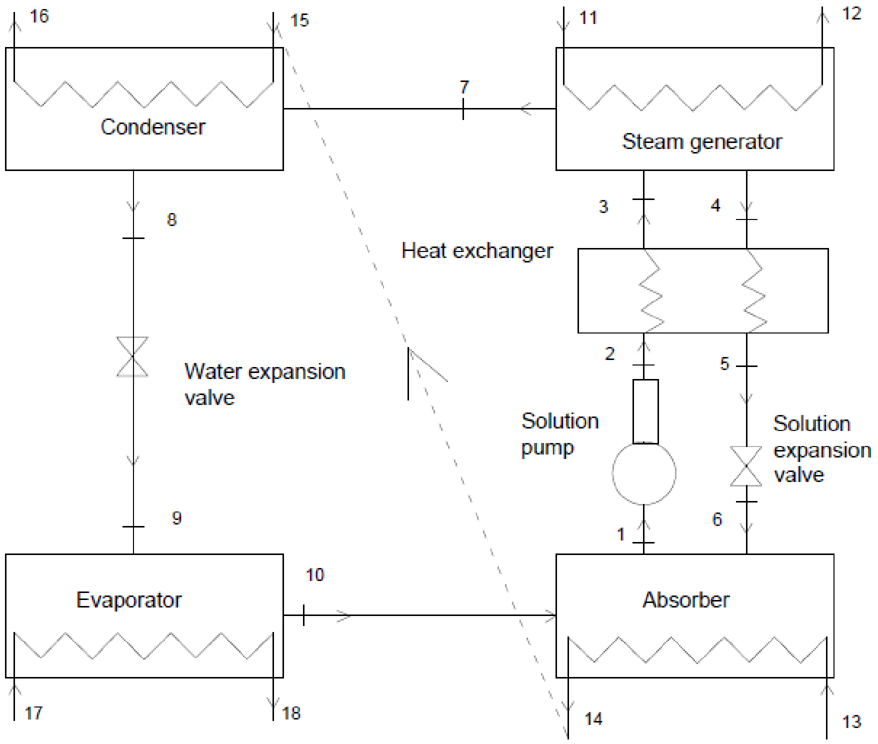

Figure 1. Control volum of the absorption refrigeration system in study.

3. THERMODYNAMIC MODELING

Energy and exergy balances were applied to calculate the heat exchanges, the irreversibilities and the performance parameters of first and second law. As a consequence, to verify the viability of the system, was calcutate the amount of LPG required to provide heat to the generator and the cost to provide this fuel. The following assumptions are considered to simplify the analysis:

1. The system operates in steady state conditions.
2. Kinect and potential energy are negligible.
3. The expansion valves are adiabatic.
4. The heat loss from the equipment to the environment are negligible.
5. Pump has constant isentropic efficiency.
6. The refrigerant is considered pure water.
7. States 8 and 10 are considered saturated.
8. The lithium bromide solution is in equilibrium condition at the outlet of the absorber and the steam generator.
9. The pressure drop by friction in the piping and in the heat exchangers are negligible.

3.1 Energy Analysis

This analysis is the application of first law of thermodynamics, the conservation law. The energy analysis was carried out based on the approach used by Herold *et al* (2016). Equation (1) can resume the mass balance:

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \tag{1}$$

Where $\dot{m}$ is the mass flow rate. The specific energy balances for the main components of the absorption chiller produces:

$$\dot{Q}_{evap} = \dot{m}_9 (h_{10} - h_9) = \dot{m}_{17} (h_{17} - h_{18}) \tag{2}$$

$$\dot{Q}_{cond} = \dot{m}_7 (h_7 - h_8) = \dot{m}_{15} (h_{16} - h_{15}) \tag{3}$$

$$\dot{Q}_{abs} = \dot{m}_{10} h_{10} + \dot{m}_6 h_6 - \dot{m}_1 h_1 = \dot{m}_{13} (h_{14} - h_{13}) \tag{4}$$

$$\dot{Q}_{ger} = -\dot{m}_3 h_3 + \dot{m}_4 h_4 - \dot{m}_7 h_7 = \dot{m}_{11} (h_{11} - h_{12}) \tag{5}$$

$$\dot{Q}_{he} = \dot{m}_2 (h_2 - h_3) = \dot{m}_5 (h_4 - h_5) \tag{6}$$

$$\dot{W}_{pump} = \dot{m}_1 v (P_2 - P_1) \tag{7}$$

Where h is the enthalpy, $\dot{Q}$ the heat load and $\dot{W}$ the power. The subscripts evap, cond, ger, abs, he indicates evaporator, condenser, generator, absorber and heat exchanger, respectively. The COP can be obtained according to the Eq. (8).

$$COP = \frac{\dot{Q}_{evap}}{\dot{W}_{pump} + \dot{Q}_{ger}} \tag{8}$$

3.2 Exergy analysis

Exergy analysis provides a more effective use of energy. The exergy (Eq.9) can be defined as the maximum work that could be obtained from a system at a specified state (Ahmadi *et al*, 2012). This property can be divided in four components: physical, chemical, kinect and potential. In this study, only the physical was considered meanwhile the changes in elevation and speed are negligible and the control volum does not include the combustion process (where this part of exergy has a significant value).

$$ex = (h - h_0) - T_0 (s - s_0) \tag{9}$$

Where *ex* is the exergy, *h* is the enthalpy, *T* the temperature and *s* the entropy. The subscript *0* refers to the dead state.

From the concept of exergy it can be calculated the exergy destruction of each component. The exergy destruction is the part of exergy that is lost due to the irreversibilities, expressed as follows:

$$I_{evap} = \dot{m}_{17} ex_{17} - \dot{m}_{18} ex_{18} + \dot{m}_9 (ex_9 - ex_{10}) \tag{10}$$

$$I_{cond} = \dot{m}_{15} (ex_{15} - ex_{16}) + \dot{m}_7 (ex_7 - ex_8) \tag{11}$$

$$I_{abs} = \dot{m}_{13} (ex_{13} - ex_{14}) + \dot{m}_{10} ex_{10} + \dot{m}_6 ex_6 - \dot{m}_1 ex_1 \tag{12}$$

$$I_{ger} = \dot{m}_{11} (ex_{11} - ex_{12}) + \dot{m}_3 ex_3 - \dot{m}_4 ex_4 - \dot{m}_7 ex_7 \tag{13}$$

$$I_{he} = \dot{m}_2 (ex_2 - ex_3) + \dot{m}_4 (ex_4 - ex_5) \quad (14)$$

$$I_{pump} = \dot{m}_1 (ex_1 - ex_2) \quad (15)$$

Where I is the irreversibility, ex the exergy and $\dot{m}$ the mass flow rate. The exergy efficiency is the product exergy output divided by the exergy input (Ahmadi *et al*, 2012). It can be calculated as follows:

$$\eta_{evap} = \frac{\dot{m}_{17} (ex_{18} - ex_{17})}{\dot{m}_9 (ex_9 - ex_{10})} \quad (16)$$

$$\eta_{cond} = \frac{\dot{m}_{15} (ex_{15} - ex_{16})}{-\dot{m}_7 (ex_7 - ex_8)} \quad (17)$$

$$\eta_{abs} = \frac{\dot{m}_{13} (ex_{13} - ex_{14})}{\dot{m}_1 ex_1 + \dot{m}_{10} ex_{10} - \dot{m}_6 ex_6} \quad (18)$$

$$\eta_{ger} = \frac{\dot{m}_4 ex_4 + \dot{m}_7 ex_7 - \dot{m}_3 ex_3}{\dot{m}_{11} (ex_{11} - ex_{12})} \quad (19)$$

$$\eta_{he} = \frac{\dot{m}_2 (ex_2 - ex_3)}{\dot{m}_4 (ex_4 - ex_5)} \quad (20)$$

$$\eta_{pump} = \frac{\dot{m}_2 ex_2}{\dot{m}_1 ex_1 + \dot{W}_{pump}} \quad (21)$$

Where η is the exergy efficiency. The system efficiency is defined in Eq. (22).

$$\eta_{system} = \frac{\dot{m}_{17} (ex_{18} - ex_{17})}{\dot{m}_{11} (ex_{11} - ex_{12})} \quad (22)$$

3.3 LPG consumption and economic viability

The mass flow rate of fuel necessary to provides heat for the hot water, responsible for the desorption in the generator is given by Eq. (23).

$$\dot{Q}_{ger} = PCI.\dot{m}_{LPG} \quad (23)$$

Where $\dot{Q}_{ger}$ is the heat load changed, *PCI*, the lower calorific power and $\dot{m}_{LPG}$ the mass flow rate of LPG. The *PCI* value is 46008,2 kJ/kg (Pereira, 2006).

The cost of LPG (C_{LPG}) consumption should be lower than the cost of the electricity consumed (C_{kW}) by the compression chiller, in order to the system to be feasible (Eq. 24 e 25).

$$C_{LPG} = \dot{m}_{LPG}.N.T_{LPG} \quad (24)$$

$$C_{kW} = Pot..N.T_{kW} \quad (25)$$

Where N is the number of hours of annual operation, T the tariff of electric power and LPG in the national currency based on the year of 2016 (R$ 1,2941 for LPG and 0,622939 for electricity) and *Pot* is the power input of the compression chiller. In the case of the cost of LPG intend to be lower than the electricity, it will be calculated the economics parameters, such as the net present value and the payback. These factors indicate if it is possible to implant the new system and have a financial return in a period of time to equalize the initial investment.

3.4 Input Data

The input data are the necessary parameters to begin the analysis. The parameters related to the concentration and to the heat exchange effectiveness have been reported by Herold *el al* (2016). The others have been defined by mall air conditioning system operating conditions.

Table 1. Input parameters to the proposed system.

Parameter	Value
Chilled water inlet temperature	14 ºC
Chilled water outlet temperature	6 ºC
Cooling tower inlet water temperature	29,5 ºC
Cooling tower outlet water temperature	35 ºC
Concentration of the weak solution	56,50 %
Concentration of the strong solution	62,20 %
Heat exchanger effectiveness	0,64
Cooling capacity	1758,43 kW

4. RESULTS AND DISCUSSIONS

In this study, a simulation program has been developed in EES software to analyze the system. Table 2 lists the main data of the cycle and the comparison between the reference. These results are also compare with Patel *et al* (2016).

Table 2. Important parameters results of the absorption chiller proposed.

Parameter	Symbol	Herold *et al*	Patel *et al*	Present Work
Temperature of the weak solution leaving the absorber (ºC)	T_1	32,72	34,9	32,7
Temperature of H_2O vapour leaving the generator (ºC)	T_7	76,76	90	74,15
Temperature of H_2O liquid leaving the condenser (ºC)	T_8	40,06	44,3	36,99
Pressure in the condenser (kPa)	P_8	7,406	9,66	6,275
Temperature of strong solution leaving the generator (ºC)	T_4	89,36	90	85,7
Pressure in the evaporator (kPa)	P_{10}	0,676	_	0,8721
Temperature of H_2O leaving the evaporator (ºC)	T_{10}	1,39	6	4,99

The implication of these values will be discussed later. Using the above data and calculating the thermodynamics property, the heat transfer rates and the performance indicator are defined and their values are shown in Tab. 3.

Table 3. Energy analysis results of the absorption chiller proposed.

Component	$\dot{Q}$ (kW)
Evaporator	1761
Condenser	1857
Generator	2412
Absorber	2315
Heat exchanger	467,2
COP	0,7301

As the heat transfers are much higher than the references, Tab.4 demonstrates how the heat transfers rates are modified by the cooling capacity.

Table 4. Variation of the heat transfer rate with the cooling capacity.

Cooling Capacity (kW)	Heat transfer rate in the absorber (kW)	Heat transfer rate in the condenser (kW)	Heat transfer rate in the evaporator (kW)	Heat transfer rate in the generator (kW)	Heat transfer rate in the heat exchanger (kW)	COP
17,581	23,14	18,56	17,59	24,1	4,668	0,7301
384,107	505,3	405,3	384,3	526,3	102,0	0,7301
841,888	1108,0	888,7	842,7	1154,0	223,6	0,7301
1300,000	1711,0	1372,0	1301,0	1782,0	345,2	0,7301
1758,1	2314,0	1856,0	1759,0	2410,0	466,8	0,7301

The considerable increase of the rates can be observed as the cooling capacity rises. The COP keeps constant because it is calculated by the ratio between the heat load of the evaporator and the generator. As both increase in the same proportion, the value remains the same. However, the COP varies with other factors. Figure 2 shows the influence of the temperature of the strong solution leaving the generator (T_4).

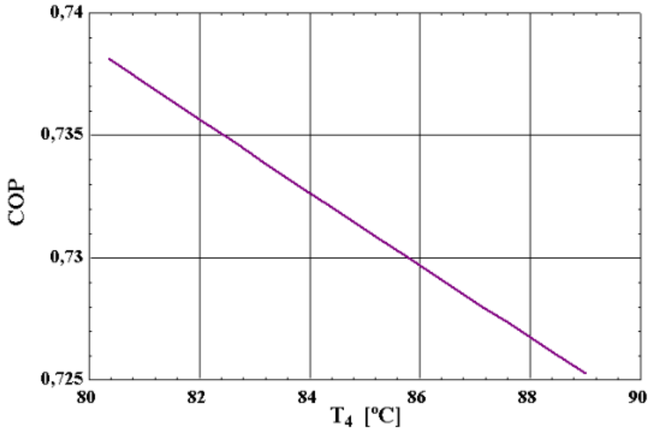

Figure 2. Relation between COP and the solution outlet temperature of the generator.

Increasing this parameter leads to a lower COP. Nevertheless, adopt lower temperatures has a negative impact on the other variables of the system, such as irreversibilities and exergy efficiency. Figure 3 shows the variation of the COP with the weak solution concentration.

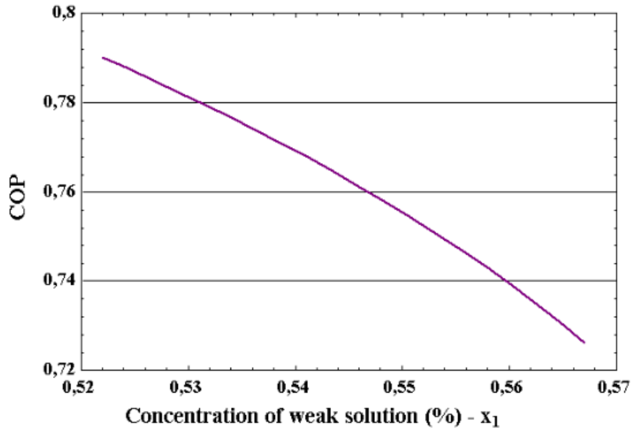

Figure 3. Relation between COP and concentration of weak solution.

As lower is the concentration, higher the COP is. However, values below 55% are not possible due to the LiBr solution commercialization. Figure 4 indicates the influence of the strong solution concentration. The COP increased as the concentration also increases. However, it is not desirable adopt a value higher than 63% owing to the severe risk of crystallization of LiBr solution.

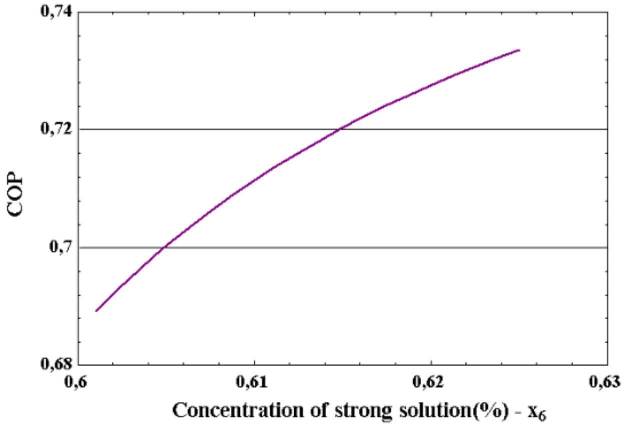

Figure 4. Relation between COP and concentration of strong solution.

The results of exergy analysis are presented in Tab. 5. The generator shows the higher value of irreversibility. It is also the component that has the higher heat exchange. It was observed that the components in general presents a good exergy efficiency.

Table 5. Exergy analysis results of the proposed system.

Component	Irreversibility (kW)	Exergy Efficiency
Evaporator	33,27	0,7354
Condenser	30,18	0,6001
Generator	136,2	0,7468
Absorber	121,9	0,3146
Heat Exchanger	51,87	0,1236
System	373,42	0,1719

These values suffer the influence of the operation of the system. Figure 5 demonstrates the relation among the exergy efficiency and the low pressure of the cycle.

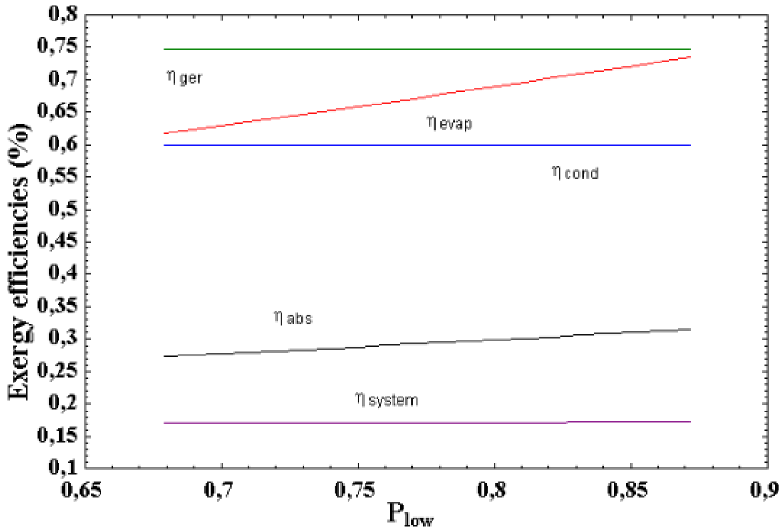

Figure 5. Relation among the exergy efficiencies and the low pressure of the proposed system.

The components that operates with the low pressure are the absorber and the evaporator. They both has a higher efficiency as the low pressure increases. Figure 6 presents the relation among the exergy irreversibilities and the low pressure. Again, the absorber and the evaporator are affected. The irreversibility falls as the value of the low pressure rises.

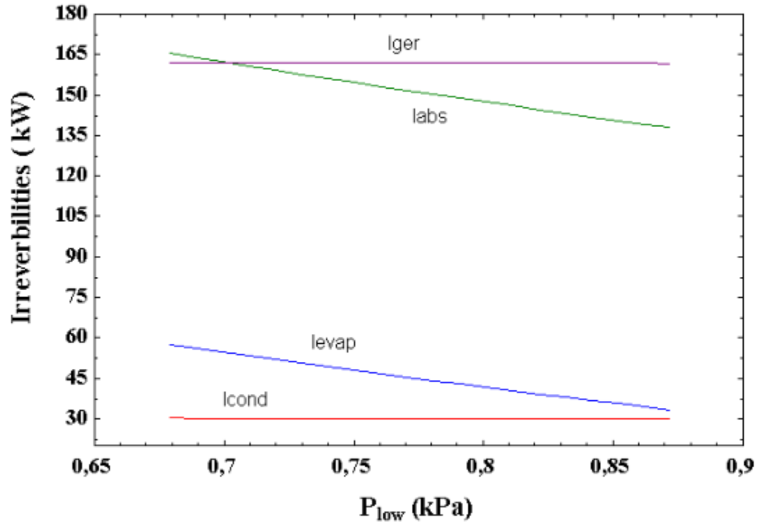

Figure 6. Relation among the irreversibilities of the main components and the low pressure of the proposed system.

Figure 7 shows the influence of high pressure on the exergy efficiency and Fig. 8 demonstrates this influence on the irreversibilities. The generator and the condenser are the components affected in different ways in both cases. As the exergy efficiency in the generator get higher, in the condenser get lower. And as the irreversilibity of the generator decreases with the increase of high pressure, the irreversibility on the condenser rises.

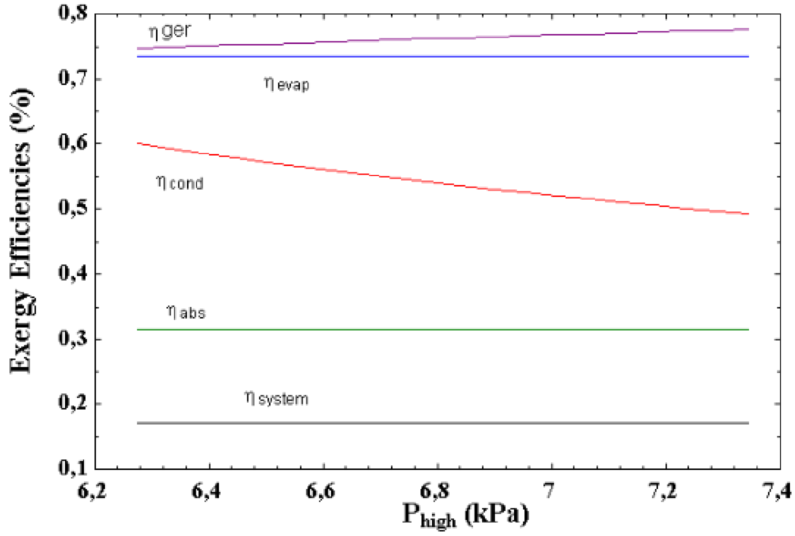

Figure 7. Relation among the efficiencies exergy of the main components and the cycle and the high pressure of the proposed system.

After the fuel flow rate was calculated. The value found was 0,05252 kg/s. Pereira (2006), in a theorical-experimental study for 17,58 kW system, found a value of 0,000727 kg/s. This difference occurs due to the cooling capacity of the system in the present study to be much higher than the reference. To evidence this point, Fig.9 shows how the fuel rate rises as the water chilled flow increases. This parameter is directly influenced by the cooling capacity.

To estimate the cost of the fuel and to compare to the electrical energy necessary to the compression chiller, a number of 4464 hours of annual operation was established based on the mall opening hours. The result can be seen in Tab. 6.

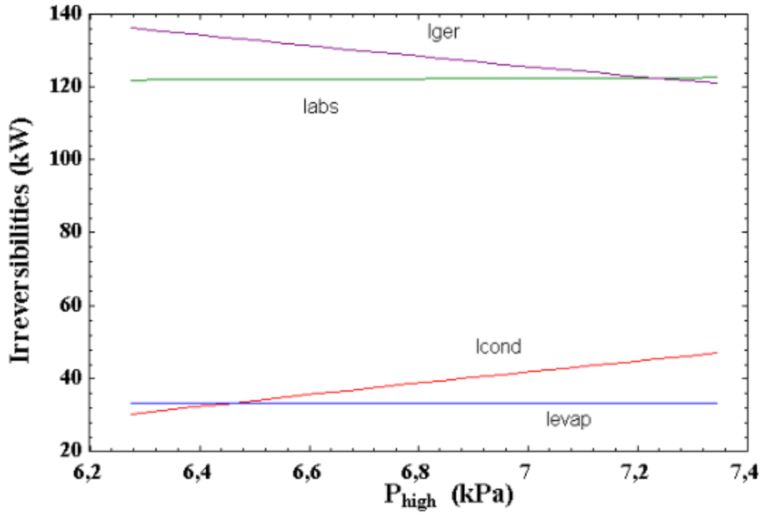

Figure 8. Relation between the irreversibilities of the main components and the high pressure of the proposed system.

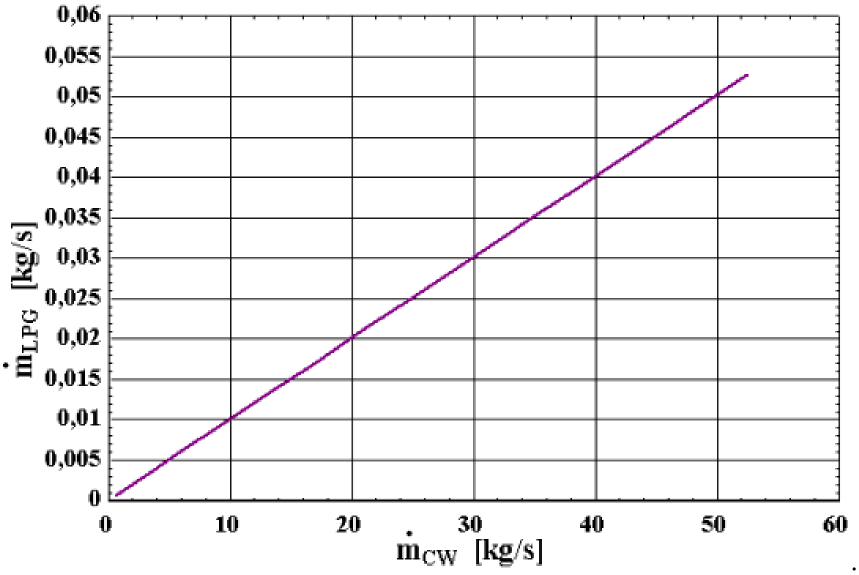

Figure 9. Relation between the LPG consumption and the water chilled flow rate of the system proposed.

Table 6. Comparison of the costs between the absorption and compression chiller based on the type of energy.

Type of energy	Cost
LPG	R$ 1.090.093,935
Eletricity	R$ 834.239,9088

The absorption chiller has a higher cost than the compression chiller due to the elevated fuel flow rate and the price fare. Therefore, the economic parameters are not necessary, since the operation cost is already high.

5. CONCLUSIONS

In this study, an absorption refrigeration system was proposed to replace a compression chiller of 1758,1 kW in a mall in Teresina, Piauí. The working fluid was the pair water-lithium bromide moved by the indirect burning of LPG.

The energy and exergy analysis was performed to quantify the values of interest, such as heat transfer rates, irreversibilities and First and Second Law efficiencies related to the absorption refrigeration cycle. Although with a good energy performance, it was verified that the absorption system using LPG does not have economic viability since this fuel has a very high tariff and a high consumption.

In order to make the system feasible, a study can be carried out to use the heat that is being discarded into the environment to exchange heat with the water to be used in the mall's food stores.

For future works, it is proposed to carry out a feasibility study of a double-effect chiller driven by direct burning to supply the mall's thermal load. In addition, the possibility of using diesel oil or biomass can be studied.

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