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EXERGY ANALYSIS OF A COMPRESSION CHILLER USED IN THE COOLING SYSTEM OF A PUBLIC HOSPITAL AT TERESINA – PI

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Abstract. *The first law of thermodynamics is about the amount of energy and ways of which it can be transformed. Exergy analysis, which is an application of the Second law, establishes the necessary ways to preserve power quality, quantifying a level of perfection. This paper aims to perform a thermodynamic analysis in a cooling system that consists in a compression chiller of a public hospital in Teresina-PI. The system has a cooling capacity of 200 TR. The software EES - Engineering Equation Solver was used to calculate the thermodynamic properties and energetic and exergetic efficiencies of the components. It was verified that the system has good energy efficiency and has a high cooling capacity. However, its condenser does not show good exergetic efficiency, and therefore the efforts to improve the performance of the chiller should be concentrated on this component.*

Keywords: *exergy analysis, thermodynamics, cooling system, energy efficiency*

1. INTRODUCTION

Refrigeration is defined as a process of temperature decrease of a place so that the humidity and air exchange are controlled. A refrigeration cycle can be applied for industrial process or for thermal comfort (Jain, *et al*, 2013). The search for thermal comfort has resulted in an increase of the demand for electricity (Shekarchian, *et al*, 2011). This fact proves that it is necessary to develop more efficient air conditioning systems (Xu and Chen, 2013). As a hospital must have a high level of thermal comfort to ensure the health of their patients, a study of the air conditioning efficiency system has a great importance. The refrigeration of the hospital is done by a chilled water system.

Chillers can work by compression, by absorption and by adsorption. The hospital has a compression chiller. It includes a compressor, an evaporator, a condenser and a metering device. Water chillers have a flow of cooling water leaving from a cooling tower passing through their condensers and a flow of chilled water passing through their evaporators to deliver the required cooling capacities (Hassan, 2012). It is used when the cooling system has a great demand.

The present work aims to analyze how efficient is the water chilled system. To make this analysis, the first law of thermodynamics is not sufficient since it considers only the quantity of the energy used. Therefore, to inquire the quality of energy consumption, the second law of thermodynamics must be applied (Mohammadi and Ameri, 2013; Koroneos, *et al*, 2011). Thus, it is important to define the appliance of the second law, the exergy. According to Çengel and Boles (2010), it can be described as useful work potential of a given amount of energy in a specified state. This property can be understood as the energy available in a system. For this to be established, it is necessary to designate an initial state, to despise the irreversibilities and that the system should be in thermodynamic balance with the environment (dead state). In real processes, there is an undoable work balance, which gives a measure of the irreversibility of the process.

From this concept, an exergetic analysis of the chiller can be performed, making the identification and quantification of irreversibilities, comparing their input and output exergy and calculating the exergetic efficiency. In this way, an analysis of a thermodynamic system determines the energy limitations of a process. In this paper, the analysis of the chilled water system of a public hospital of Teresina will be done.

The chiller is composed by an electric compressor with the capacity of 200 TR. For calculation of thermodynamic properties, the software EES (Engineering Equation Solver) was used. Through this program, it will be possible to determine which system component loses more energy, considering its destroyed exergy (irreversibility) and its exergetic efficiency. As a result, it will be possible to suggest improvements in the component therefore making the system more efficient and more economical, and wasting less electricity.

2. SYSTEM DESCRIPTION

The chilled water system is basically composed of three electric chillers with a refrigeration capacity of 600 TR. Each one consists of a screw compressor with maximum power of 173.10W, a condenser of 2 passes, storage capacity of 0.226 m³ of water with maximum flow of 0.083m³/s, an expansion valve and an evaporator of 3 passes and storage capacity of 0.311 m³ of water and maximum flow of 0.104m³/s. The system also includes three cooling towers, one for each condenser, several fan coil units responsible for cooling the entire area of the hospital and auxiliary components, such as pumps, water distribution networks and flow control valves. The refrigerant fluid is R-134a and each chiller has a refrigerant charge of 238 kg. It is important to mention that only two chillers are used simultaneously, and the other is reserved for possible failures. The control volumes for the application of the exergy method are restricted to a single chiller.

The compression chiller aims to remove heat from the water, thus lowering its temperature. This occurs through a simple cooling system, which operates as it follows: the screw compressor increases the refrigerant pressure to the pressure required so it can be condensed. On the condenser, R134-a rejects heat to the water that goes to the cooling tower. Afterwards the fluid is directed to an expansion valve that reduces pressure of R-134a and is then immediately led to an evaporator. At this time, the refrigerant exchange heat and cools the water that goes to the fan coil units, cooling the different areas of the hospital. Figure 1 shows a representation of the hospital chilled water system.

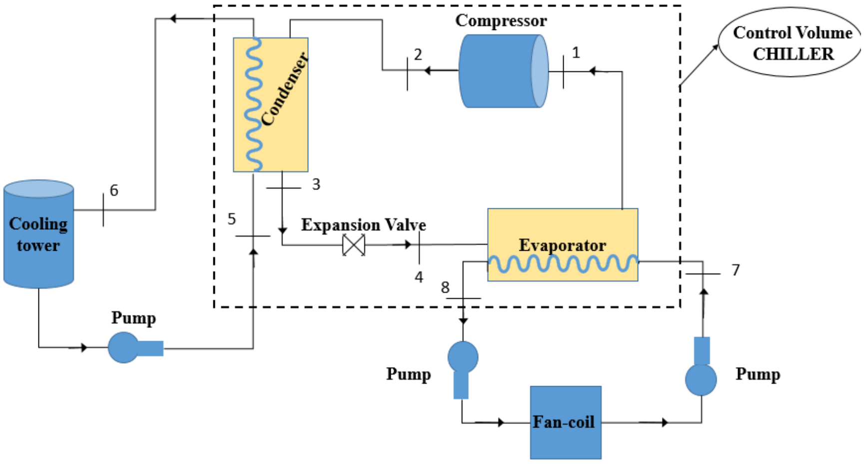

Figure 1. General representation of the hospital cooling system included the control volume (Chilled water system).

In the process 1-2, the work enters in the system through the compressor and in step 2-3, the refrigerant loses latent heat to the water from the cooling tower. At 3-4, the expansion valve decreases the pressure of the fluid and in the process 4-1, it is possible to verify the exchange heat in the evaporator where the refrigerant gains sensible heat from the water that goes to the fan coil units.

3. THERMODYNAMICS ANALYSIS

3.1 Energy analysis

Based on the first law of thermodynamics, the energy analysis can be done applying the laws of conservation of mass and energy in each component. The energy balance applied to each process of the system was (Eq. 1):

$$\frac{dE}{dt} = \dot{Q} - \dot{W} \tag{1}$$

where dE/dt is the time rate of the change of the energy included in the system at time t; $\dot{Q}$ is the net rate energy that is being transferred by heat at time t; and $\dot{W}$ is the net rate energy that is being transferred out by work at time t (Moran and Shapiro, 2006).

The mass fraction ($\dot{m}$) of the fluid R-134a was calculated by refrigerant effect ($\dot{Q}_L$) system, which is the cooling capacity for a refrigeration system in kW/s provided by the manufacturer of the chiller (Eq. 2)

$$\dot{Q}_L = \dot{m}(h_s - h_e)_{evaporator} \tag{2}$$

where h_s is the output enthalpy and h_e the input enthalpy.

To complete the analysis of the first law, the coefficient of performance (COP) of the refrigerator (Eq. 3) was calculated.

$$COP = \frac{\dot{Q}_L}{\dot{W}} \tag{3}$$

Assumptions which were considered to analyze the system energetically:

1. Flow in Steady State;
2. Adiabatic process;
3. Potencial energy change is zero;
4. Kinect energy change is zero;
5. Constant properties;
6. The global heat transfer coefficients are assumed constant throughout the process.

3.2 Exergetic analysis

The study of exergy determines the potential of useful work at a specified state. For exergetic analysis it was considered the physical exergy (*exf*), which is the maximum work when the system goes out of its original state and reaches the dead state, when it is in thermodynamic balance with the environment (reference temperature named T_0). The exergy of each point of the system in different states is given by Eq. 4 and was calculated using the fluid enthalpy(h), the enthalpy reference(h_0), the entropy s and s_0 represented by the fluid entropy and the entropy reference, respectively (Eq.4).

$$exf = (h - h_0) - T_0(s - s_0) \tag{4}$$

The equations used to calculate the destroyed exergy and exergetic efficiency of each component as well as the complete system are show as it follows. All formulas used for the calculation were based on Çengel and Boles (2010).

3.2.1 Exergy balance of the evaporator

The destroyed exergy from the evaporator ($\dot{X}_{dest}$) corresponds to the difference between variation exergy of the working fluid in the evaporator and the exergy of the heat flow ($\dot{Q}_L / T_L$) received from the water (Eq.5)

$$\dot{X}_{dest,evap} = T_0\left[\dot{m}(s_s - s_e) - (\dot{Q}_L / T_L)\right] \tag{5}$$

where s_s is the output entropy; s_e the input entropy and T_L the temperature of the cooled water.

The exergy efficiency of this component (Eq.6) is the ratio of the exergy rate recovered (the removed heat multiplied by the difference of temperatures divided by T_L), and the exergy rate provided

$$\varepsilon_{evap} = \frac{\dot{Q}_L (T_0 - T_L) / T_L}{ex_e - ex_s} \tag{6}$$

where ex_e is the input exergy and ex_s the output exergy.

3.2.2 Exergy balance of the condenser

The equations for calculating the destroyed exergy (Eq.7) and exergetic efficiency (Eq.8) of condenser uses the same principle of the evaporator equation, changing only the heat flow, which becomes the heat rejected to the water ($\dot{Q}_H$)

$$\dot{X}_{dest,cond} = T_0\left[\dot{m}(s_s - s_e) - \frac{\dot{Q}_H}{T_H}\right] \tag{7}$$

$$\varepsilon_{cond} = \frac{\dot{Q}_H (T_0 - T_H) / T_H}{ex_e - ex_s} \tag{8}$$

where T_H is the temperature of the heated water.

3.2.3 Exergy balance of the compressor

In the compressor, the internal irreversibility (Eq. 9) is equivalent to the flow of exergy of the working fluid during the compression process.

$$\dot{X}_{dest,comp} = T_0 \dot{m}(s_s - s_e) \tag{9}$$

The efficiency of second law of this component (Eq.10) is defined by the ratio between the reversible work (difference between exergies) and the useful work (difference between enthalpies).

$$\varepsilon_{comp} = \frac{ex_s - ex_e}{h_s - h_e} \tag{10}$$

3.2.4 Exergy balance of the expansion valve

Since the valve does not have recoverable exergy, there is no exergetic efficiency. Its destroyed exergy (Eq. 11) is equal to the given.

$$\dot{X}_{dest,valv} = T_0 \dot{m}(s_s - s_e) \tag{11}$$

3.2.5 Exergy balance of the complete system

The destroyed exergy of the system (Eq. 12) is the sum of destroyed exergies of each component. The second law efficiency (Eq. 13) is the ratio between the power that can be produced by a reversible machine and the actual work cycle.

$$\dot{X}_{dest,total} = \sum \dot{X}_{dest} \tag{12}$$

$$\varepsilon_{total} = \frac{\dot{Q}_L (T_0 - T_L)/T_L}{W_{real}} \tag{13}$$

4. RESULT AND DISCUSSION

The data of pressure and temperature were observed in the chiller communication interface and are represented in fig. 2.

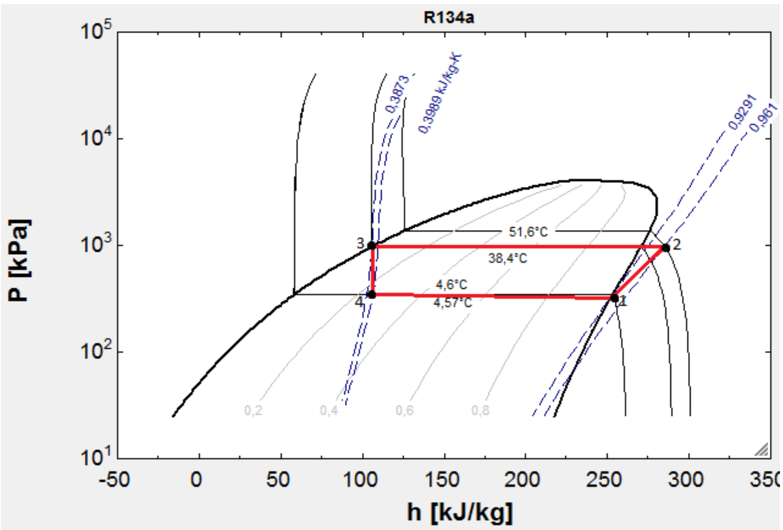

Figure 2. Diagram of pressure versus enthalpy of the hospital refrigeration cycle

The enthalpy and entropy were calculate using the software EES (Engineering Equation Solver) and can be seen below (Tab 1).

Table 1. Termodynamics properties of the refrigerant fluid R134a of the water chilled system calculated by the software EES

Points	Temperature (K)	Pressure (kPa)	Enthalpy (kJ/kg)	Entropy (kJ/kg.K)	Massic Fraction(kg/s)
1	277.75	344.7	253.1	0.9291	4.777
2	324.35	976	284.5	0.9597	4.777
3	311.55	976	105.9	0.3873	4.777
4	277.72	344.7	105.9	0.3989	4.777

It was possible to observe the real compressor work ($\dot{W}$), the system coefficient of performance (*COP*), the amount of heat absorbed by the refrigerant ($\dot{Q}_L$) and the amount of heat rejected ($\dot{Q}_H$) in the condenser (Tab.2).

Table 2. Result of the thermodynamic analyses of first law of the hospital refrigerator

$\dot{W}$ (kW)	$\dot{Q}_L$ (kW)	$\dot{Q}_H$ (kW)	COP
150	703.4	853.4	4.69

Finally, the exergetic analysis can be viewed through the destroyed exergy of each component and its exergetic efficiencies (Tab. 3). To perform the calculations, it was used the properties relating to the fluid R-134a at a temperature of 302.15 K and a pressure of 101 kPa. Moreover, the components were considered adiabatic without pressure drop.

Table 3. Exergetic analysis result of the hospital refrigerator

Components	Exergy (kJ/kg)	Destroyed Exergy (kW)	Exergetic Efficiency(%)
Evaporator	12.94	6.312	89.79
Condenser	5.7	15.55	42.94
Expansion Valve	3.51	16.74	-
Compressor	22.15	44.18	70.55
Total	44.3	82.782	37.01

The destroyed exergy reports how much energy is lost due to the irreversibility of the system. Although it has been observed that the compressor destroys more exergy, it is the component that provides more energy to the system. On the other hand, the condenser showed a low exergetic efficiency, which means there is little exergy recovered compared to the system provided by this component.

To analyze this low condenser efficiency, the proximity of the output temperatures of the refrigerant and water in the condenser should be investigated. It has been verified that fluid rejected heat at 311.55 K and the water receives until 306.35 K (temperatures obtained in the chiller interface). This suggests that energy transfer is not as efficient because water does not absorb too much heat, then the fluid rejects less heat than it should, therefore harming the efficiency of the thermodynamic cycle (Çengel and Ghajar, 2011).

This can occur due to various reasons. One of them is an inefficient thermal isolation, since the heat loss to the environment is not used by the system. There is also the possibility of encrustation on the condenser, which can reduce the heat transfer coefficient and hence the energy transfer. Additionally, the compressor may be operating at an inadequate pressure for the environmental conditions.

There are some options in order to increase the condenser's performance. One of them is to modify the working pressure of the compressor, so that the fluid output temperature decreases, and thereby may be a bigger heat exchange with the water. Another option would be to increase the area of heat exchanger to guarantee an improvement in heat transfer. This increase can be done by cleaning the tubes removing the encrustations (Çengel and Ghajar, 2011). Moreover, it is also important to check the conditions of thermal isolation.

It is worth to note that the evaporator showed great exergy efficiency and low destruction of exergy, which means that the exchange of heat between the fluid and the water that goes to the fan coil units is quite satisfactory. On the other hand, the expansion valve has a great amount of exergy that is destroyed due to the sudden pressure difference. There Carnot heat engine *COP* shows that to improve the performance of the refrigeration system, it is necessary to reduce the difference between the temperature that the fluid goes out of the evaporator and the one when it goes out of the condenser, in order to ensure the evaporation temperature to the highest possible and the condensation to the lowest possible (Stocker and Jones, 1985).

5. CONCLUSION

The system has a high efficiency when analyzed just energetically. When analyzing each component exergetically, it was observed that the condenser has a large deficit in its performance. Therefore, it needs to be improved so that the chiller could be better at its role. However, the system works well in its cooling function at the hospital, providing to the patients a high level of thermal comfort.

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