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EXPERIMENTAL ANALYSIS OF THE BEHAVIOR OF AN ABSORPTION REFRIGERATION SYSTEM USING A RESIDENTIAL SOLAR HEATING SYSTEM

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Abstract. *The present work deals with an experimental analysis of the behavior of a refrigerator with absorption system, with ammonia-water pair and single total pressure, using water from a solar heating system, commonly used in homes. The objective of this study is to evaluate the technical feasibility of the proposed system by comparing with the original heating system of the refrigerator, via combustion of LPG, as well as verify the impact on the water heating system as a temperature variation. It was noticed that the solar heating system obtained the expected temperatures for the environmental conditions present during the study, but the temperature and energy transferred from the hot water to the refrigerator were not enough to cause the evaporation of the ammonia and consequent cooling, which makes the proposed project unfeasible for the conditions under which the study was carried out.*

Keywords: *Solar Energy, Cooling by Absorption System, Flat Plate Collector, LPG Gas, Coefficient of Performance*

1. INTRODUCTION

Since the late century to the present times, refrigeration has become the main way used by humanity to conserve perishable products, such as foods and medications, in addition to the increasing demand for equipments and climate control systems, in order to improve human comfort in a house. Today it can be inferred that refrigeration is an essential technique to human subsistence into modern life standards.

As stated by a publication made by the Programa de Conservação da Energia Elétrica (PROCEL) published by Eletrobrás (2005), the residential sector stands for 24% of electrical power consumption of the whole country and, under this sector, refrigerations has a 32% share. Therefore, it can be said that only domestic refrigeration stands for 7% of the entire nation's electric power consumption. Other PROCEL's data indicates that 20% of nationwide power consumption are due to refrigeration equipment.

Among refrigeration systems that operate under heat source, the absorption one is the most common, due to its ability to harness dissipated energy from another process and the need of small or none power source. This makes solar systems very attractive as a thermal source, because it is clean and renewable. The coefficient of performance, COP, from refrigeration systems fed through thermal sources is as higher as the evaporation temperature of the refrigerant (DOSSAT, 2007).

2. THEORETICAL FOUNDATIONS

According to Dossat (2007), absorption refrigeration systems can contain two or more fluids necessary to its perfect functioning. Generally binary mixes are used, being one refrigerant fluid and the other an absorbent fluid, however there are cases where an inert gas is added in order to keep the necessary pressure to the system works, eliminating the need of pumping equipment. The systems still can be classified accordingly to their working cycle, being permanent or intermittent.

Absorption systems are more silent, free of vibrations and require less maintenance than vapor compression systems, in addition they are more simple than systems with the same power. However, the coefficient of performance is smaller in the absorption machine than the vapor compression system, in a relation of 1 to 4, considering the same working conditions (DOSSAT, 2007)

Srikhirin (2001) showed that, in absorption refrigeration systems that operate with single total pressure and water/ammonia pair, the coefficient of performance (COP) can vary between 0,05 and 0,2, depending on the heat absorption rate. Due to this, this kind of system become unfeasible when it needs to “pay” for the thermal source, however it shows extremely useful when the heat comes from another existing or natural process, as is the case of solar energy.

Based on this, studies and prototypes are being developed based on absorption refrigeration systems that uses the water/ammonia pair (H_2O-NH_3) and the heat from the sun as energy source. The ammonia stands out among other refrigerants due to its ability to provide temperatures below 273 K and low environmental impact.

2.1 Single Total Pressure Absorption Refrigeration Cycle

The fluxogram of a single total pressure absorption refrigeration is shown on Fig. 1.

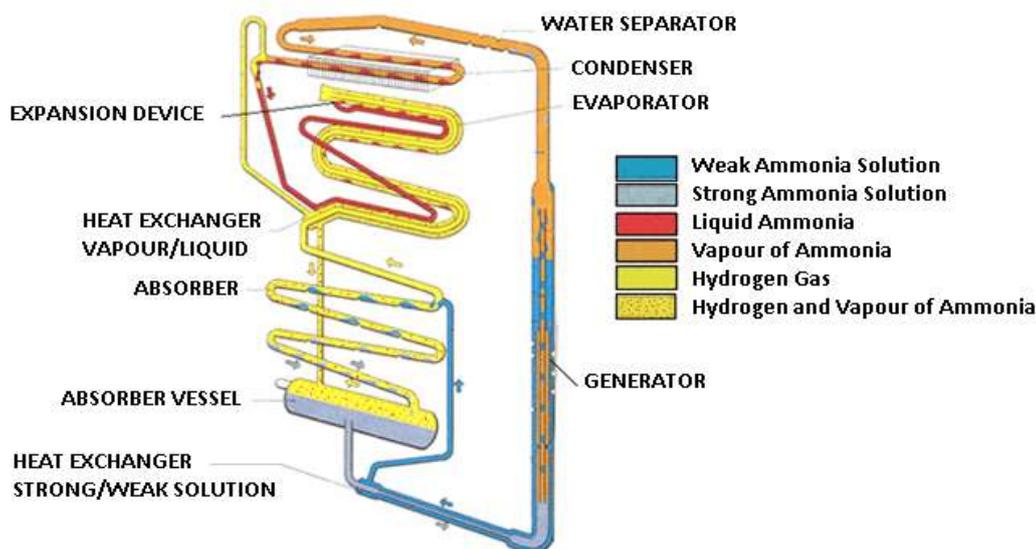


Figure 1. Basic Cycle of an Absorption Refrigeration System

The refrigerant vapor goes from the evaporator at low pressure in the form of superheated vapor or saturated, depending on the amount of heat absorbed in the refrigeration chamber’s interior, and is directed into the absorber vessel. The water present in the absorber vessel will absorb the ammonia vapor at low pressure forming a strong solution of ammonia at liquid state.

The hydrogen present between the condenser exit and the absorber vessel will pressurize the strong solution, making it flow until the generator. The absorber vessel and the syphon present in the exit of the condenser make liquid seals that prevent the migration of hydrogen to the generator, which could cause serious damage. It is worth noting that the hydrogen presence does not affect the evaporation pressure of the ammonia, due to Dalton’s Law, where the pressure of an homogeneous system mix, it will be equal to the mean of the partial pressures of each substance.

The strong ammonia solution is heated in the generator making that it dissolves the ammonia vapor (NH_3) and liquid water with low ammonia solution concentration, making a weak solution. The ammonia vapor goes through a rectifier, or water separator, whose objective is prevent the presence of water in the condenser, which affects negatively the

refrigeration process. The water that comes from the rectifier mixes into the weak solution and then is directed to the absorber where it will absorb the ammonia vapor that were not absorbed by the absorber.

From the condenser, the absorption refrigeration system has the same characteristics that a vapor compression system. The high-pressure ammonia vapor will transfer heat with the environment, making that it alters itself into liquid state. As it leaves the condenser, the liquid ammonia will pass through an expansion device, where it will reduce its pressure and consequently its temperature. Part of the liquid vaporizes due to the expansion process, therefore, forming a solution of liquid and saturated ammonia vapor at low temperature and pressure into the evaporator, thus allowing that the cycle restarts.

In order to enhance the system's efficiency, the heated weak solution in the generator transfer heat with the strong solution while it is directed back again into the absorber. In a similar way, the ammonia vapor, as it leaves the evaporator transfer heat with the condensed ammonia in the condenser exit, causing a pre cooling of the refrigerant.

2.2 Solar Heating System

The solar collectors are devices that can obtain the thermal radiation from the sun and transmit it to a fluid that flows into its insides. The flat-plate collectors generally are the more used to residential heating. This kind of collector is made of a metallic box closed with one or two glasses and in its interior there are pipes connected to the metallic plates, usually painted in matte black. Between the plates and the bottom of the box there is a thermal insulation, usually rock wool.

The thermal solar radiation has a short wavelength, ranging from 0,1 to 100 μm (INCROPERA et al., 2007). In respect of the flat-plate collectors, the thermal radiation will be focuses over the glass, going to the absorber plate. When hitting the absorber plate, the black painted surface will convert approximately 15% of the radiation in thermal energy, thus reflecting the rest with longer wavelength ($\lambda > 6\mu\text{m}$) (SHCUBERT, 1981). However the glass has the property of being transparent to radiation with short wavelength (range $0,25 < \lambda < 6\mu\text{m}$) and opaque to longer wavelengths ($\lambda > 6\mu\text{m}$) (INCROPERA et al., 2007). Due to this, the reflected radiation by the absorber plate is reflected once again by the glass, directing it once more to the absorber plate (greenhouse). This process repeats itself until all radiation that passes through the glass are converted in thermal energy (SCHUBERT, 1981). According to Schubert (1981), in a common flat solar collector, around 88% of the thermal radiation is absorbed, when the glasses have low iron level. The collectors with one glass allow to get temperatures among 343 and 353 K, with the possibility of reaching 373 K with two glasses (BEZERRA, 1982). As the absorber plates are connected to the pipes, a heat transfer by conduction and lately by convection until it reaches the work fluid.

2.3 Proposed Project

Sodré (2014) found the ammonia condensation pressure from the used refrigerator model being equal 1,522MPa, in tur Silveira (2010) found the value of 2,000MPa. In conformity with thermodynamic tables, these values indicate a condensation temperature of ammonia ranging from 313 to 323 K (ASHRAE, 2009). In accordance with Dossat (2007), commercial projects usually adopt a difference of 10 K between the refrigerant temperature and the environment due to the thermal resistances of the heat transfers. In the condenser, the refrigerant must be 10 K warmer than the environment, and in the evaporator, 10 K cooler. From this principle and considering the highest saturation temperature of the ammonia equals 323 K, it will be necessary that the hot water, coming from the solar heating system, achieves a minimal temperature of 333 K while passing through the generator, which is compatible with the flat-plate solar collectors with a single glass (BEZERRA, 1982).

3. METHODOLOGY

The equipments used was a refrigerator from Consul, model CQG22D, with nominal capacity of 205 liters, 16 temperature sensors, one temperature and relative humidity sensor, one flow sensor, one flat-plate solar collector with 2m area, from the Jelly Fish brand, model JFS 20 MAX, one boiler with nominal capacity of 200 liters, one rotative pump, from Emicol brand, model 322067 with 5 liters/min flow and 30W power to ensure hot water circulation through the refrigerator and a data acquisition system. The pump suction was connected in the superior part of the boiler, because the water is hotter in this point due to natural convection, and the discharge in the inferior part of the generator, where is the heat input, in accord with the manufacturer. The positioning of the sensor is shown in Fig. 2.

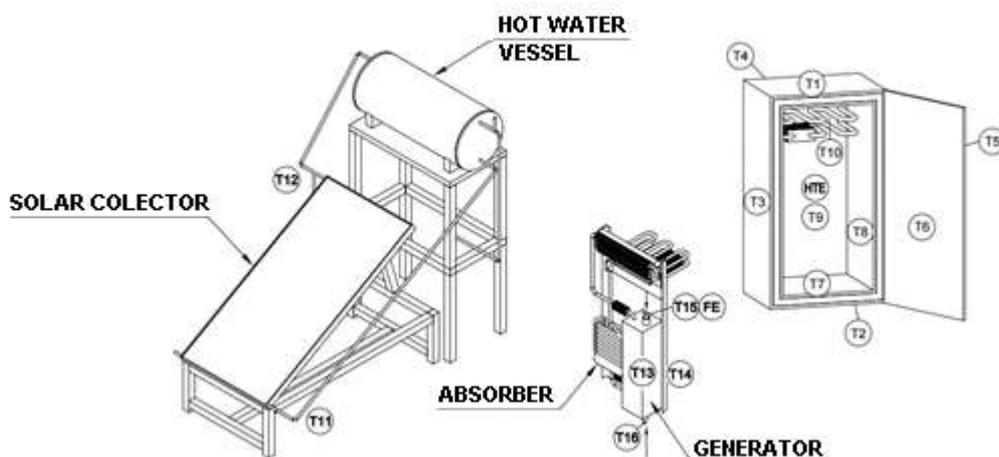


Figure 2. Position of the Sensors

Sensor identification and features shown in Tab. 1.:

Table 1. Features and TAGs of the sensors

Instrument	Range	Accuracy	Quant.	Place where installed	TAG	Utility
Analog temperature sensor LM35	from 218 to 423 K	$\pm 0,5$ K	13	Inside wall - side	T8	Parameters to measure the heat load through the refrigerator's wall
				Inside wall - top	T10	
				Inside wall - bottom	T7	
				Inside wall - back	T9	
				Outside wall - side	T3	
				Outside wall - top	T1	
				Outside wall - bottom	T2	
				Outside wall - back	T4	
				Inside door's surface	T6	
				Outside door's surface	T5	
				Inside generator's surface	T13	Parameters to measure the heat loss through the generator's isolation
				Outside generator's surface	T14	
				Environment	-	Parameters of comparison to verify the heat load behavior
Digital temperature sensor DS18B20	from 223 to 398 K	$\pm 0,5$ K	4	Solar collector's input	T11	Parameters to calculate the heat absorbed through the solar collector
				Solar collector's output	T12	
				Absorption system's generator's in	T16	Parameters to calculate the heat absorbed through the generator
				Absorption system's generator's out	T15	
Hall effect flow sensor YF-S201	from 1 to 30 l/min	$\pm 0,2$ l/min	1	Absorption system's generator's out	FE	
Digital relative humidity (RH) and temperature sensor DHT-22	from 0 - 100% (RH) from 223 to 398 K	± 2 % $\pm 0,5$ K	1	Inside the refrigerator	HTE	Parameters to calculate the refrigeration load

According to Manzela (2005) the internal temperature change to this kind of refrigerator is around 0,001 K/seg, due to this the measuring range is 1 minute. As the objective of this study is power efficiency, the heating electrical resistance from the vessel was turned off.

The heat given by the hot water system was determined by Eq. 1:

$$\dot{Q} = \dot{m}_{H_2O} C_p (T_{in} - T_{out}) - \dot{Q}_{loss} \quad (1)$$

Where: \dot{Q}_g is the heat given to the generator [W], \dot{m}_{H_2O} is the hot water mass flow [kg/s], C_p is the water's specific heat [J/kgK], T_{in} is the water temperature in the generator's input [K], T_{out} is the water temperature in the generator's output [K], \dot{Q}_{loss} are the thermal losses of the generator to the environment [W].

The heat loss in the system generator were determined through the analysis of the equivalent thermal circuit, shown in Fig. 3, where the measure of each material thickness was necessary.

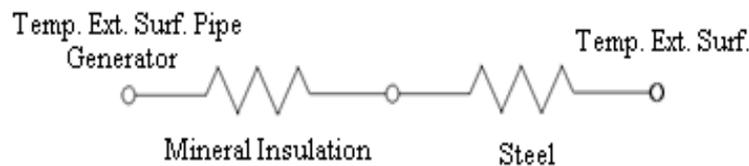


Figure 3. Equivalent Thermal Circuit for thermal loss in the generator.

In a similar way, the thermal load acting in the walls of the refrigerator can also be found through the analysis of its equivalent thermal circuit, as shown in Fig. 4.



Figure 4. Equivalent Thermal Circuit of thermal load in the walls

So these heat rates were calculated through Eq.2.

$$\dot{Q} = \frac{T_h - T_c}{R_{eq}} \quad (2)$$

Where: \dot{Q} is the transferred heat [W], T_h is the hot surface temperature [K], T_c is the cold surface temperature [K], R_{eq} is the equivalent resistance of each represented thermal circuit [K/W].

Considering the refrigerator as a closed system, is possible to apply the first Law of Thermodynamics, as shown in Eq. 3.

$$\frac{dU}{dt} = \dot{Q} - \dot{W} \quad (3)$$

Where, dU/dt is the internal energy variation rate in time [W], \dot{Q} is the sum of heat rates that enters the system [W] and \dot{W} is the sum of works that leaves the system [W].

As this equipment do not do work, $W=0$. The heat that enters the system is the thermal load that passes through the walls due to the temperature difference between the interior of the refrigerated space and the external temperature of the refrigerator. The heat that leaves the systems is the absorbed heat by the evaporator of the refrigerator, as shown in Eq. 4.

$$\frac{dU}{dt} = \dot{Q}_{hc} - \dot{Q}_{evap} \quad (4)$$

Where \dot{Q}_{bc} is the thermal load [W] and \dot{Q}_{evap} is the heat absorbed by the evaporator [W].

Considering that, in small measurement ranges, the internal energy vary linearly, is possible to express the internal energy variation as Eq. 5.

$$\frac{dU}{dt} = \frac{U_f - U_i}{\Delta t} \quad (5)$$

Where U_f is the internal energy in the end of the measurement rangel [J], U_i is the internal energy in the beginning of the range [J], Δt is the measurement range [s].

The internal energy of the air inside the refrigerated environment was determined through thermodynamic tables, through the internal relative humidity and temperature. To the calculation of its change in time the measurement range of 60 seconds was considered. Hence, it was possible to determine the refrigeration load through Eq. 6.

$$\dot{Q}_{evap} = \dot{Q}_{hc} - \frac{U_f - U_i}{\Delta t} \quad (6)$$

Once in possession of the heat provided by the generator and the refrigeration load is possible to determine the coefficient of performance (COP) of the system through Eq.7 (SRIKHIRIN, 2001).

$$COP = \frac{\dot{Q}_{evap}}{\dot{Q}_g} \quad (7)$$

4. RESULTS

The experiments were done on the course of 8 day during the first half of November 2016. During the measurements, rainfalls, wind gusts, cloudless, partially or totally cloudy days happed, which allowed the tests to happen under various conditions.

In a general way, regardless of the day, the solar heating system was not able to provide sufficient energy so that the hot water reached a temperature higher than 313 K, therefore the presented results are about the best condition obtained during the measurements. Fig 5 shows the higher temperature change in hot water achieve through the day.

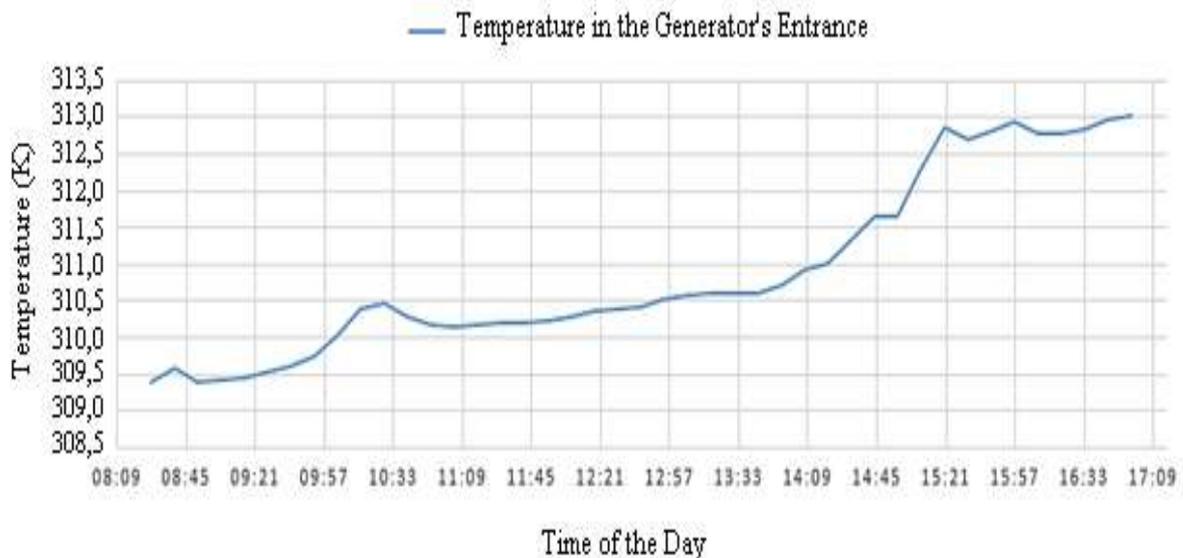


Figure 5. Hot Water Temperature.

It was also noted that during all the measurement, the thermal load was superior than the refrigeration load, as shown in Fig.6.

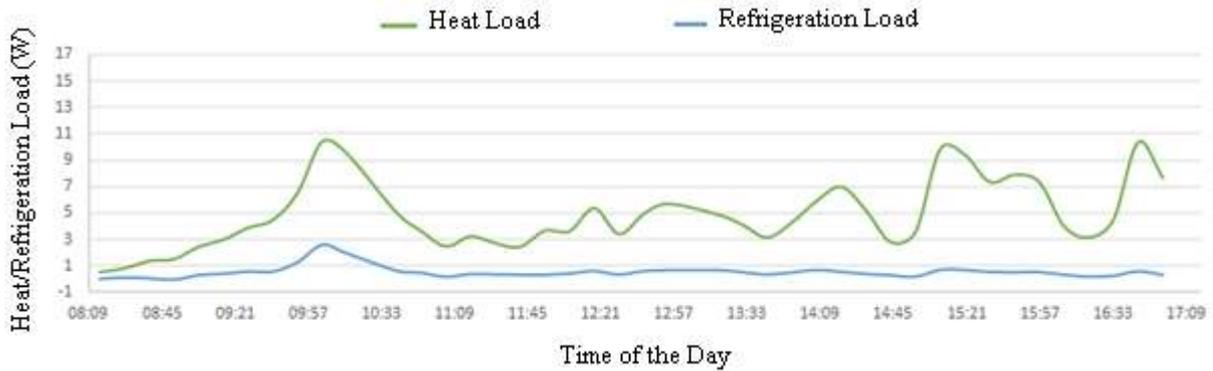


Figure 6. Thermal and Refrigeration Loads through the day.

The variation in the thermal load happened because the refrigerator was installed in an open place, exposed to wind gusts. A blanket was installed around the refrigerator in order to minimize these effects, however it was not possible to isolate them. It was noted that the refrigeration load was close to zero along the day, having small variations and reaching a peak of 3W around 10h. As the water temperature was not enough to cause the evaporation of ammonia, this increase in the refrigeration load was due to the climate variations, as the wind gusts in the refrigerator surface. As the thermal load was superior than the refrigeration load during every moment, the internal temperature of the refrigerator increased along the day, as shown in Fig. 7.

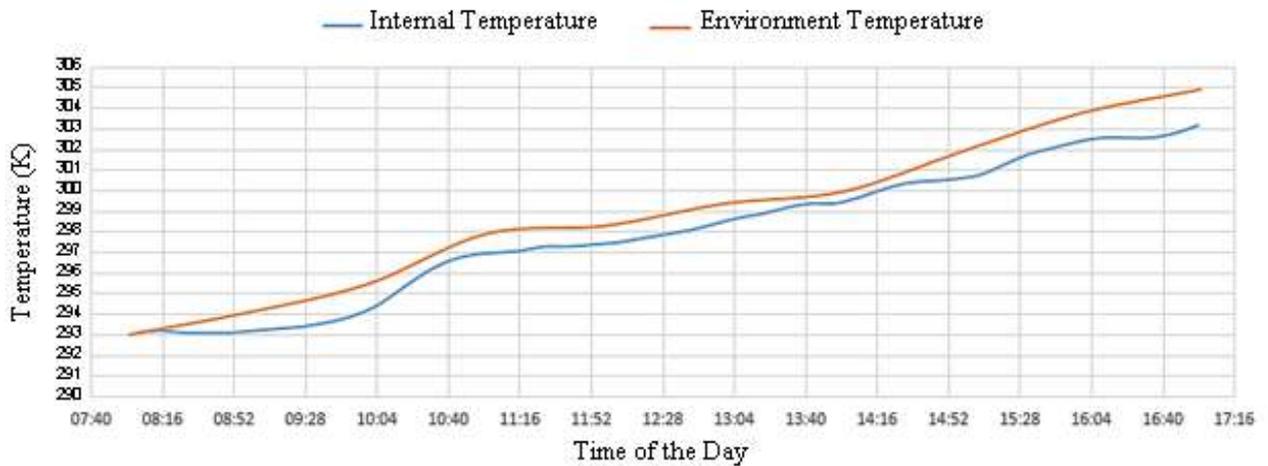


Figure 7. Internal temperature change of the refrigerator and environment along the day.

As the water temperature was inferior than 313 K along the majority of the day, the ammonia did not evaporate, and consequently the difference between the input and output temperatures of the generator occurred basically because of the thermal losses and not due to the heat transfer of the hot water to the refrigerant fluid. With this, the mean energy given to the system in the best conditions was of 90 W approximately, as shown in Fig. 8.

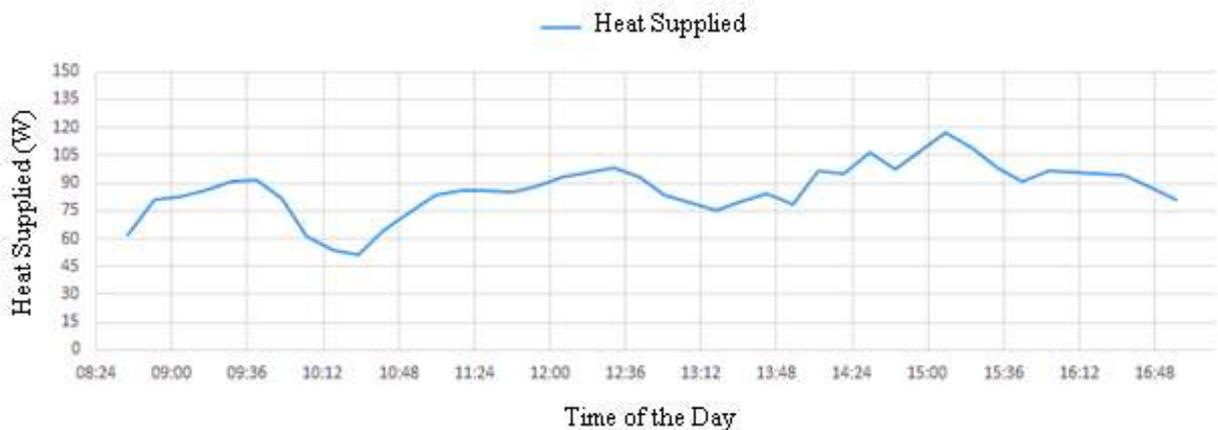


Figure 8. Heat change given by the generator along the day.

The manufacturer's manual of the refrigerator indicates that for the functioning of the equipment, a minimal rate of heat input of 250 W is required, being the nominal rate (or maximum performance of the refrigerator) of 500 W (CONSUL, 2009). Through Eq. 1 the temperature differential obtained in the tests is considered, it is noted that a minimum flow of 15 L/min would be necessary for the recirculation pump, 30 L/min being the ideal, to reach the rates required by the manufacturer. According to other manufacturers' information like Lorenzetti (2016) and Komeco (2016), pumps used in hot water residential systems with a maximum flow of 30 L/min consume 120 W while 236L refrigerators by vapor compression consume around 90 W, according to information by Consul (2016) manufacturer. Nevertheless, as the ammonia evaporation requires it reaches a minimum temperature of 323 K, in this case, the minimum heat provides indicates which heat transfer must be achieved in order that a minimum quantity of refrigerant vaporizes to cause a refrigeration effect, that is, even though the pump flow was increased in order to reach the minimal 250 W, the refrigeration processes would not occur, because the temperature would still be below the ideal.

The variation of the coefficient of performance can be seen in Fig. 9.

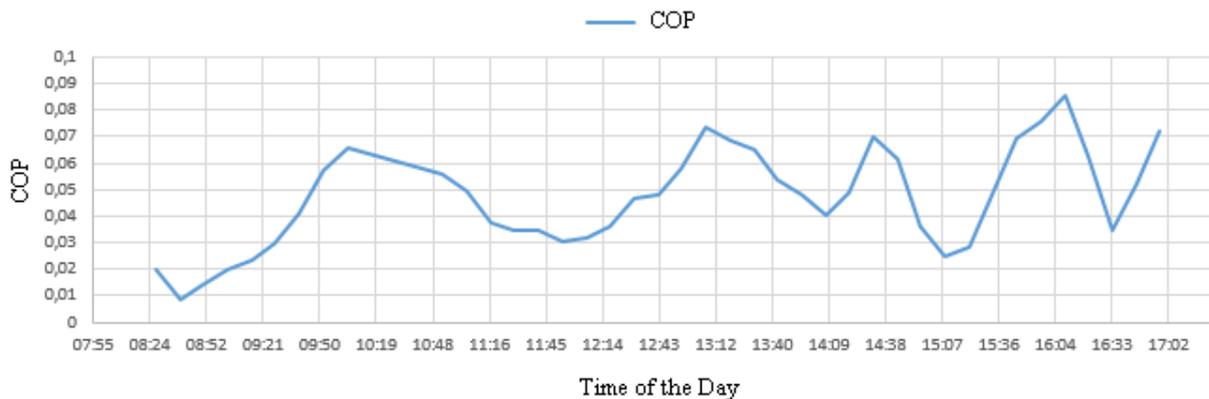


Figure 9. COP variation along the day.

The coefficient of performance (COP) changed according to the heat variation provided and the thermal load along the day, reaching a mean of 0,005 and a peak of 0,085. During most part of the day, the COP had a variation of 0,04. These values, despite being in accord with Srihirin (2001), Sodr  (2014) and Manzela (2005), do not indicate that the system actually worked. As the hot water did not reach the minimum required temperature, the moments that the internal temperature maintained constant or increased in a rate inferior to the rate the environment temperature increased, was not due to the refrigeration effect but to the thermal load variation due to the conditions of the installation site.

5. CONCLUSION

The proposed system must operate with minimal parameters such as a temperature in the water vessel equal or higher than 333 K and, to the flow used in the tests, a temperature difference between the input and output of the generator higher than 0,72 K, being higher than 1,44 K the ideal. This could be obtained through some modifications in the refrigerator's generator. As the system was originally designed to work with gas combustion GLP, whose flame temperature is higher than the hot water temperature, the heat transfer process is done by convection of the combustion gasses from the tube to the chimney, by conduction from the chimney tube to the refrigerant tube and then by convection from the refrigerant tube to the refrigerant itself. In the proposed system, the hot water circulated around the generator chimney, with this, the possible adoption of a shell and tube heat exchanger would eliminate that need of the convection transfer to the chimney and by conduction to the refrigerant tube, thus allowing the direct transfer by convection to the refrigerant tube.

The fact that a 200 liters vessel was used for a single 2m² collector made that the captured energy was not enough to heat all the water volume to a temperature superior than 313 K with the insolation time and temperature measured in this test. To the use in residential hot water, the ideal is that the water temperature be superior than 313 K so it can be mixes with cold water, in order to reduce the hot water consumption. As the proposed system had no consumption and the hot water reached at a maximum of 313 K during all the study, it is concluded that, despite it being a great temperature for residential use, the fact of using only hot water, that is, do not mixing cold water, it would enhance the consumption of the first, making that, probably, in subsequent days with the same environmental conditions, the water heated each time less due to its constant replenishing with lower temperatures. Thus the use of this exclusive heating system for a refrigerator with low capacity is not attractive, because today photovoltaic vapor compression refrigerators are easily found, and are much more efficient than absorption systems (DOSSAT, 2007)

It was noted with this that the proposed system under the specified conditions is not technically feasible for a continuum operation through the year. Furthermore, the project features a power economy of 60 W in relation with a vapor compression refrigerator with the same volume, however, the COP of this refrigerator, in accord with the one found by Sodré (2014) and Manzela (2005), matches only 2,5% of the COP of a refrigerator of the same size operating under vapor compression (SILVEIRA, 2010).

According to this analysis, it is concluded that to this adopted configuration, the single total pressure absorption refrigeration is unfeasible to be used in residences replacing conventional vapor compression systems.

6. ACKNOWLEDGMENT

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