ANALYSIS OF THE COEFFICIENT OF PERFORMANCE OF A DOMESTIC REFRIGERATOR MODIFIED ASSOCIATED WITH A STORAGE TANK

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Abstract. *The domestic refrigerators dissipate heat to the environment through the condenser, but this heat can be recovered and stored for domestic use. This study used two refrigerators, one modified and one unmodified, the latter being used as a reference. Modified in the refrigerator, was added a heat exchanger between the compressor and condenser. The heat exchanger is of the type in which concentric tubes, the refrigerant (R134a - flowing internally) exchanges heat with water (flowing externally) in counter-current flows. The heated water is injected at the top of a thermal storage, positioned beside the refrigerator. In this thermal storage, the water will be stored by thermal stratification. Thus, if the thermal storage tank has finished charging, i.e., fully charged with hot water, the water will not exchange heat with the refrigerant in the heat exchanger. With that, the refrigerator will dissipate heat through the condenser, as if it were an original refrigerator. This prevents the collapse of the cooling system. This study is to compare the coefficients of performance (COP) of the original and modified refrigerators, and calculate the coefficient of accumulated performance of the system, i.e., the modified refrigerator system and thermal storage. With these results, we observed that the recycling system of the heat produced by the refrigerators is viable and useful for domestic, since 40% of the energy consumed by domestic refrigerators be recycled and used to heat water to water tap and even as an aid in heating water for bathing.*

Keywords*: thermal energy, thermal storage, refrigeration system, coefficient of performance.*

1. INTRODUCTION

The Earth's natural resources are exploited intensely and degrading treatment, which is of great concern to the population in general. This exploration, inconsequential, is to provide better conditions of life and comfort to humans, but this makes it necessary the extraction of large amounts of energy on the planet. This energy comes from various sources among which the most petroleum, which due to its massive exploration and by having various forms of derivatives, is in exhaustion. For obtaining large amounts of energy needed to the maintenance of life on Earth, dissipates into the atmosphere pollutants of all forms, of which the highlight was the heat, responsible for the increase of temperature on the planet and consequently intensifying environmental catastrophes. Therefore, new energy sources for special attention by the researchers, which seeks to these sources efficiency, low costs of production and distribution, which are less degrading to the environment. The justification for realization of this work is to recycle the heat generated in a household refrigerator condenser, so that this heat can be used, for example, heating water for domestic use. With the reutilization of such energy as heat, we seek to optimize the residential energy consumption, since water heating in these cases is done by expensive electric resistance. Thus, we increased the rational use of alternative energy, preserving part of the traditional and primary sources for future generations.

2. LITERATURE REVIEW

Jordan and Furbo (2005) analyzed through theoretical and experimental study, the influence of the entry of cold water on a hot water storage thermally stratified. For both commercial tanks capacity 144 and 183 liters of storage was a used device to prevent mixing between hot and cold water at the entrance of the tank. At the entrance of tank 183 liters was fixed a flat plate located 30 mm from the edge, while in the tank of 144 liters a device shaped half sphere located 10 mm from the edge. Compared with unmodified systems, tank of 144 liters was more efficient to use hot water storage.

Through an energy balance for the storage system by thermal stratification, Padilha (1982 and 1983) proposed a semi-empirical one-dimensional and transient, which obtained the behavior of the profiles of temperatures of the liquid and the reservoir wall during periods of loading, unloading and natural cooling. It was verified the influence of height / diameter of the storage on the efficiency of thermal stratification, through the First and Second Laws of Thermodynamics. The theoretical results were compared with available experimental literature.

Savicki et al (2011), using three-dimensional numerical analysis, investigated the temperature field and velocity of water in a horizontal cylindrical tank. In this analysis it is considered the phenomena of natural convection and thermal stratification. The mathematical model developed for the transient period, composed by the equations of energy conservation and the equation of moment was solved by finite volume the numerical technique. The numerical simulation showed the formation of thermal stratification of water through the profiles of temperatures, which coincide with those obtained experimentally. Thus, through the mathematical model, proposed a correlation to determine the level of thermal stratification in the interior of tank, depending on the thermal and geometric parameters. Since then the solution of the model produces the fluid temperature profiles over time. The experimental apparatus connected to the solar heater resulted in increased overall system efficiency and thus improving the degree of thermal stratification. In that study may also observe the behavior of baffles in the vortex of water into the tank and its influence on thermal stratification. In the case of the storage tank, connected to solar collector, the numerical investigations showed that the presence of baffles allows, through the formation of profiles of temperature, improved thermal stratification.

Amaral Filho (2005) built and analyzed the efficiency of a heat exchanger shell and tube type with water flow counter-current gas. The exchanger was used as a condenser of a refrigerator modified, providing smooth operation and high efficiency for water as coolant gas. The shell and tube type heat exchanger maintained the normal operation of the refrigerator modified compared with the original, and does not dissipate heat to the environment, yet provides heated water for domestic use.

With experimental work, Marchi Neto (2007), obtained and compared the coefficient of performance (COP) of two refrigerators, conventional and modified. The refrigerator modified, has a heat exchanger shell and tube type, which replaces the original refrigerator condenser, with water flow counter-current gas. By studying the amount of heat stored in the tank attached to the refrigerator changed, we calculated the Coefficient of Thermal Performance System (COPS) of new storage and refrigerator modified. The cooler condenser amended, was more efficient when compared with the conventional system, reducing electricity consumption. The results show that the modified refrigerator does not dissipate heat to the environment and also to the walls of the compartment to be chilled.

This study uses a thermal storage water, operating on thermal stratification, built on the geometric format proposed by PADILHA (1982 and 1983), which allowed the calculation of flow and amount of stored energy. The refrigerator modified has brought an innovation in relation to MARCHI NETO (2007). The maintenance of the finned condenser allowed dissipating excess heat, preventing collapse of the vapor compression cycle.

The objective of this study is to compare the coefficients of performance *(COP)* between the original and modified refrigerators. Also using the experimental results obtained from this comparison, we calculate the coefficient of performance (COP_{SA}) for the integrated system, i.e., modified refrigerator / thermal storage.

3. PROPOSED METHODS

Figure 1 presents the experimental scheme that consisting in a vertical thermal storage capacity of 122 liters for household refrigerators and two 338 liters duplex refrigerator. One of the refrigerators, as shown in Fig.1, has its condenser increased with type heat exchanger concentric tubes with water refrigerant in counter current. The function of the heat exchanger is to condense the refrigerant by exchanging heat with water. Then water heated is then stored in the storage tank for thermal stratification. For measuring the energy consumption was used equipment SAGA 4000, 1380 model.

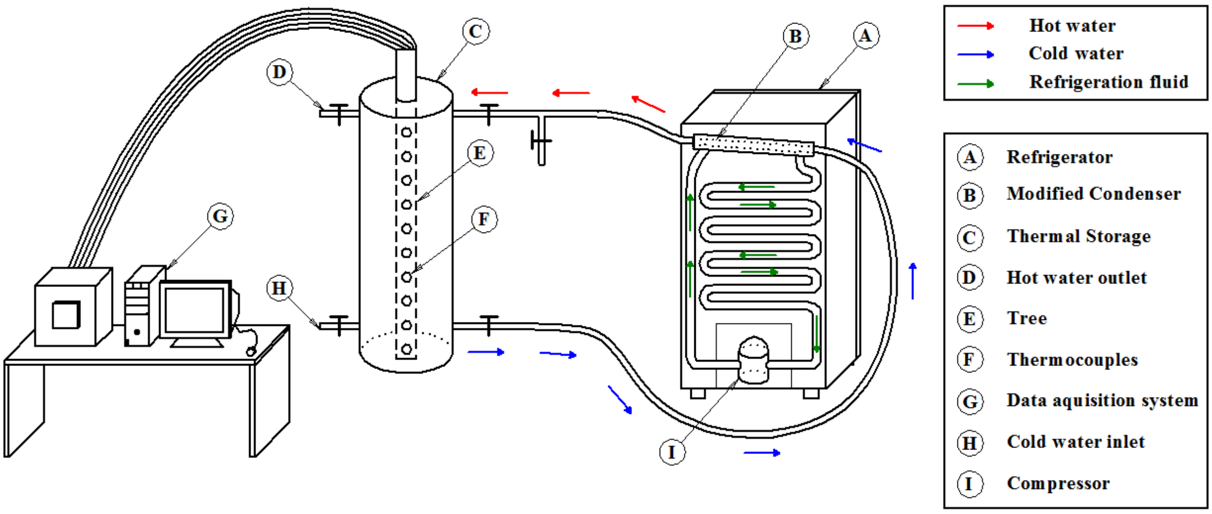

Figure 1. General diagram of the experimental apparatus.

The concept for the performance of a refrigeration cycle is expressed as the coefficient of performance *(COP)*, which in the case studied is the ratio between the energy required (Q_L) and the energy consumed *(W)*, (Stoecker and Jones, 1985) , thus:

$$COP = \frac{Q_L}{W} \tag{1}$$

Or, in form of heat rate:

$$COP = \frac{q_L}{w} \tag{2}$$

With:

$$q_L = q_F + q_R + q_{Pt} \tag{3}$$

Where, q_{PtF} and q_{PtR} are the heat transfer rates for freezer and refrigerator, respectively.

So, the amount of heat removed from the freezer *(Q_F)*, Eq. (4), and the refrigerator *(Q_R)*, Eq. (5) was calculated. Then was estimated the theory rate of heat transfer loss (q_{Pt}) which enters in the refrigerator through the difference temperature between the refrigerated compartment and the environment.

To determine the useful cooling *(Q_L)* was necessary to calculate the amount of heat removed from the freezer *(Q_F)* and refrigerator *(Q_R)* using thermocouples that measure the air temperature inside the compartments has Eq. (4) end (5).

$$Q_F = \left(m_{air} \cdot c_{p_{air}} \cdot \Delta T\right)_F \tag{4}$$

$$Q_R = \left(m_{air} \cdot c_{p_{air}} \cdot \Delta T\right)_R \tag{5}$$

For convenience, Eq. (4) and (5) were written in Watts by dividing the amount of heat removed from the refrigeration system by loading time t^c.

$$q_F = \frac{\left(m_{air} \cdot c_{p_{air}} \cdot \Delta T\right)_F}{t^c} \tag{6}$$

$$q_R = \frac{\left(m_{air} \cdot c_{p_{air}} \cdot \Delta T\right)_R}{t^c} \tag{7}$$

Using Eq. (6) and (7), the total heat transfer rate that enters through the walls of the refrigerator, expressed by:

$$q_{PtF} = \frac{K \cdot \left(A \cdot \Delta T\right)_F}{e_F} \tag{8}$$

$$q_{PtR} = \frac{K \cdot \left(A \cdot \Delta T\right)_R}{e_R} \tag{9}$$

In this test was adopted, from literature, the thermal conductivity of expanded polyurethane (K = 0.02 W/m K).

To calculate the heat transfer into the refrigerator, eight thermocouples were used. Four of these, arranged in the four walls of the freezer and the refrigerator walls, positioned on the outer and inner surfaces.

As refrigerators are duplex, its walls have variable thickness. So was calculated the heat flow separately in accordance with the variation of insulation thickness in each compartment, as Tab. 1.

Table 1. Areas and thicknesses for each compartment.

Freezer	Area [m²]	Insulation Tickness [m]
Top and sides	0.516	0.060
Door	0.172	0.075
Backside	0.172	0.075
Refrigerator	Area [m²]	Insulation Tickness [m]
Top and sides	1.311	0.030
Door	0.626	0.045
Backside	0.626	0.045

Thus, using the following equations, the heat transfer rates were calculated through the walls of the refrigerator, resulting in:

$$q_{Pt} = q_{PtF} + q_{PtR} \tag{10}$$

With this, is possible to calculate the total heat rate removed from refrigerator, by the Eq. (3).

But for calculating the COP_{SA}, it was necessary to measure the amount of energy stored in the thermal storage. For that amount of heat stored in each layer of fluid inside the tank was used the Eq. (11). It represents sum of the stored heat at every moment of acquisition, from first to last thermocouple.

This equation C_n represents layers of the fluid stored, ranging from $1 \leq n \leq 30$, because there are 31 thermocouples inside the probe, totaling 30 layers between the first and last thermocouple probe. The symbol t_{aq} represents the time elapsed between two data acquisitions.

Thus the total amount of heat stored in the thermal storage tank for all time steps, is given by:

$$Q_T = \sum_{i=1}^{t_{aq}} \sum_{n=1}^{30} \left[m_{water} . c_{p_{water}} . \left(Tm_2 - Tm_1 \right) \right]_{Cn} \tag{11}$$

Were:

m_{water} : water mass between two consecutive thermocouples

c_{pwater} : fluid specific heat at constant pressure

T_2-T_1: difference of temperature between two thermocouples

Once calculated $Q_{T,}$ the coefficient of cumulative performance of the system *(COP_{SA})* was determined, relating the amount of stored energy and the energy consumed by compressor.

With calculated, determine the coefficient of performance driven system *(COP_{SA})* correlating the quantity of stored energy Q_T and the energy consumed by compressor *(W).*

$$COP_{SA} = \frac{Q_T}{W} \tag{12}$$

4. RESULTS AND DISCUSSIONS

Table 2 shows that the amount of heat removed from the compartments are too close for both experiments. However, the energy required to remove it from the refrigerator modified is lower in comparison to the original refrigerator.

So the COP of modified refrigerator reaches 1.45, while the original one only reaches 1.13. This represents an increase of approximately 32% efficiency of the refrigerator with the heat exchanger.

Thus, the modified refrigerator is more efficient when compared to the original, as well as consuming smaller amount power, and still produce hot water for domestic use.

Table 2. Amounts of heat into and removed the refrigerators, electric power consumption of refrigerators and *COP* modified and original.

Conventional refrigerator	Refrigerator	Freezer	Total [kJ]
Heat that enters in the system [kJ]	7679.2	2816.7	10495.9
Removed heat of the system [kJ]	-9.8	-4.7	-14.5
Electric energy consumed [kJ]	0	0	9244.8
COP	0	0	1.13
Modified refrigerator	Refrigerator	Freezer	Total [kJ]
Heat that enters in the system [kJ]	7818.1	2643.7	10461.8
Removed heat of the system [kJ]	-9.7	-4.7	-14.4
Electric energy consumed [kJ]	0	0	7200.0
COP	0	0	1.45

Table 3 show the amounts of heat stored, the amount of energy consumed and the COP_{SA} for a test of 24 hours.

The *COP* represents the energy removed from the refrigerator and recovered by the heat exchanger. From Table 3 shows that its value is only 0.40, while the *COP* of this refrigerator is much higher (1.45).

The COP_{SA} value should be at least the value of the *COP*, because the heat recovery system is similar to a heat pump.

However does not occur. Although the entire heat recovery system provide thermal insulation, this is not as efficient enough to retain all the energy recovered, resulting in a low COP_{SA}.

Table 3. Energy consumed and stored, used for calculating the coefficient of thermal heating system accumulated COP_{SA}.

Heating system	***Loading***
Amount of heat stored [kJ]	2915.2
Electric energy consumption [kJ]	7200.0
COP_{SA}	0.40

Although, the water stratification in the storage does not affect COP_{SA}, it is important to observe how it's behaved during the test, since heated water is one of the advantages brought by this work.

Figure 2 show that, from the beginning the test, already producing hot water. Thus, the temperature profile, corresponding to the higher thermocouple of storage, contrast from others because it shows an abrupt increase of approximately 8°C in the first 6000s.

Noteworthy, the formation of three distinct regions of temperatures distributed along the height of the storage, a hot region at the top, a cold region in the bottom and a region between those two. Thus, the temperature profiles follow the method of thermal stratification, proposed here.

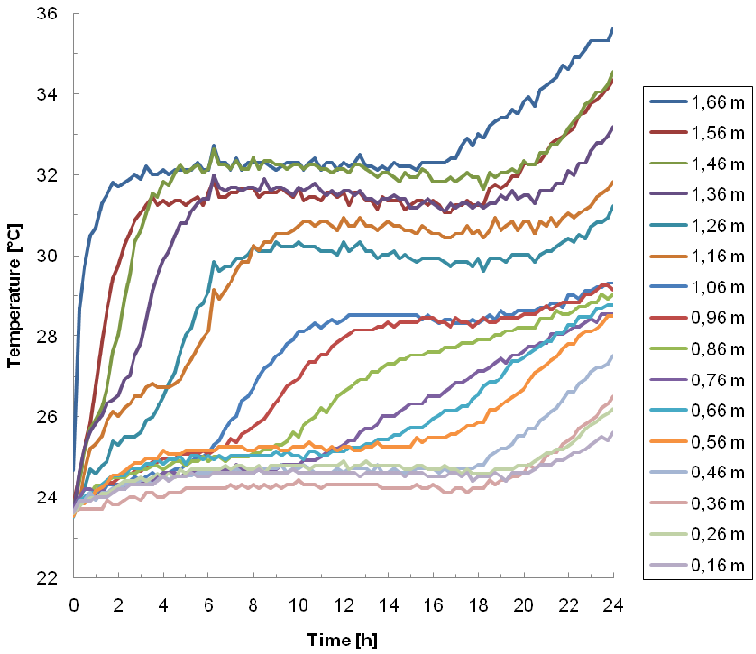

Figure 2. Evolution the temperature profiles of every thermocouple inside the storage tank

Figure 3, was obtained the results of the behavior of temperature profiles along the height of the tank every two hours of test for 24 h a charge period.

There is a deformation of the initial profile (t = 0 h) over time, simulating the dynamic load of warm water in the storage. At the end of the test, the last temperature profile shows a wide variation between bottom and top temperature of storage. At this time the difference temperature between these two points is greater than 9°C, with the top to reachs 35°C.

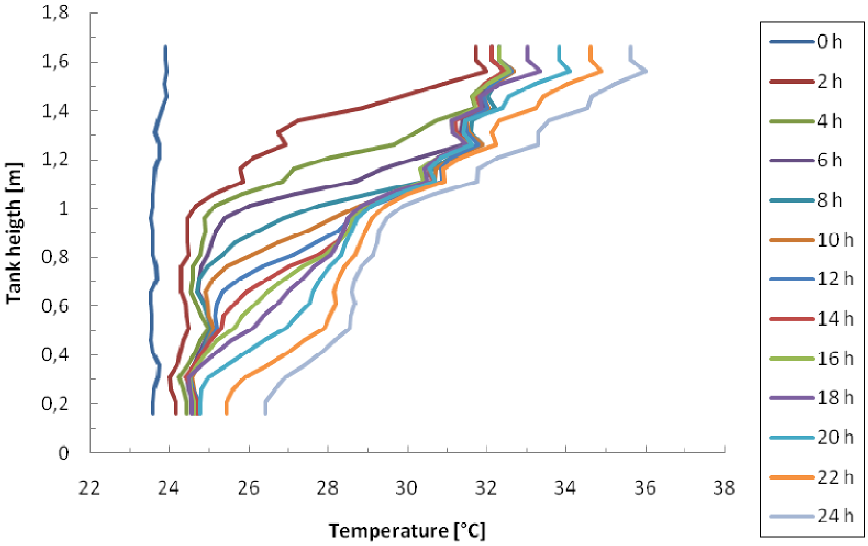

Figure 3. Behavior the isoclines through the tank height

5. CONCLUSIONS

From the results obtained in this work, it can be concluded that the *COP* of the modified refrigerator is higher when compared to the original refrigerator, thus showing better efficiency compared of modified one.

It also follows that the amount of recovered energy system is not enough to raises the value of the COP_{SA}. This occurs because the heat loss system, through the isolated parts and also from the compressor surface.

Even so, the modified system has two major advantages, since it saves energy (more efficient) and still generates hot water for domestic use.

6. ACKNOWLEDGEMENTS

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