Heat absorption cooling with renewable energies: A case study with photovoltaic solar energy and biogas in Cordoba, Colombia

Refrigeración por absorción de calor con energías renovables: Un estudio de caso con energía solar fotovoltaica y biogás en Córdoba, Colombia

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Resumen

Introduction— The use of renewable sources for energy generation has grown in importance due to the adverse effects that fossil fuels generate on the environment. From the available sources, generation of energy through biomass has great advantages because of its high energy potential and low cost.

Objective— To evaluate the performance of a heat absorption refrigeration system using photovoltaic solar energy conversion and biogas as renewable energy sources.

Methodology— The energy characterization of the implemented sources was carried out collecting data on solar radiation and biogas calorific value to calculate the Coefficient of Performance (COP). All the experimental tests were made by placing 1 liter of water inside of the system.

Results— It was found that the operation of the equipment takes approximately 8 hours, the biogas chemical composition was 58% methane and 42% carbon dioxide, and a calorific value of 23.05 MJ/kg was attained. The Coefficient of Performance obtained were 0.58; 0.08; 0.27 and 0.07 for electrical energy, LPG, solar energy and biogas respectively.

Conclusions— There is an important energy potential in the usage of solar energy and biogas for cold generation processes and it was proved that it is possible to implement renewable energies in absorption cooling systems.

Keywords— Biogas; photovoltaic solar energy; hot; stabilization time; operation coefficient

Resumen

Introducción— El uso de fuentes renovables para la generación de energía ha crecido en importancia debido a los efectos adversos que los combustibles fósiles generan en el medio ambiente. De entre las fuentes disponibles, la generación de energía a través de la biomasa presenta grandes ventajas por su alto potencial energético y su bajo coste.

Objetivo— Evaluar el rendimiento de un sistema de refrigeración por absorción de calor utilizando la conversión de energía solar fotovoltaica y el biogás como fuentes de energía renovable.

Metodología— La caracterización energética de las fuentes implementadas se realizó recogiendo datos de radiación solar y poder calorífico del biogás para calcular el Coeficiente de Rendimiento (COP). Todas las pruebas experimentales se realizaron colocando 1 litro de agua en el interior del sistema.

Resultados— Se comprobó que el funcionamiento del equipo dura aproximadamente 8 horas, la composición química del biogás fue de 58% de metano y 42% de dióxido de carbono, y se alcanzó un poder calorífico de 23.05 MJ/kg. Los coeficientes de rendimiento obtenidos fueron de 0.58; 0.08; 0,27 y 0.07 para la energía eléctrica, el GLP, la energía solar y el biogás respectivamente.

Conclusiones— Existe un importante potencial energético en el uso de la energía solar y el biogás para los procesos de generación de frío y se demostró que es posible implementar las energías renovables en los sistemas de refrigeración por absorción.

Palabras clave— Biogás; energía solar fotovoltaica; calor; tiempo de estabilización; coeficiente de operación

I. Introduction

Given the progressive decrease in conventional energy resources, it is difficult to imagine how many of the day-to-day activities can be carried out without energy utilization. There is a need to implement research projects that allows the usage of new energetic resources in a reliable way. The International Renewable Energy Agency (IRENA) indicates that 19.3% of the world's primary energy was produced from Renewable Energies (RE). This percentage is comprised by 9.1% from traditional biomass, while the remaining 10.2% derives from modern renewable energies, where the contribution of hydroelectric plants stands out with 3.6% and the remaining percentage contains modern renewable energies: geothermal, wind, biogas and solar energy [1]. The continuous increase in the biomass useage for heat generation and electricity has been approximately 64.5% according to data from REN21 (Renewable Energy Policy Network for the 21st Century) [1], where traditional biomass such as firewood, waste and animal manure are the main resources thar are being transformed to produce heat for homes, but also for cold cogeneration processes. It is important to mention that in Colombia from the approximately 65,935 GWh of the generated electricity in 2016, 3.20 GWh used biomass as energy source [2]. In Colombia, the Ministry of Mines and Energy reports that between 39% and 50% of household electrical energy consumption is associated with food refrigeration processes [3]. However, the National Interconnected System (NIS) covers only 34% of the national territory, that is where 96% of the Colombian population lives, registering a national coverage of 96.38% [4]. Nevertheless, the Non-Interconnected Areas (NIA) have a coverage that ranges between 45% and 77%, with an electrical service characterized by its high cost and poor quality. This is evidenced by the following two indicators; average service delivery hours is 4-8 hours/day and an average electricity rate of COP $1200/kWh [5], which is worsened by cost reductions programs in generation from conventional sources. It is evident that the territory considered as NIA is normally rural, and in 2014, agricultural crops area closed at 4.9 million hectares with a yield of 27 million tons of agricultural products and 4.1 million tons in livestock production, which represents 6.8 % of national GDP (Gross Domestic Product) [6]. Studies carried out by the National Planning Department (NPD) in 2016, showed that in Colombia 9.76 million tons of these products get lost, which is equivalent to 34% of the national food supply, and the post-harvest and storage loss is about 19.80% of total loss, which is equivalent to 657 thousand tons of products not used due to inadequate storage [7]. This data gives relevance to a research project to improve the performance of food preservation systems, because refrigeration has become one of the fundamental processes in our food production chain by guaranteeing the preservation of food for long periods of time and is used domestic and industrial sectors. Additionally, it has the advantage of not affecting the taste, texture or nutritional value. The aim of this work is the evaluation of a heat absorption refrigeration equipment using photovoltaic solar energy and biogas as renewable energy sources, using conventional sources like electrical equipment with 110V Electric Power and LPG as benchmark for its performance. This will be used as a preliminary study for possible implementations of these systems in NIA.

II. Literature review

The environmental pollution increase and the decline of fossil fuels has created more and more attention on energy distribution systems using renewable energies, such as biomass, solar energy, etc., because the advantages of green environmental protection and inexhaustibility [8] renewable energy resources appear to be the one of the most efficient and effective solutions. That is why there is an intimate connection between renewable energy and sustainable development. Anticipated patterns of future energy use and consequent environmental impacts (focussing on acid precipitation, stratospheric ozone depletion and the greenhouse effect) [9]. Similarly, due to the high energy consumption in the world, the use of renewable energy is a necessity. Biogas is obtained through a biochemical process that transforms biomass into two main components such as methane and carbon dioxide, with small fractions of other gases such as sulfide of hydrogen [10]. The presence of some gases like carbon dioxide causes pollution, while hydrogen sulfide creates thermal degradation of the obtained biogas, in the same way, the presence of the aforementioned impurities leads to the corrosion of the devices where the fuel is burn [11]. Likewise, the energy received from the sun on the planet's surface is 10 000 times the energy required worldwide [13]. The increase in the implementation of solar energy requires an improvement in the performance of some solar energy plants [14]. There are two ways for solar cooling according to the literature; solar thermal cooling and solar electric cooling. In solar thermal refrigeration systems, solar energy is stored and used in the form of heat for cold production either by absorption refrigerators or adsorption refrigerators [15]-[16]. On the other hand, in solar electric cooling systems, the energy is transformed into electricity and then used in thermoelectric or magnetic refrigerators. Absorption cooling systems have some advantages over adsorption cooling systems, since they do not have corrosion and crystallization problems and also can work efficiently with a low-range heat source [17]-[18]. However, the performance of this equipment is low, due to the thermal inertia of its heat exchangers [19]. These problems can be solved by redesigning the system, improving its heat and mass transfer process, or optimizing system operating conditions [20]. One of the most widely implemented uses of biogas are in rural or hard-to-reach areas where there is no access to services such as natural gas and even electricity, for NIA it becomes the best energy source to take advantage of the biomass resources that are abundant in these areas, and there are low cost biodigesters that are easy to implement for this type of population [21]-[24].

III. Methodology

A. *Characterization of solar energy*

To evaluate the refrigeration system operation, it was necessary to perform an energy characterization of the used sources, which are shown below:

The system was structured to work with a solar panel that has the characteristics shown in Table 1.

Table 1. Technical data of the solar panel.

Module type	USP-5M-200P-36
Maximum power (Pmax)	200 W
Generation tolerance	3%
Maximum power current (Imp)	11.14 A
Maximum power voltage (Vmp)	17.95 V
Short circuit current (Isc)	12.05 A
Open Circuit Voltage (Voc)	22.02 V
Dimensions [mm]	1320X992X35
Maximum system voltage (Voc)	1000

Source: Authors.

The number of functional solar hours of the solar-powered refrigeration system was defined by using hourly solar radiation data from Montería (Colombia). Starting from the fact that the refrigeration equipment needs 500 W of power to operate, the radiation necessary to obtain this power with the solar panel used was calculated by (1).

$$I_{rrad} = \frac{P}{\eta_{pf} \times Area_{pf}} \qquad (1)$$

Where,

$Area_{pf}$ = Panel Area.

n_{pf} = Photovoltaic panel efficiency.

P = Equipment power.

Then, the functional solar hours were chosen as those where the radiation exceeded the radiation calculated for the operation of the equipment. Because of this, it was necessary to carry out a Gaussian adjustment model for the data [25].

B. *Biogas characterization.*

Biodigesters were developed to obtain gas with cattle manure, during its production stage the temperature and pressure of the system were monitored. Then the gas obtained was analyzed by gas chromatography using an Agilent Technologies Micro 490-gc chromatograph with three columns and applying the standard ASTM E260-96. The composition is used to calculate the average calorific value. The pH variation was monitored every three days during the first 26 days of gas production using a digital pH meter.

C. *Experimental setup.*

The refrigerator used in the experiments was a single absorption cycle multi-way, using R-717 as a refrigerant, originally designed to run on 110 V AC electricity, 12V DC electricity and LPG. Table 2 shows the general characteristics of the equipment.

TABLE 2. TECHNICAL CHARACTERISTICS OF THE REFRIGERATION EQUIPMENT.

Model	XC-60
Nominal voltage	AC 110V / DC 12V
Input power	AC 90W / DC 90W
Nominal frequency	60 Hz
Fuel	Propane
Fuel consumption	25 g / h
Refrigerant	R-717
Serial	1311808090007

Source: Authors.

1. *Experimental Assembly for Solar Energy and Biogas.*

For solar energy test, the panel was directly coupled to the refrigerator on the terminal for direct current at 12 V, which is internally connected to a resistance that generates the input heat in the absorption cycle.

For the experiment carried out with biogas, the system was coupled to the burner of the refrigerator using flexible tubing, the system was equipped with a regulating valve at the outlet of the cylinder and an internal pressure gauge in order to monitor and to recognize if the biogas will begin to run out.

Fig. 1a illustrates the setup carried out for the experiment implementing solar energy while Fig. 1b shows the experimental setup used with Biogas, both implemented to the absorption refrigeration system.

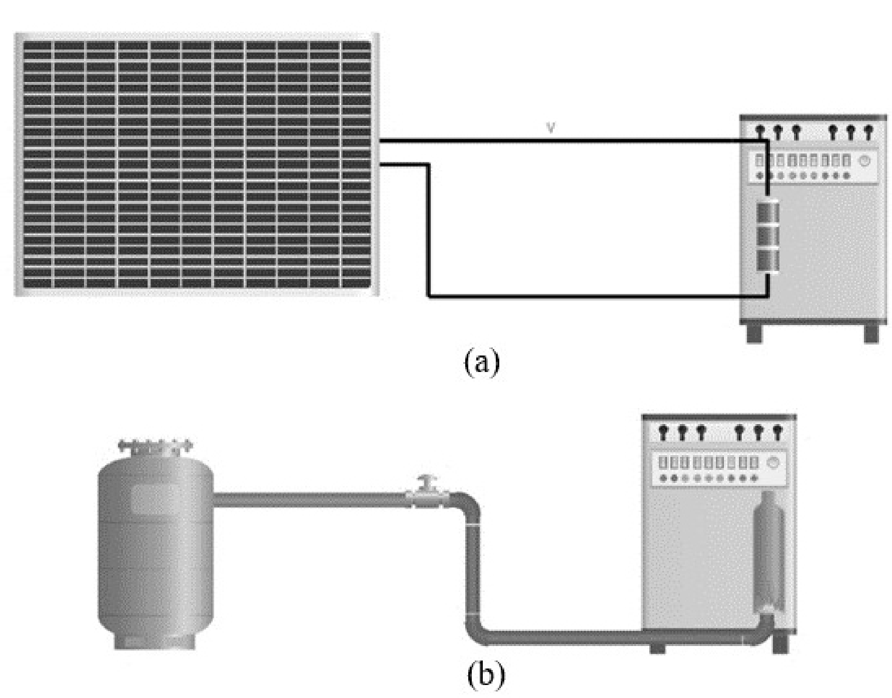

Fig. 1. Experimental setup for solar energy.
Source: Authors.

D. *Determination of stabilization temperatures by source.*

In order to define the stabilization time of each source, a liter of water was used as thermal load, its temperature was measured by a type (K) thermocouple, data was recorded using an Applent AT4208 datalogger, the stabilization time for the thermal load temperature was set when the temperature of the load did not show a variation of more than 5% with respect to the temperature of the previous time. Finally, they were compared with the stabilization times of conventional sources.

E. *Estimation of the coefficient of performance (COP) for each source.*

With the system's input energy, the cooler's coefficient of performance for each source was calculated using heat removed from the system as the heat that was extracted from the thermal load. It was compared with the performance coefficients of the traditional sources for which the system is originally designed. For the absorption refrigeration system, the COP can be defined as the relationship between the heat extracted by the evaporator (Qt), at the cooling temperature (Te), and the heat that the generator manages to supply (Qs), at the temperature at which it generates (Tg) [26]. Then the COP of the absorption refrigeration cycle can be set as shown (2).

$$COP \quad \frac{Q_t}{Q_s} \tag{2}$$

Where,
Q_t = is the absorber's heat.
Q_s = is the extracted heat from the Evaporator.

III. Results

A. *Characterization of solar energy.*

With the solar energy data in Monteria, it was possible to define the behavior of solar radiation per day all year long, noting that January is the month with the highest solar radiation in the region. Fig. 4 shows the behavior on a day of average radiation.

With the refrigerator's power, it was possible to establish that a minimum irradiance of 200 W/m^2 was required for the system to work, then comparing this with the daily irradiance as shown in Fig. 2, it was outlined that the system could run 7.56 hours from 8:13 am to 3:47 pm daily (values above the plotted line). The Gaussian model used for data regression had a 75% degree of fit.

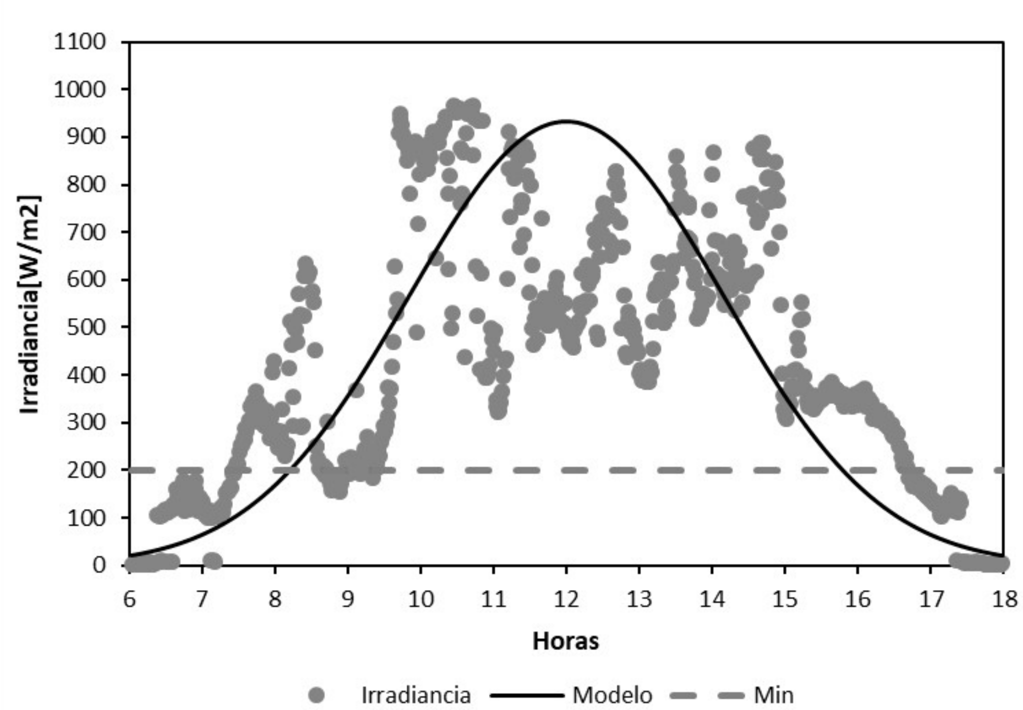

Fig. 2. Hourly irradiance data.
Source: Authors.

The data from 10 am in this work have some similarity to the results obtained by other Chinese researchs [27], which performed a solar characterization that registered a solar irradiation of approximately 680 (W/m^2) and in this investigation was around 650 (W/m^2), on the other hand, their maximum peak is obtained after 12:00 pm registering a value close to 820 (W/m^2) and in this work the peak is after 12:00 pm but exceeds 900 (W/m^2). Finally, the irradiation reaches 0 (W/m^2) after 5:30 p.m., being similar to those found by Chinese studies in 2020 [27].

The temperature generation depends on the percentage of solar irradiation that is obtained either in a collector or a solar panel, similarly the COP will also depend on that temperature, therefore, if a higher percentage of irradiation is obtained, the equipment's performance will increase.

B. *Biogas characterization.*

The composition of the biogas produced was obtained by gas chromatography and is observed in Table 3 along with the estimated calorific value, the gas is mainly made up of methane and carbon dioxide, methane is in a higher percentage and is the fuel used for the generation of heat in the refrigerator.

TABLE 3. THE COMPOSITION OF THE BIOGAS PRODUCED.

Component	Mass fraction
CH_4	58%
CO_2	42%
LHV	29.05 MJ/kg

Source: Authors.

The composition of the gas varies depending on the used raw material and the operation of the biodigester. Usually, biogas contains between 50-75% CH_4 and 25-50% CO_2, it also has other components such as ammonia (NH_3), hydrogen sulfide (H_2S) and water vapor (H2O).

As for CH_4, this is the only component related to the heating process, for example, 1m^3 of biogas at standard pressure and temperature, that contains 60% of CH4, has a calorific value of 21.5 MJ which is equivalent to 5.97 KWh of electricity, compared to 35.8MJ/m^3 of 100% CH_4 (equivalent to 9.94 KWh of electricity) at constant pressure and temperature [28]. Therefore, the results of this research are validated because 58% CH_4 produces a calorific value of 19.08 MJ/m^3 as shown in Table 3.

On the other hand, the main energy application for these gases have been in Internal Combustion Engines (ICE) since they have a great applicability to work with this fuel. A 2020 research carried out in India used a four-stroke ICE with a Compression Ratio (RC) between 10-14 that is operated with biogas and the engine power and efficiency was improved 12.72% and 5.68% respectively, thus reducing fuel consumption by 5.42%; the chemical composition of this gas was 56% CH4 [29].

C. *Temperature and stabilization time for each source.*

Fig. 3 shows the variation the thermal load temperature variation over time for each evaluated source, and the behavior of the system when operating with the energy sources for which it was designed (Electric energy and LPG). It is noted that after approximately 570 mins, the electrical is the first energy source that reaches the stabilization temperature at about 6.80°C. On the other energy sources the stabilization time increases considerably.

The biogas shows a quite similar behavior as LPG, which is an indication that gas from bio-digestion is a suitable substitute for this petroleum fuel, which brings advantages from an environmental point of view. Regarding the behavior of solar energy, it is important to note that during the experiment heat removal rate was higher than LPG and biogas, however, it presented a higher stabilization time than LPG because it reaches a lower stabilization temperature as shown in Table 4. The process occurs rapidly with electrical energy due to the constant voltage supply to the system, unlike the other sources of energy where fluctuations occurred that delayed the process duration.

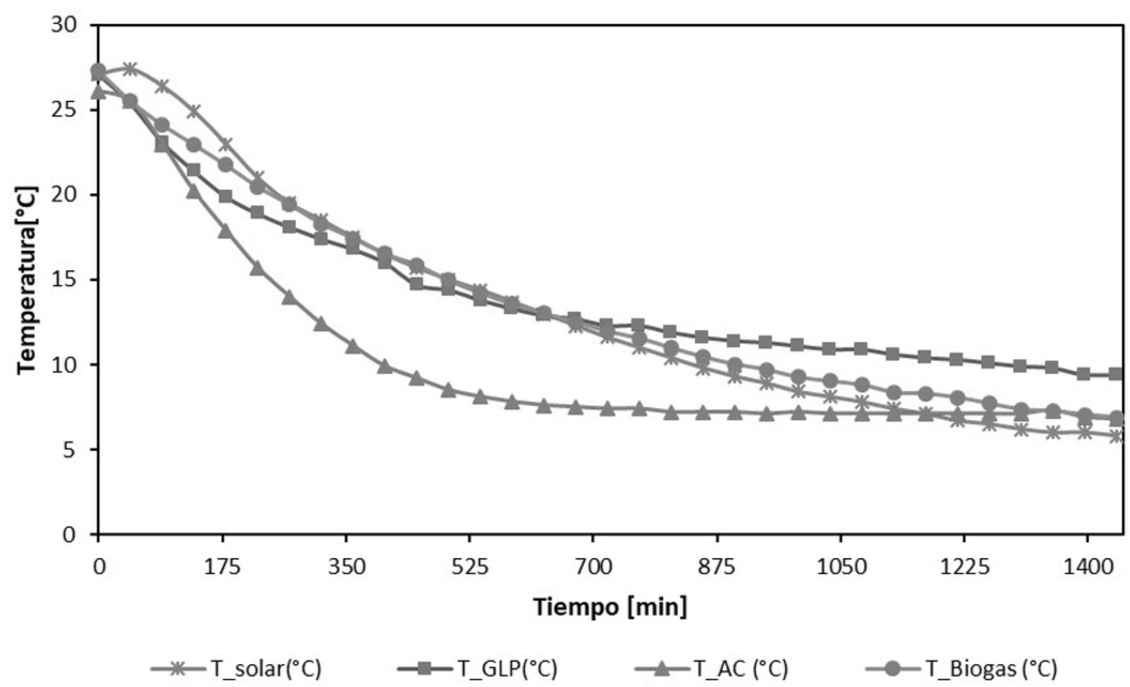

Fig. 3. Variation of the temperature of the thermal load for each source.
Source: Authors.

Table 4. Stabilization time and temperature values for all sources.

Power source	Stabilization time [min]	Stabilization temperature [°C]
Electrical	570	6.8
LPG	1170	9.4
Solar	1230	5.8
Biogas	1275	6.9

Source: Authors.

It is to be highlighted that the lowest stabilization temperatures were reached by the Photovoltaic Solar energy and Biogas, which is an indicator of efficiency. LPG presented the highest stabilization temperature of all sources.

D. *System operation coefficient with each source.*

The performance coefficient of the refrigeration system was evaluated for each implemented energy source and the results are shown in Fig. 4. It is observed that the highest COP was obtained by electrical energy, registering a value close to 0.60, Followed by Solar Energy whose value was 0.27. Results compare with other experimental studies in a refrigerator powered by solar cells recording a COP of approximately 0.30 [30]. Similarly, they investigated the performance in a portable solar refrigerator with a COP close to 0.16, indicating that the performance of the equipment is good [31].

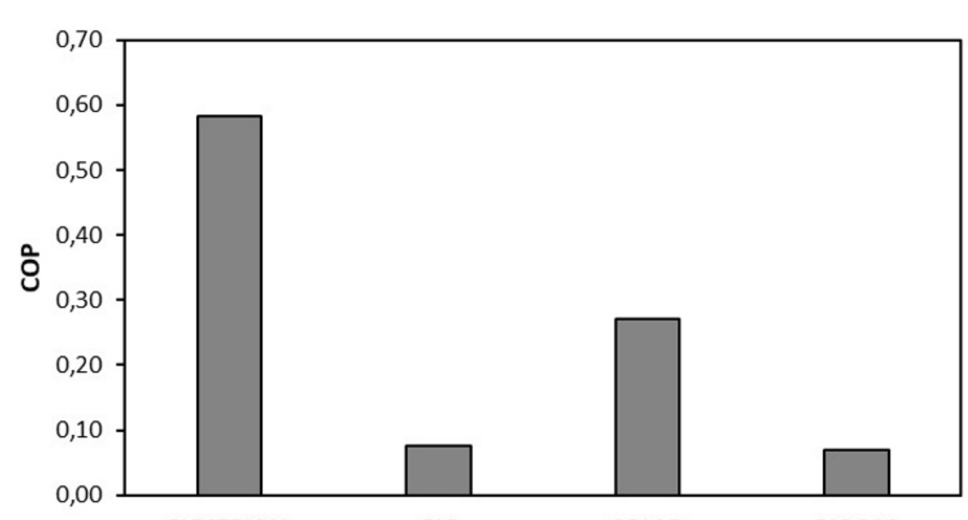

Fig. 4. Coefficient of operation (COP) of the cooling system.
Souce: Authors.

The COP recorded when implementing LPG and biogas was 0.08 and 0.07 respectively. When comparing the results obtained with other fuels Biogas [32], where the performance of an absorption refrigerator implementing the exhaust gases of an (ICE) reaching a COP of 0.05 as the maximum value in the system, and the temperature registered at the entrance to the generator exceeded 450°C, while for biogas the inlet temperature reached 1170 ° C, which indicates a significant difference regarding the heat utilization.

IV. Conclusions

The solar radiation characterization as a renewable energy source in Monteria (Colombia) allowed to establish that there is an energy generation potential in this region due to the high irradiance and the wide peak of solar hours. On the other hand, the biogas produced from cattle manure shows good properties for energy utilization due to its high methane composition and its high calorific value.

The obtained temperatures and cooling times allowed to conclude that solar energy is a good source for cold generation through heat absorption, since it has a considerable stabilization time with a low stabilization temperature. Biogas also an important source of energy for the cold generation since it presents better performance than conventional sources used today such as LPG.

Analyzing the performance coefficient for each energy source, it was found that between the renewable energies, the best performance coefficient obtained was solar energy, however, when the heat generation is at low temperature using electrical energy, it may not be as attractive from the exergetic point of view due to the destruction of exergy that this implies. On the other hand, biogas shows better performance than LPG, especially when considering the operating coefficient with respect to the reversible cycle.

The performance obtained with Biogas can be increased by improving the heat transfer losses, which can be achieved by redesigning the geometries of both the burner and the absorber of the system.

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