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The Effect of Solar Irradiance on Innovative Autoclave Operated by Solar Energy

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Abstract
An autoclave is a device for sterilizing medical and surgical tools in hospitals and healthcare centers. The lack of electric power supply in some hospitals and rural health centers, in addition to pollution caused by fossil fuels, reinforces the need to search for other energy sources to operate the autoclave. Solar autoclaves can be utilized as an alternative choice in such circumstances. This work describes the effectiveness of the solar-powered autoclave, which is used for wet sterilization. The device is designed from a parabolic dish reflector covered with mirrors that reflect solar radiation toward the center of a focus for heating a vessel. It was found that the highest value of the average energy efficiency was 19 % and the average exergy efficiency was 2 % at 9:00 am and the lowest value of the average energy efficiency was 1.5% and the average exergy efficiency was 0.4 % at 12:00 noon. The effectiveness was tested against *(pseudomonas aeruginosa)* bacteria, where the highest values of steam temperatures for sterilization were recorded between 121 °C to 122 °C. It was also found that the sterilization efficiency was 100 % under steam pressure of 1.18 bar for every 30 minutes of the sterilization cycle for the periods 11:00 am to 11:30 am, 11:30 am to 12:00 noon, and 12:00 noon to 12:30 pm).

Keywords: Solar autoclave, Sterilizing, Parabolic Dish, Solar energy, Exergy.

تأثير الإشعاع الشمسي في الأوتوكلاف المبتكر الذي تديره الطاقة الشمسية

ندى صباح صالح *, حازم حمود حسين
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الخلاصة
الأوتوكلاف هو جهاز لتعقيم الأدوات الطبية والجراحية في المستشفيات ومراكز الرعاية الصحية. إن نقص إمدادات الطاقة الكهربائية في بعض المستشفيات والمراكز الصحية الريفية، بالإضافة إلى التلوث الناجم عن الوقود الأحفوري، يعزز الحاجة إلى البحث عن مصادر طاقة أخرى لتشغيل الأوتوكلاف. يمكن استخدام الأوتوكلاف الشمسية كخيار بديل في مثل هذه الظروف. يصف هذا العمل فعالية الأوتوكلاف الذي يعمل بالطاقة الشمسية، والذي يستخدم في التعقيم الرطب. الجهاز مصمم من صحن عاكس مكافئ مغطى بمرايا تعكس الاشعاع الشمسي باتجاه مركز البؤرة لتسخين الوعاء، وقد وجد أن أعلى قيمة لمتوسط كفاءة الطاقة كانت 19٪ ومتوسط كفاءة جهد الطاقة هو 2 ٪ الساعة 9:00 صباحًا وكانت أقل قيمة لمتوسط كفاءة الطاقة 1.5٪ ومتوسط كفاءة جهد الطاقة 0.4٪ عند الساعة 12:00 ظهرًا. تم اختبار الفعالية ضد بكتيريا

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(pseudomonas aeruginosa) حيث سجلت أعلى قيم لدرجات حرارة البخار للتعقيم بين 121 درجة مئوية إلى 122 درجة مئوية. كما وجد أن كفاءة التعقيم كانت 100٪ تحت ضغط بخار 1.18 بار لكل 30 دقيقة من دورة التعقيم للفترة من 11:00 صباحاً حتى 11:30 صباحاً، ومن 11:30 صباحاً حتى 12:00 ظهراً، و 12:00 من الساعة 12:00 ظهرًا حتى الساعة 12:30 ظهرًا.

1. Introduction

The use of renewable energy has become necessary because it is inexpensive and environmentally friendly [1]. As a consequence of this, researchers throughout the world are endeavoring to develop non-traditional renewable energy sources and related technologies. One of these technologies is the modern autoclave powered by renewable energy (especially solar energy), which can be used in remote health clinics as an inexpensive and effective sterilization tool [2], where solar energy is regarded as a prominent and vital source of renewable energy in Iraq and around the world [3]. Autoclaves have a major role to play in saving millions of people's lives in developed countries, through the use of sterile reusable operative tools, which do not give way to the transference of pathogenic microorganisms [4]. As a result of the conditions of global warming gas and emissions into the atmosphere that have caused global climate change and the severe shortage in energy supplies in Iraq, it has become necessary to introduce renewable energy sources, in order to lessen reliance on fossil fuels [5,6]. This ultimately leads to reducing the dangerous consequences of polluting gases on human health and the negative impacts on the economy and the environmental system [7]. Renewable energy has a significant advantage over fossil fuels, because renewable energy sources emit far less CO_2 into the atmosphere than fossil fuels, which are the greatest pollutant [8].

An autoclave is a pressure chamber that generates high temperatures of compressed steam that are higher than the temperature and pressure of the surrounding air. It is utilized in medical applications to carry out sterilization. Standard temperature and pressure for autoclaves done at high temperatures for short periods are better than low temperatures for longer periods [9]. To ensure the effectiveness of autoclaves, these devices must be examined to be sure that the sterilization performance meets the requirements. There are three pointers that can be utilized to reveal the effectiveness of the autoclave operation: (1) Physical: pressure and temperature registration devices [10]. Standardized autoclave sterilization is performed either at 121 °C and 1.1 bar for 20–30 min or at 135 °C and 2 bar for 5–7 min [11]. (2) Chemical: indicators that change color when exposed to specific temperatures, like temperature-sensitive tape. The autoclave tape consists of a porous paper coated with a lead carbonated thermochromic dye, if used correctly, black lines appear on the tape if the temperature reaches 121 °C. Unfortunately, the autoclave tape does not indicate for how long a temperature is maintained in the cycle but only indicates that it has been reached, it does not indicate whether sterilization has been done or not [12]. (3) Biological: *Bacillus stearothermophilus* spores are employed for analyzing the biological performance of the autoclave operation due to their heat resistance [13].

2. Material and Methods

2.1. Device engineering

During the study period in (March 2022) from 9:00 am to 3:00 pm local time in Baghdad city (33.31 latitude, 44.361 longitude), 500 ml of water was put into the vessel. The bacterial type was examined (*Pseudomonas aeruginosa*) to check the sterilization performance of the solar autoclave.

2.1.1. Parabolic Dish: Is a satellite dish elliptical that is old and neglected, and was recycled and painted with reflective chrome, then to increase the amount of reflected solar radiation, it was covered with square pieces of aluminum-coated mirrors whose dimensions were 0.05 x 0.05 m^2 at a reflectivity rate of 95% [14]. The manufactured design has the following geometric features: the diameter is 95 cm, the depth is 11 cm, the focal length is 51.3 cm, and the dish area is 1.473 m2 (See Figure 1).

2.1.2. Control and steering base: The device consists of an iron structure designed in a way that allows the plate to move 360° horizontally and vertically, which achieves the required flexibility to trace the sun during its movement to obtain the most irradiance and enhance the reflectivity toward the focal (vessel) without barriers, with moving wheels at the ground base.

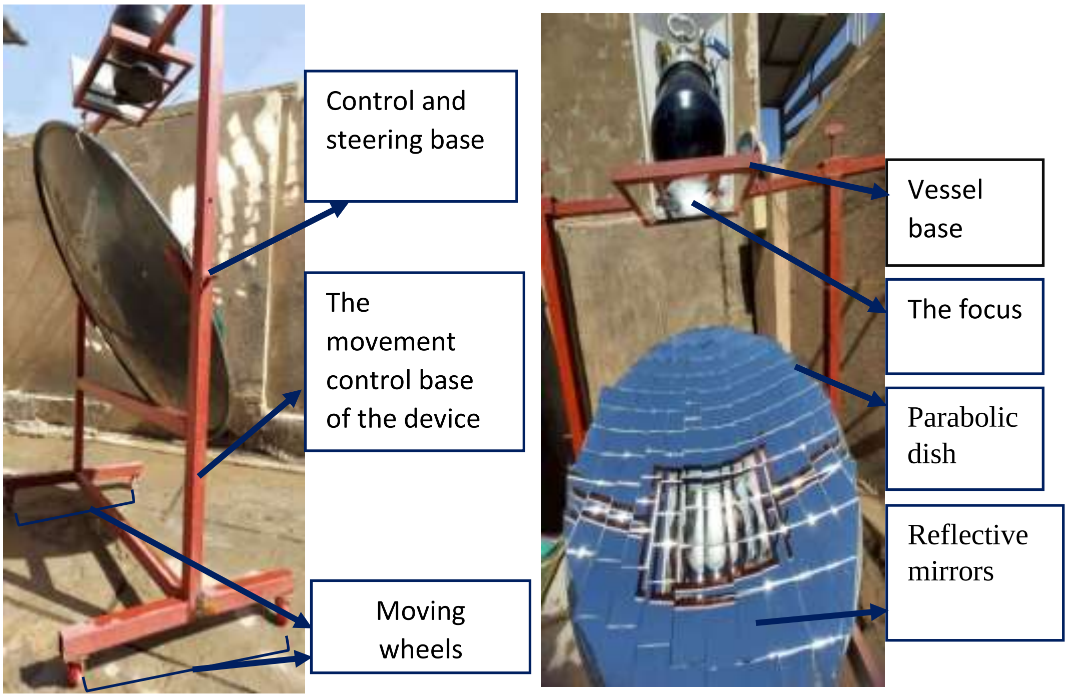

Figure 1: Solar autoclave parts

2.1.3. Vessel: It is made of steel capacity (7 liters) and painted in a matte black color in order to maximize the absorption of sunlight. The vessel was modified by installing a pressure device to measure the pressure of the steam within the vessel, a thermometer to measure the temperature of the steam within the vessel, and a steam control valve inside the vessel that can be tightly closed to reach the temperature of the pressurized steam required for sterilization or opened to edit the steam, as shown in Figure 2.

2.1.4. Added tools to improve performance: An old light cover made of white acrylic plastic was added, in addition to two pieces of remnants of secondary ceilings made of the same plastic material that surrounds the vessel on three sides. This type of plastic is able to selectively reflect near-infrared radiation [15], and its reflection of solar radiation is about 80 % [16]. They act as windbreaks to maintain pot temperature without wasting energy.

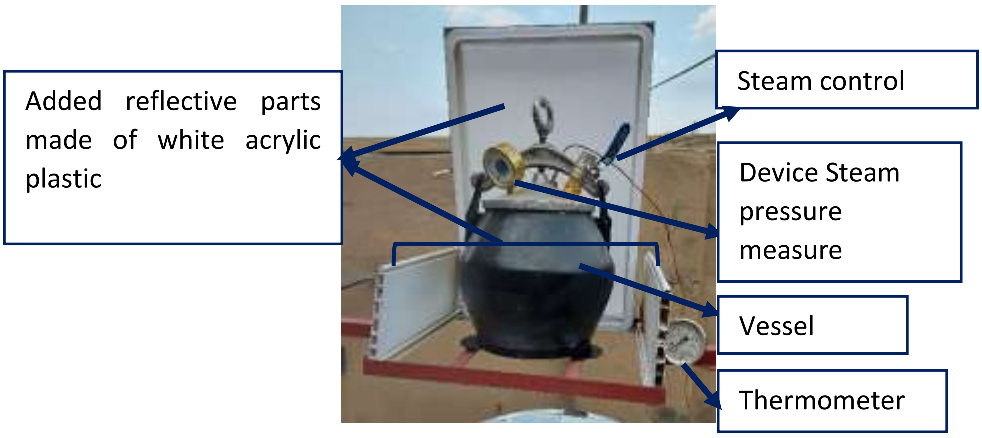

Figure 2: Parts of the solar autoclave with parts added to improve performance

2.2. Thermal Energy efficiency

Energy analysis is based on the first law of thermodynamics, which focuses only on the amount of energy used and the competence of energy processes. For the energy performance of a solar autoclave, the input and output amounts of energy must be estimated, and the total energy balance of a solar autoclave is written in the following form [17].

$$Energy\ input\ =\ Energy\ output\ +Energy\ loss \tag{1}$$

Energy efficiency indicates how much solar radiation energy falls on the reflector which is used for sterilization purposes [18]. The energy input of the solar autoclave is the total solar energy that falls on the solar burner on its reflective surface per unit of time per unit area [19], which is given by:

$$E_i\ =\ I_b\ \times A_{sc} \tag{2}$$

Where: E_i is energy input to the solar autoclave in Watt.
I_b: Intensity of solar irradiance (W/m^2) during the time interval Δt.
A_{sc}: The parabolic dish surface area (m^2) can be given using the following equation:

$$A_{sc} = \frac{8\times\pi}{3}\times f^2\left[\left(\left[\frac{d}{4f}\right]^2+1\right)^{3/2}-1\right] \tag{3}$$

$A_{sc} \simeq\ 7452\ cm^2 = 0.7452\ m^2$

Where: d: Diameter , f: (focal length): The distance between the center and the focus point that is called the focal length [20].

$$f = \frac{d^2}{16\times h} = (95)2/16\times 11 = 51.3cm\ = 0.513m \tag{4}$$

h: The depth of the dish

The energy output (heating power) of a solar autoclaving system is the energy stored in the receiver dish to be used in sterilization as the water temperature is raised by the heat transferred from (T_{wa}) to (T_{wb}) and can be calculated by the next expression: [21].

$$E_o = \frac{M_w\, C_{pw}\ (T_{wb} - T_{wa})}{\Delta t} \tag{5}$$

E_o: Energy output in watts **,** M_w: Mass of water (kg)**,** C_{pw}: Specific heat of water = (4186 J/Kg.K)[22]. T_{wa} : First temperature of the water in (K) **,** T_{wb}: End temperature of the water in (K)**,** Δt: Is the time in(s).
The relative of energy output to input is given by [23].

$$\eta = \frac{E_o}{E_i} \times 100 \tag{6}$$

(Where: η = Energy efficiency)

2.3. Thermal Exergy Efficiency

Exergy analyses are based on the second law of thermodynamics, which not only takes into account the system's non-return but is also directly related to the quality of the energy that is on hand. Exergy is defined as the maximum amount of action that may be generated by exploiting a system or an energy influx that is available at a certain temperature [24]. Considered exergy is a true measure of system performance. This way offers a replacement means of assessing and comparing solar autoclave because exergy efficiency takes into account the temperatures correlating with the energy transport from and to a solar autoclave, also the amounts of energy transported and, hence, beget an approximation metric of the idealistic yield of these devices [25].

$$E_{xo} = \frac{(M \times C_P)w\,[(T_{wf} - T_{wi}) - T_{air}\, ln\,(T_{wf}/T_{wi})]}{\Delta t} \tag{7}$$

Terms: (E_{xo}): Exergy output**,** T_{wi}: First water temperature (K)**,** T_{wf}: End water temperature (K)**,** T_{air}: Ambient temperature of reference during the specified time interval (K)**,** Δt: Recording time between two instants (s).
Exergy input may be introduced as:

$$E_{xi} = I_b\left[1 + \frac{1}{3}\left(\frac{T_{air}}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_{air}}{T_s}\right)\right]A_{SC} \tag{8}$$

T_s= The sun's surface temperature (~5800 K)
The exergy efficiency (ψ) of the solar autoclave can be branded as the exergy output (E_{xo}) linked with water in the form of an increase in temperature to the exergy input (E_{xi}) linked to solar radiation indicated in eq. (10). This offers a quality metric of beneficial energy that is available for consumption [26].
The overall exergy balance of solar autoclave can be written as [26, 27]:

$$Exergy\ Input = Exergy\ Output + Exergy\ Loss \tag{9}$$

$$\psi = \frac{\text{Exo}}{\text{Exi}} \times 100 \tag{10}$$

terms: ψ = exergy efficiency.

3. Results and Discussion

Figure 3 shows that the average steam temperatures for the month of (March 2022) at the beginning of the day had low values, when the values of the average intensity of solar radiation were low, as the lowest value of the average steam temperature was (30 °C) recorded inside the vessel and the lowest value of the average steam pressure was (0 bar) at (9 am), when the average intensity of solar radiation was (328 W/m^2) and the values gradually increased until they reached the highest values at (12 noon), of the average steam temperature inside the vessel became (122 °C) and the higher values to the average steam pressure inside the vessel was (1.18 bar). When recording the highest average intensity of solar radiation (592 W/m^2), the values began to decrease gradually until the average steam temperature inside the vessel reached (80 °C) and the average steam pressure became (0.16 bar) at (3 pm), while the average intensity of solar radiation was (418 W/m^2). Through the values shown in the figure, we notice that the best sterilization period for the device was between (11:00 am to 12:30 pm), where the average steam temperature was recorded between (121 °C to 122 °C) under a steam pressure of (1.18 bar).

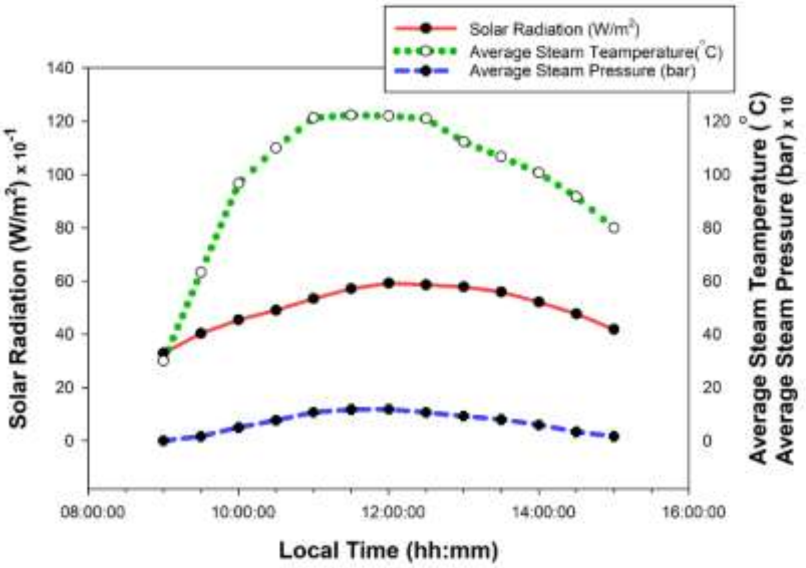

Figure 3: Relation between solar radiation and steam temperature average and steam pressure average with time in March.

Several samples of bacteria *(Pseudomonas aeruginosa)* were used to examine the sterilization efficiency of the solar autoclave device. One sterilization cycle took 30 minutes, and the sterilization efficiency reached 100%, knowing that the period between (10:00 am - 11:00 am) and the period from (1:00 pm until 2:00 pm) were tested during which the sterilization was successful at steam temperature average values ranged between (100 °C to 112 °C), at steam pressure average ranging from (0.7 bar to 0.9 bar), but it took a longer time for one Cycle, ranging from (40 to 60) minutes. All samples were examined in the Department of Biology Sciences in the College of Science at Mustansiriyah University, and the results showed that they were completely sterile, as shown in Figure 4-a,b. c

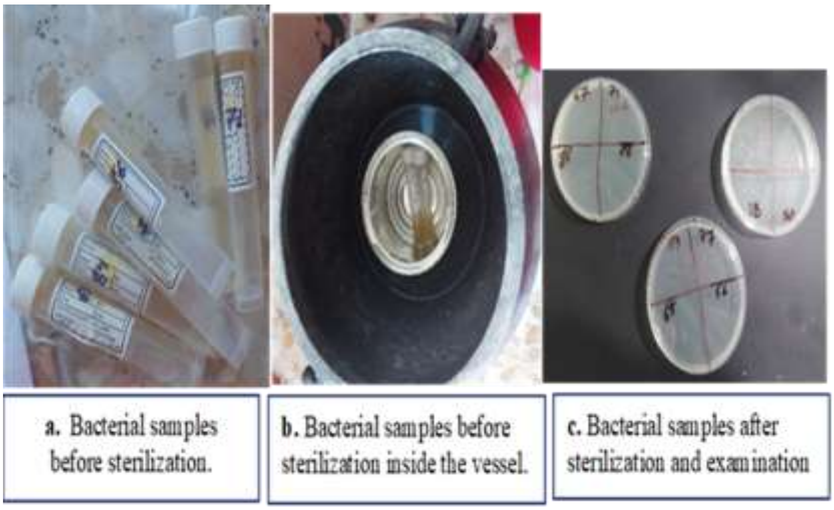

Figure 4: Photographs of bacteria samples prior to sterilization inside the solar autoclave and sterilization test results

Figure 5 shows the correlation between the average solar radiation intensity, and the energy efficiency rate in the solar autoclave with time from (9 am to 3 pm) for (March 2022). We note that when the value of the average intensity of solar radiation was at its lowest value at the beginning of the day at (9 am) which amounted to (328 W/m^2), the average energy efficiency reached the highest value of (19%). This means that the amount of energy necessary to raise the water temperature from the ambient temperature to the boiling point was very high as a consequence of the low intensity of solar radiation. After that the average intensity of solar radiation gradually increased to reach the highest value (592 W/m^2) at (12:00 noon), then the average energy efficiency rate gradually decreased until it reached (1.5%) at the same time. This means that the energy required to raise the water temperature from the ambient temperature to the boiling point was very low because of the excess in the average intensity of solar radiation. After that, the average intensity of solar radiation began to decrease gradually to reach (418 W/m^2) at (3 pm) and average energy efficiency began to increase gradually until it reached (4.2%). This means that the energy required to lift the water temperature from ambient temperature to boiling point became higher because of the lower mean intensity of solar radiation.

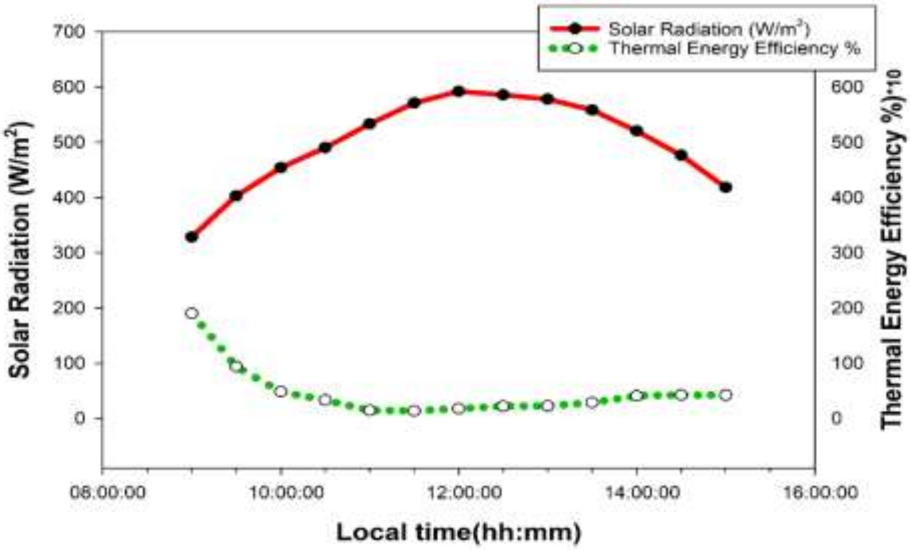

Figure 5: Relationship between average solar radiation and average thermal energy efficiencies with time in March.

Figure 6 shows the correlation between the average solar radiation intensity and the exergy efficiency rate in the solar autoclave with time from (9 am to 3 pm) for the month (of March 2022). We note that when the value of the average intensity of solar radiation at the beginning of the day was its lowest value at (9 am), which amounted to (328 W / m^2), the average energy efficiency rate reached the highest value (2%) because of the low intensity of solar radiation, meaning that the useful energy was consumed by the device virtually to lift the water temperature to the boiling point the highest value. After that, the average intensity of solar radiation gradually increased to reach the highest value (592 W/m^2) at (12:00 noon), then the average exergy efficiency gradually decreased to reach (0.4%) at the same time, meaning that the useful energy was consumed by the device virtually to lift the water temperature to the boiling point, a very low value because of the low intensity of solar radiation. After that, the average intensity of solar radiation began to decrease gradually to reach (418 W/m^2) at (3 pm), and the average exergy efficiency began to increase its values gradually, to reach (0.8%) at this time, meaning that the useful energy consumed by the device virtually to lift the water temperature to the boiling point became higher because of the rise in the average intensity of solar radiation

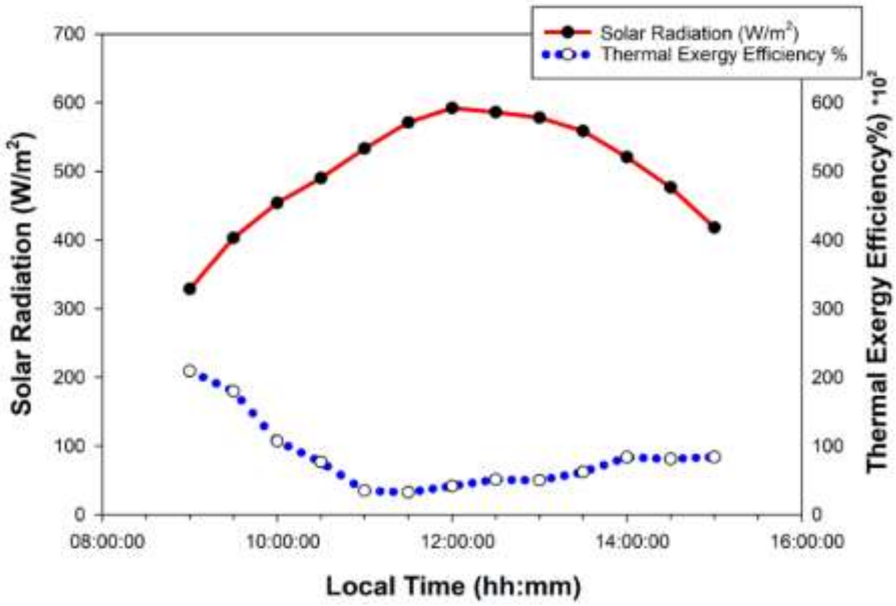

Figure 6: Relationship between average solar radiation and average thermal exergy efficiencies with time in March

Figure 7 shows the relationship between the average solar radiation intensity and the solar autoclave efficiency rate with time from (9 am to 3 pm) for the month (of March 2022). We note that when the value of the average intensity of solar radiation was its lowest value at the beginning of the day at (9 am) which amounted to (328 W/m^2), the device efficiency rate reached the lowest value (of 81%), after which the average intensity of solar radiation gradually increased to reach the highest value (592 W/m^2) at (12:00 noon), then solar autoclave efficiency rate gradually increased to reach (99%) at the same time. After that the average intensity of solar radiation began to decrease gradually to reach (418 W/m^2) at (3 pm), and the solar autoclave efficiency rate began to decrease its values gradually, to reach (93%) at this time.

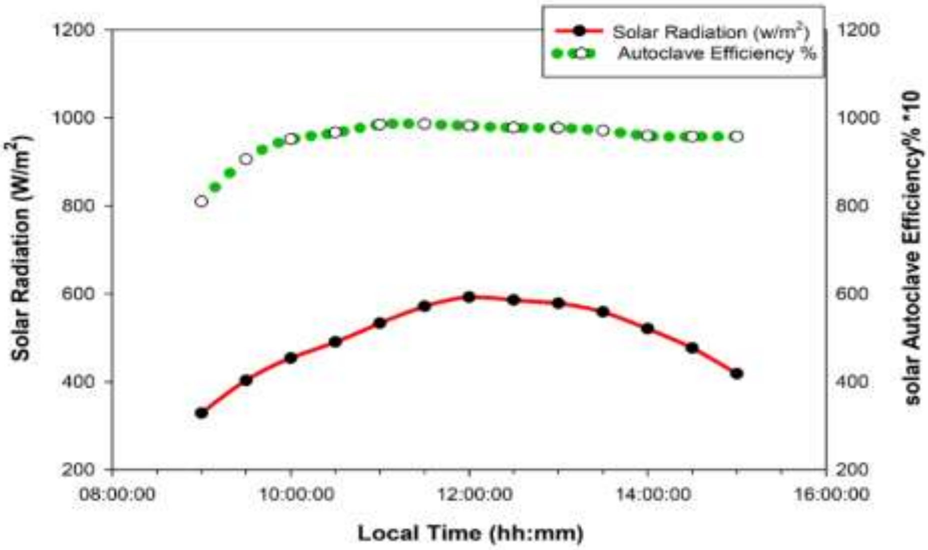

Figure 7: Relationship between solar radiation and solar autoclave efficiency rate with time in March

5. Conclusions

The solar autoclave was designed to contribute to solving sterilization problems in an economical manner, which reduces the consumption of fossil fuel energy and helps in exploiting renewable energies, reducing pollution problems, environmental problems, and costs. This device uses energy freely available from solar energy sources in Iraq. The oval solar autoclave was designed using available local materials after recycling, an abandoned TV satellite dish was recycled and some abandoned and scattered materials, such as remnants of secondary surfaces, the old lamp shade is made of plastic white acrylic. This contributes to reducing the volume of accumulated materials in our environment and reusing them for useful things to reduce pollution. It was found that the efficiency of the sterilization device increased with the increase in the intensity of solar radiation. The efficiency of the thermal energy required to heat the device and the efficiency of the useful thermal exergy consumed to boil water were increasing whenever the intensity of solar radiation was low, and the efficiency of sterilizing the device was 100% whenever the intensity of solar radiation exceeded (530 W / m^2) between (11:00 am and 12:30 pm).

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